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APPLYING PHOTONICS IN CANADIAN INDUSTRY

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APPLYING PHOTONICS

IN

CANADIAN INDUSTRY

Prepared for

Industry Canada

as part of the

Photonics Sector Campaign

October 1993

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Photonics - A Strategic Technology

A significant opportunity exists for Canada to capitalize on the emergence of photonics as a key enabling technology. The opportunity includes the potential not only for building a competitive photonics sector but also for achieving growth in sectors where photonics offers new capabilities that were not possible before. Photonics, or advanced light-based technologies, has been identified as a strategic family of technologies which will result in the advent of new equipment with capabilities that are impossible to obtain with any other technologies. Photonics has the potential to play as key a role in the next fifty years as electronics played in the last half of the present century.

The current worldwide production of photonics components, equipment and systems is about $72 billion, and is forecast to increase to $300 billion by the year 2000. Photonics is rapidly becoming a pervasive technology, with the potential for application in the following crucial areas of the Canadian economy: telecommunications and information technologies, aerospace, medical, automotive, resources, energy and civil engineering sectors, and especially manufacturing, where the use of photonics in flexible manufacturing systems is becoming increasingly critical.

The Vision

The vision that we propose is a strong and vibrant export-oriented photonics sector with a $5 billion annual production of photonics components, equipment and systems by the year 2000. In achieving this vision, Canada's current strengths in the application of photonics technology to telecommunications and avionics would be enhanced. At the same time, photonics technology would add value to other sectors of the Canadian economy. In particular, a window of opportunity exists for using the unique capabilities of photonics to promote the vertical integration of Canada's machinery industry sector, the vitality of which would increase the international competitiveness of the industry sectors that use machinery, especially manufacturing and the resources-based sectors.

The production target of $5 billion represents a growth rate of 20 per cent per year from the 1992 estimated production of $1.2 billion, and would maintain Canada's share of world photonics production at the current 1.7 per cent of this high growth strategic sector.

The Canadian Photonics Sector

The Canadian photonics sector consists of about 90 companies. The industry is dominated by a small number of large companies, with ten per cent of the companies generating three quarters of the output. Along with a handful of large companies that produce photonics equipment as part of their product mix, there are numerous small companies that produce specialized components and equipment for niche markets. For many of these companies, domestic sales constitute only a minor portion of their total sales.

The largest photonics application area in Canada is telecommunications, which accounts for approximately one half of Canada's photonics output. Another important sector is aerospace, which accounts for approximately one-quarter of Canadian photonics production.

Most of the remaining Canadian production is in other manufacturing-related areas, in remote sensing equipment and in forestry sector equipment. Collectively, these areas encompass well over half of the companies but account for only one-quarter of current Canadian production. It is this segment which has the greatest impact on other sectors of the Canadian economy, and which appears to have the greatest growth potential.

Opportunities for Photonics Applications

In arriving at the vision, the following application areas for photonics technology were examined for business opportunities and for potential barriers that could hamper effective pursuit of these opportunities: aerospace, manufacturing equipment, oil and gas and forestry (the application of photonics to telecommunications equipment was investigated in a companion study). In each of the sectors, a number of promising, but as yet unrealized, opportunities were identified through consultations with industry representatives at a number of industry working group meetings supplemented by individual meetings with key individuals.

One of the opportunities identified has the potential for impact on several sectors. An opportunity exists for developing a smart structure interface chip, which would provide an interface between fibre-optic sensors embedded inside structural materials and external measurement systems. This key component would allow smart structures to be used to advantage in construction, pipeline and aerospace applications.

In the manufacturing sector, there is an opportunity for a laser material processing centre, which would not only provide a systems integration function for Canadian component suppliers to produce advanced laser-based materials processing systems but would also provide a state-of-the-art facility for manufacturers requiring access to fast turn-around solutions to advanced materials and manufacturing problems. Another promising opportunity in manufacturing is for automated integrated imaging systems.

In the forestry sector, there appears to be an opportunity for developing equipment for three-dimensional profiling of logs through multiple-axis scanning. In the oil and gas sector, opportunities were identified in pipeline remote leak detection and in just-in-time gas compressor maintenance. Flat panel displays, imaging and sensing systems, virtual reality interfaces, smart structures and human-machine interfaces were identified as promising areas in avionics.

Opportunities for the application of photonics in telecommunications, which were identified in the companion study, were for photonic backplanes, components for an ATM switch, wavelength-division-multiplex components, solid-state waveguide and heterojunction bipolar transistors.

Barriers

Our study also showed that these opportunities are not being pursued for a variety of reasons. A common theme that ran through most of the sectors was the lack of a strong systems integration capability. The main area of Canadian strength in most of the sectors examined were small, innovative manufacturers of components and small equipment. They are dependent to a large degree on other firms to provide the required systems integration capability, which can take either the form of large equipment and systems suppliers that produce a line of products for a large number of customers or of specialized integrators who provide custom installations for small number customers, to supply end users with fully integrated, operational and user friendly equipment and systems.

Another prevalent theme was the relatively low level of domestic user demand in the application areas studied. In many cases, these users were relatively sophisticated enterprises involved in the manufacture or supply of commodities or goods. Most of them were not interested in becoming actively involved in the design and production of equipment used by them, looking for others to keep them supplied with high-performance equipment. In this regard, the lack of a vibrant machinery and equipment sector is a disadvantage, not only to these user companies, but also to the technology suppliers whose components and equipment could be incorporated into comprehensive equipment and systems. A demanding domestic market can provide a good springboard for proving innovative products, but they must continue to compete in, and be successful in, global markets, which are becoming increasingly competitive.

The overall level of R&D in photonics appears reasonable, but it is concentrated in two sectors, telecommunications and aerospace. In several of sectors there is a need for an increase in collaborative R&D. The maintenance of R&D is particularly important for the smaller, niche players that make up the bulk of Canada's photonics sector. Unless they stay at the cutting edge of technology in their respective areas of specialization, they will not be able to continue in business.

Recognizing the strategic importance of photonics technologies, a number of countries are positioning themselves to ensure their involvement in the development and application of photonics. Japan has been the leader in this respect, closely followed by the U.S. and by the European Communities. Many of the Canadian photonics companies are highly export-oriented. The ability of Canadian companies to compete in this strategic area could be irreparably eroded if Canada does not take an aggressive approach to the development of the photonics industry.

Achieving the Vision

This report recommends proceeding with Phase III of Industry and Science Canada's Photonics Sector Campaign and presents an action plan that consists of two basic elements:

- allocation of government funding to support the formation of vertical alliances for the development and application of photonics in Canadian industry; and

- formation of the Canadian Photonics Corporation to promote and stimulate the application of photonics in user sectors and to collect and manage funds for that purpose.

Exhibit 2 shows estimates of the government funding required to implement the Photonics Sector Campaign. Together with the $155 million proposed in the companion study on the application of photonics to telecommunications, the maximum government funding required is estimated to be $340 million for the five-year period from 1994 to 1999. The minimum level of funding required to carry out a serious Photonics Sector Campaign would be about one-quarter of this amount, or $85 million, of which about ten per cent, or $8.5 million, would be required in the first year, 1994.

Exhibit 1: Government Funding Requirements for the Photonics Sector Campaign Implementation ($ million)

ACTIVITY	MAXIMUM 5-YEAR FUNDING	MINIMUM 5-YEAR FUNDING	FIRST YEAR FUNDING
Support for non-telecom collaboration	$175		
Support for telecom collaboration	155		
Operation of Photonics Corporation	10		
Total	$340	$85	$9

Exhibit 2 presents the proposed Canadian Photonics Corporation and its primary activities. It would work with industry to ensure that market-pull forces are brought to bear on photonics development and application projects. It would manage the funding provided to it by the government, allocating funds to specific projects on a cost-sharing basis with private sector participants, and it would carry out other promotional and networking activities to create a dynamic and cohesive user-oriented photonics industry in Canada.

The successful development and application of photonics technology will require the active participation of companies and organizations at some or all of the following five levels: technology generators, component and device manufacturers, equipment manufacturers, systems integrators and users, as shown in the shaded box on the right-hand side of Exhibit 2. In photonics, Canada is reasonably well represented at the first level, and has a number of small, highly innovative companies at the second level. The plan has been designed to build up the weakest level, systems integration, and at the same time to continue the development of the levels by connecting them more effectively to the levels above and below through the formation of alliances.

The action plan that we propose would overcome the identified barriers and stimulate the development of the photonics sector and, furthermore, would promote the application of photonics in other sectors of the Canadian economy, such as those examined in this study. The increase in productivity resulting from the innovative application of photonics technology would increase the competitiveness of these sectors in the face of strong international competitive pressures.

Exhibit 2
Dynamic Model of the Canadian Photonics Industry

1.0 INTRODUCTION

A significant opportunity exists for Canada to capitalize on the emergence of photonics as a key enabling technology in a range of industry sectors. The opportunity includes the potential for building a competitive photonics sector and for achieving growth in sectors where photonics offers new capabilities that were not possible before. This document presents a bold, new vision for the Canadian photonics sector and recommends an action plan for achieving this vision.

This section outlines this vision and presents the context in which the current study was conducted.

1.1 A Vision for the Canadian Photonics Sector

The vision that we propose is a strong and vibrant export-oriented photonics sector with $5 billion annual production of photonics components, equipment and systems by the year 2000. Our vision also includes significant value-added to a range of other industry sectors, achieved through the enabling effects of photonics technology. In particular, the opportunity exists to substantially enhance the Canadian manufacturing equipment sector and to add significant value to a number of other important Canadian sectors, such as telecommunications, aerospace, oil and gas and forestry. The increase in productivity resulting from the innovative application of photonics technology will increase the competitiveness of Canadian industry in the face of strong international competitive pressures.

A Canadian production target of $5 billion represents a growth rate of 20 per cent per year from the 1992 estimated production of $1.2 billion, and would maintain Canada's share of world photonics production at the current 1.7 per cent of this high growth strategic sector.

In arriving at the vision, a number of application areas for photonics technology were examined for business opportunities and for potential barriers that could hamper the effective pursuit of these opportunities. In each of the sectors, a number of promising, but as yet unrealized, opportunities were identified. It is apparent from our research that there is a dire need within Canadian industry to develop or expand the capability to integrate available technology and components into fully operational equipment and systems that meet user needs. Also evident was the low level of awareness on the part of users about the strategic role that photonics technology could play in increasing their capabilities.

1.2 The Strategic Importance of Photonics Technology

Photonics, or advanced light-based technologies, has been identified as a strategic family of technologies which will result in the advent of new equipment with capabilities that are impossible to obtain with any other technologies[1]. Photonics has the potential to play as key a role in the next fifty years as electronics played in the last half of the present century.

Elliott Consulting[2] defines photonics as "modern (post 1960s) science and technology concerned with manipulating both electrons and electromagnetic radiation (i.e. photons) at frequencies close to those of light". Photonics Spectra, the monthly U.S. trade magazine, defines photonics as the technology of generating and harnessing light and other forms of radiant energy whose quantum unit it the photon. The range of applications of photonics extends from energy generation to detection to communications and information processing." Both definitions are very similar, and appear to include the optical analogues of both electrical and electronic phenomena.

For consistency, we have adopted Elliott Consulting's definition not only for photonics but also for photonics equipment and systems, which counts the full value of the end product if that product would not exist without photonics technology and the value of the photonics component only if the photonics technology could be equally be replaced by another technology[3].

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1 See, for example, *"The Light Fantastic"*, Business Week, May 10, 1993 p. 44, or E.A. Martin, *"Photonics: A Lever to Change the World"*, Photonics Spectra, January 1991, p. 84.

2 Elliott Consulting, *"Photonics: A Canadian Perspective"*, prepared for Industry, Science and Technology Canada, April 24, 1991.

3 The definition adopted here should be kept in mind in considering the estimates of photonics production presented in this study.

The worldwide production of photonics components, equipment and systems is estimated to be \$72 billion in 1992, and is forecast to increase to \$300 billion[4] by the year 2000. Photonics is rapidly becoming a pervasive technology, with the potential for application in the following crucial areas of the Canadian economy: telecommunications and information technologies, aerospace, manufacturing, medical, automotive, energy, civil engineering, etc. Although its application is developing at different rates in each of these areas, the use of photonics technology is becoming increasingly critical to flexible manufacturing systems.

Recognizing the strategic importance of photonics technologies, a number of countries are positioning themselves to ensure their involvement in the development and application of photonics. Japan has been the leader in this respect, closely followed by the U.S. and by the European Communities. Canada's ability to compete could be irreparably eroded if it does not take an aggressive approach to the development and application of photonics.

1.3 The Photonics Sector Campaign

In 1990, Industry and Science Canada (ISC) recognized the potential of photonics and commenced Phase I of its Photonics Sector Campaign by commissioning a study by Elliott Consulting[5] to make a preliminary assessment of the economic potential for the application of photonics to Canadian industry. The study concluded that there were major opportunities in three sectors: industrial applications, avionics and telecommunications.

These results were sufficiently encouraging that ISC decided to proceed with Phase II of the Photonics Sector Campaign, commissioning two study contracts, one to examine opportunities for the application of photonics to telecommunications[6] (which will be referred to in subsequent discussions as the TECH TEAM study), and this study, which examines the application of photonics to a number of other sectors. The output of the two studies will be used to produce a proposal for an action plan, which is recommended to be implemented in Phase III of the Photonics Sector Campaign.

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4 We arrived at the estimate for 1992 using the figures provided by the Optoelectronics Industry and Technology Development Association (OITDA) of Japan in the OITDA Activity Report Vol. 6 for the fiscal year ended March 31, 1993 for 1992 Japanese production of ¥3.68 trillion, along with previous estimates of Elliott Consulting (see footnote 2). The year 2000 prediction was arrived at by blending the predictions of the OITDA for the year 2000 Japanese production of ¥16.2 trillion with the estimates of Elliott Consulting for the rest of the world.

5 See footnote 2.

6 TECH TEAM Management Inc., NGL Nordicity Group Ltd. and *i*/FO Technologies, *"Applying Photonics to Telecommunications"*, prepared for Industry and Science Canada, July 1993.

Photonics defines a generic family of technologies which can be applied over a broad spectrum of industrial sectors. ISC has a number of sector campaigns that relate to specific application areas, such as the Advanced Manufacturing Technology Sector Campaign. The implementation of these campaigns will reinforce the impact of the Photonics Sector Campaign.

1.4 This Study

This study examines opportunities and barriers for the application of photonics to a number of sectors, with particular attention paid to aerospace, manufacturing equipment, oil and gas, and forest products sectors. The report produced by this study is organized into two volumes. The first volume contains the following:

- an Executive Summary;
- the Strategic Approaches report, which recommends an action plan for overcoming barriers and pursuing business opportunities in photonics;
- the Business Opportunities report, which presents a number of business opportunities identified for the application of photonics in the sectors studied (Annex A);
- a report on collaborative R&D programs and practices in other countries (Annex B); and
- a photonics technology assessment (Annex C).

The second volume is the Photonics Industry and Research Capability Guide containing profiles of Canadian photonics suppliers and research institutes. It is bound separately for convenience of use as a stand-alone reference volume.

In order to carry out this comprehensive study a team of experts was assembled with expertise in photonics and in the application areas studied. This team was formally organized as Technical Business Facilitators Ltd., and included the following:

- NGL Nordicity Group Ltd., of Ottawa, Ont., provided overall project management, prepared the bulk of the profiles in the Capability Guide, was responsible for the strategic approaches and for report writing;

- *i*/FO Technologies, of Ottawa, Ont., provided specific technological capability in photonics, along with a broad knowledge of the photonics industry, contributed to the technology assessment and to the Capability Guide and provided advice and information on strategic considerations;

- TECH TEAM Management Inc., of Etobicoke, Ont., provided advice on strategic considerations and acted as facilitator at a number of industry meetings;

- J.C. de la Riviere and Associates Ltd., of Toronto, Ont., organized industry input and contributed to the report on business opportunities in small-scale manufacturing;

- J.R. Technologies, of Windsor, Ont., organized industry input and contributed to the report on business opportunities in large-scale manufacturing;

- Habitec Systems, of Montreal, Que., organized industry input and contributed to the report on business opportunities in aerospace;

- Technology Brokers Inc., of Edmonton, Alta., organized industry input and contributed to the report on business opportunities in oil and gas; and

- Cabot Management Ltd., of Vancouver, B.C., organized industry input and contributed to the report on business opportunities in forestry and to the Capability Guide.

The information for the Strategic Approaches and Business Opportunities reports was gathered mainly at separate Industry Working Group meetings held for the manufacturing, aerospace, oil and gas and forestry sectors. These meetings were supplemented by one-on-one meetings and telephone interviews with industry representatives, by a comprehensive literature search[7] and by a technology survey, which is reported in Annex C.

7 The report on the literature search was submitted separately.

2.0 OPPORTUNITIES AND BARRIERS

This section presents an overview of the Canadian photonics industry, followed by descriptions of the five sectors examined for opportunities for the application of photonics technologies: telecommunications equipment, aerospace, manufacturing equipment, oil and gas and forest products. Barriers preventing a more widespread application of photonics technology in these sectors are also discussed.

An important aspect of this section is to present a solid rationale (by concentrating on these five key sectors) for the recommended strategic approaches presented in Section 3.0. This following Section presents a generalized approach for achieving the vision and stimulating the application of photonics on a more general basis throughout all economic sectors.

The opportunities presented in this report are not intended to be exhaustive. They are, in fact, illustrative of the opportunities that exist for Canadian companies. While companies were willing to discuss possible opportunities, they were quite rightly reluctant to discuss in much detail opportunities that were closer to commercialization. There were strong indications, however, that they would be willing to talk in more specific terms once the government's intentions to act were more clearly signalled.

2.1 The Canadian Photonics Sector

The Canadian photonics sector[8] consists of about 90 companies with a total photonics-related production[9] of over $1.2 billion annually. The industry is dominated by a small number of large companies, with ten per cent of the companies generating three quarters of the output. Along with a handful of large companies that produce photonics equipment as part of their product mix, there are numerous small companies that produce specialized components and equipment for niche markets.

The largest photonics application area in Canada is telecommunications, which accounts for approximately one half of Canada's photonics output. The leading companies in this sector include Northern Telecom, MPB Technologies, EG&G Optoelectronics Canada, JDS Fitel and Canstar Communications.

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8 A separate volume of the report of this study, *"The Photonics Capability Guide"*, contains profiles of number of the photonics companies and research institutes.

9 The production estimate is dependent on the definition of photonics used. See Sec. 1.2.

Another important sector is aerospace, which accounts for approximately one quarter of Canadian photonics production, led by CAE Electronics, Canadian Marconi, AlliedSignal and Spar Aerospace.

Most of the remaining Canadian production is in other manufacturing-related areas, in remote sensing equipment and in forestry sector equipment. The leading companies in these areas are Lumonics, the largest pure photonics company in Canada, and Hughes Leitz Optical Technologies. Collectively, these areas encompass well over half of the companies but account for only one-quarter of current Canadian production. It is the segment which has the greatest impact on other sectors of the Canadian economy and which, in our opinion, has the greatest growth potential.

There are three research institutes dedicated to photonics: the Solid State Optoelectronics Consortium, the National Optics Institute and the Ontario Laser and Lightwave Research Centre. There are also significant photonics research capabilities in other publicly supported research institutes, for example, TRLabs, the Canadian Institute for Telecommunications Research, the Telecommunication Research Institute of Ontario, the Communications Research Centre and the National Research Council. Most of the activities in these institutes focus on telecommunications. The total annual expenditure on applied photonics research in these institutes is about $50 million.

2.2 The Telecommunications Equipment Sector

The Canadian telecommunications equipment sector[10] consists of some 300 companies with an annual production in the range of $6 billion. The global market for telecommunications equipment in 1990 was estimated to be about $130 billion annually[11], so that Canadian production represents just under five per cent of world production.

[10] See, for example, NGL Consulting Ltd., *"A Proposal Towards a Strategic Plan for the Canadian Telecommunications Equipment Industry. Part I: The Canadian Telecommunications Equipment Industry in a Global Context"*, prepared for Industry, Science and Technology Canada and the Canadian Telecommunications Action Committee, January 1991.

[11] ISTC Industry Profile: *Telecommunications Equipment*, 1993.

The sector is dominated by one large Canadian-based multinational systems house, Northern Telecom. It also includes a number of branch plants of foreign-based firms, several medium-sized suppliers, a series of smaller product development companies, and several systems integrators. The sector is involved in the production and marketing of a broad spectrum of systems and equipment used in the public switched telecommunications network, in private networks and by end users.

In photonics-based telecommunications technology, the dominance of Northern Telecom is even more striking. Other than Northern Telecom, the main photonics expertise resides in 15 to 20 smaller companies whose annual sales range from less than $1 million to about $50 million. These companies are mainly suppliers of test equipment and sub-components, and most of them lack access to large system design capability. Their time horizons are necessarily extremely short, and they are dependent upon larger laboratories for the generation of the technology that they in turn apply to their niche markets.

Telecommunications equipment manufacturing is a high-technology activity requiring enormous investments in R&D. The sector spends about 18 per cent of revenues on R&D, or approximately $1 billion annually[12]. Bell-Northern Research, which is owned jointly by Northern Telecom and Bell Canada, is the only Canadian industrial laboratory that is carrying on medium-term research activities in photonics technology for application in telecommunications. Canadian capability in photonics R&D is enhanced by the existence of a number of government and university-based laboratories and by several R&D consortia. The annual expenditure on photonic-related R&D is estimated to be no more than $25 million.

The main current application of photonics in telecommunications is fibre optics, which has become the "transmission technology of choice" for a broad spectrum of applications. The market pull for applications requiring the use of photonics technology in other parts of the telecommunication infrastructure has not yet materialized to any significant extent. When it does occur, however, there will be opportunities for photonics applications in the following areas, which were identified and are discussed more fully in the TECH TEAM study[13]:

- photonic backplanes
- components for an ATM switch
- wavelength-division-multiplex components
- solid-state waveguide
- heterojunction bipolar transistor

12 See preceding footnote.

13 See footnote 6.

The main barriers to the development of these opportunities identified by TECH TEAM were:

- lack of market pull
- lack of access by small and medium-sized companies to large system design capability

Currently, photonics represents about $600 million, or about ten per cent of the sector's annual Canadian production. If the market need materializes for some of the advanced photonics applications listed above, the photonics-related production could reach $2 billion in the year 2000, or ten per cent of the target of $20 billion for Canadian production in the sector set by the industry[14]. These figures translate to a growth in photonics products at an annual rate of 16 per cent, and could be achievable even if the total production target is not achieved, if the proportion of photonics in the product mix of the Canadian companies will increase to a somewhat higher level than the current ten per cent in the ensuing eight-year period.

2.3 The Aerospace Sector

The Canadian aerospace sector[15] is comprised of 150 companies with an annual production of about $9 billion. About 75 per cent of Canadian production is exported, primarily to the U.S. The Canadian production represents about three per cent of the global aerospace and defence market, estimated to be in excess of $300 billion annually.

The sector's markets include transport and general aviation aircraft manufacturers, regional airlines, business aircraft users, major civil and defence aerospace contractors and governments. In 1988, about 70 per cent of sector sales was to civilian markets, while the remainder was defence-related.

[14] NGL Consulting Ltd., *"A Proposal Towards a Strategic Plan for the Canadian Telecommunications Equipment Industry. Part II: A Framework for Action"*, prepared for Industry, Science and Technology Canada and the Canadian Telecommunications Action Committee, January 1991.

[15] ISTC Sector Profile: *Aerospace*, 1992.

The companies that make up the Canadian aerospace manufacturing industry can be divided into three tiers:

- the first tier, which is composed of 15 large companies with integrated design, development, manufacturing, marketing and product support activities and which account for 45 per cent of Canadian production;

- the second tier, which is composed of 40 medium-sized companies that are primarily suppliers of proprietary products and build-to-print components and which accounts for another 45 per cent of production; and

- the third tier, which is composed of more than 100 small companies with annual sales less than $20 million, predominantly suppliers of subcontract products and services and which accounts for the remaining 10 per cent of production.

The sector has a high degree of vertical integration, with third-tier companies being predominantly suppliers of subcontract products and services provided mainly in support of first-tier and second-tier companies.

The sector's production of photonics equipment and systems is currently about $300 million[16], or three per cent of the total. Most of the photonics capability resides in the first-tier companies, which are for the most part foreign-owned, exceptions being CAE and Spar Aerospace.

In the past, the prime motivation for the use of photonics in aerospace has been weight reduction and immunity to electromagnetic interference - characteristics used largely by the defence industries. And, although photonics technology will continue to play a major role in military applications, such as target recognition systems, surveillance and guidance systems, the maturation of the technology should encourage more widespread use with other qualities such as reliability and performance. Photonics sensors will enable smart structures to be incorporated in all industry sectors requiring real-time monitoring of structural soundness. Photonics-based human-machine interfaces will develop around display technologies, such as those which were developed initially for defence and aerospace applications.

16 This estimate of sector photonics production is highly dependent on the definition used for photonics. One of the leading companies in this field, CAE Electronics, produces simulators, much of which we have classified as non-photonics, following the definition of photonics explained earlier. See Sec. 1.2.

The industry views photonics as a technology necessary for the continued growth of the sector. The growth rate anticipated for photonics-related products in this area is in the range of 16 per cent per annum, which would result in a year 2000 production of about approximately $1 billion, or more than three times the current production. This growth rate may be a little high, in comparison with overall sector growth predictions. We have allowed for the possible distortion that could arise from the definition of photonics[17] used in compiling our data, and believe that the target production is consistent with the industry's own predictions for production growth.

Aerospace is one of the most R&D intensive industry sectors in the world. Canadian firms in this sector are niche players, who must continue to develop innovative products that embody leading edge technologies. Overall, the Canadian aerospace industry invests about 10 per cent of revenues on R&D. Photonics-related R&D in the aerospace sector is currently estimated to be in the $50 to $100 million range.

To date there has been very little R&D collaboration among the large companies in the aerospace sector. However, increasing global competition has forced these companies to recognize the necessity of working together. Canadian Marconi and CAE indicated that they were actively pursuing strategies of technology acquisition rather than depending solely on in-house development. This need for an R&D collaborative agreement within the industry will become ever more crucial as the decline in defence spending continues and the companies' expansion into commercial product lines requires links to civilian research and technology-specific institutes.

Within the aerospace sector, photonics is used essentially as an enabling technology. Significant opportunities for the use of photonics in the aerospace industry exist in upscale technology, high reliability and high performance specialized niche programs and projects. Canadian aerospace firms are incorporating many aspects of photonics technology in their current products, right up to the systems level. Research for this report revealed further business opportunities[18] in the following subjects:

- flat-panel displays
- imaging and sensing systems
- virtual-reality interfaces
- smart structures
- human-machine interfaces

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[17] See Sec. 1.2.

[18] See Annex A for a detailed description of these business opportunities.

Canadian aerospace companies are highly sensitive to the extraordinary economic and geopolitical changes that are occurring around the world. A significant barrier facing the growth of photonics within the Canadian aerospace industry is the marked reduction in defence spending - the response to the end of the NATO/Warsaw Pact. The end of the "Cold War" meant reduced military procurement, particularly by the U.S., Canada's largest export market. Current forecasts indicate a cumulative 25 per cent reduction in military procurement over the next five years. Canadian aerospace manufacturers are accordingly looking for diversification and also a higher civil content in their production.

The defence component of the Canadian aerospace industry was a vital base load and spur to R&D. As all products destined for use in the aerospace sector are benchmarked by performance rather than by cost, R&D must have high priority in order for the industry to maintain its leading edge in the competitive marketplace.

A second barrier to the more widespread use of photonics technology within the industry is the current global economic slow-down which is seriously affecting air traffic. Although air travel is likely to return to normal (high) growth levels in the near future, the fact remains that all aerospace procurements are relatively limited for the time being.

The Canadian aerospace industry is in dire need of R&D support in order for it to reach larger, more diversified markets and ultimately remain viable. The solution to financing this required R&D lies in the establishment of a mutually supportive, collaborative, pre-competitive photonics R&D program. This type of collaboration, as yet unprecedented within the industry, is becoming evermore vital as global competition continues to force the restructuring of the aerospace industry. The era of the virtual corporation is emerging in order to supply goods and services more efficiently.

Some of the larger companies in Canada and elsewhere are cautiously pursuing this solution of sharing the R&D risk, thus enabling each company to develop a portion of a system that showcases the leading edge technological strengths of the participants in the project.

However, regardless of how compatible the relationship may be between companies' R&D departments, Canadian government support has been deemed essential in a start- up and growth phase in order to allow the aerospace industry to compete on a level playing field. This is because the R&D risks with regard to photonics are primarily financial, rather than technology based. Foreign governments may very likely opt to support critical technologies used within their own technology infrastructure rather than subject embryonic projects to the fate of market forces.

2.4 The Manufacturing Equipment Sector

The manufacturing sector is the largest sector of the Canadian economy, with an annual production of about $200 billion. Since its annual expenditure on purchases of machinery, equipment and replacement parts is about $20 billion, the supply of modern, high performance machinery is an important factor of the sector's ability to remain competitive.

The Canadian production of machinery[19] in 1988 was $16.7 billion, the major part of it being machinery for manufacturing. Currently, the Canadian machinery and equipment sector runs a trade deficit in virtually all classes of equipment. Canadian imports exceed Canadian exports, indicating questionable overall Canadian competitiveness. This is due to the fact that the Canadian marketplace is too small to support the development of a wide range of specialized internationally competitive machinery and equipment. Added to this is the impetus of global manufacturing where certain machinery and equipment users standardize and harmonize technologies internationally. Overall, this set of structural circumstances has conspired to limit growth in the manufacturing equipment sector in Canada.

The Science Council study[20] concluded that the small domestic machinery sector is a serious structural impediment in the Canadian economy. Increasing global competition among manufacturers is so intense that Canadian manufacturers must adapt to the changing technological climate, if they are to survive. In this regard they are hampered by the absence of a dynamic machinery and equipment industry in Canada.

The study also concluded that machinery is sold to a relatively small number of sophisticated customers on the basis of their value to the businesses that will use them. Technology is a major factor in the success of failure of firms in the sector; for the more advanced technology firms, it is a dominant factor in business performance. Most of the R&D in the Canadian machinery sector is carried out by dedicated "specialist" companies Canada has some exceptionally creative and entrepreneurial firms, but most are small and unable to conduct significant R&D.

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19 Science Council of Canada, Sectoral Technology Strategy Series No. 10, *The Canadian Machinery Sector*, 1992. The Science Council defines machinery as equipment used to turn raw materials into finished goods.

20 See preceding footnote.

Machinery companies are being driven to improve their technology by customer demands for better service and higher-quality, higher-performance products; by increased competition due to fewer trade barriers; and by the need to increase the scale of their operations to support worldwide distribution. This puts a premium on innovation, which is also being driven by rising labour costs and environmental regulations.

The Canadian machinery sector spends about one per cent of its sales revenues on R&D, compared with 3.3 per cent in Sweden, 2.6 per cent in Germany, 1.7 per cent in Japan and 1.5 per cent in the U.S. However, the spending of Canadian-owned companies in the sector is at a much higher rate, four per cent of revenues. R&D in the sector tends to concentrate on incremental improvements, customized development and new product development rather than on applied research, and most of it is carried out by dedicated "specialist" companies. Canada has some exceptionally creative and entrepreneurial firms, but most are small and unable to conduct significant R&D.

Along with information technologies, photonics is expected to play a key role in increasing the performance capabilities of the manufacturing equipment in the year 2000, which will be faster, more accurate and more flexible. Photonics can be the technology that gives Canadian manufacturers that new competitive edge. Both the structure of the Canadian machinery industry and the nature of technological change in machinery products globally suggest photonics is an admirable lever for upgrading Canadian manufacturing.

The use of photonics within the manufacturing equipment sector, will occur in the following three areas: factory control, material processing and sensing and vision. The immunity of photonics to electromagnetic interference will be the primary instigation for its use in factory control. Material processing can be exemplified by laser-based metal cutting and welding for high precision machining. Photonic sensing will for the most part be used in high precision non-contact gauges for robotics systems and for material inspection. For these applications, the basic technologies required are now available.

The global market for advanced manufacturing equipment is predicted[21] to grow from the estimated 1990 level of $61 billion to nearly $220 billion by the year 2000. During this period, the Canadian market for advanced manufacturing equipment is predicted to grow from $2 billion to $7 billion. The Canadian production of photonics-related manufacturing equipment is difficult to estimate, but it is probably no more than ten per cent of the production of advanced manufacturing equipment. If this percentage does not change by the year 2000, the predicted production of photonics-related manufacturing equipment will be $700 million.

The fastest growing areas in Canada are predicted[22] to be production control systems and advanced test and inspection systems, followed by automated assembly and packaging systems. In North America, the fastest growing category is expected to be automated assembly and packaging systems, while in Europe the fastest growing category is expected to be production control systems.

Most Canadian manufacturers appear to be interested in using photonics as critical enabling technologies in their activities, e.g. laser welding and machining, in-process inspection, bar-code tracking of components and products. Moreover, some large-scale equipment manufacturers are also interested in incorporating photonics in their products.

Research with industry representatives for this report identified five potential collaborative projects that would incorporate photonics technology in the Canadian manufacturing sector. These five projects[23] are:

- automated integrated imaging systems: inspection systems for film, paper and steel, where one looks for the deviation against the norm in a continuous media, and also where one looks at individual characteristics rather than at a standard;

- technology centre for laser materials processing and manufacturing: establishment of a core business unit in an industrial laser systems integration facility;

[21] Industry, Science and Technology Canada, *"Advanced Manufacturing Technology: The Year 2000"*, undated.

[22] See previous footnote.

[23] See detailed descriptions in Annex A.

- fibre-optic location, orientation and machine compensation: use of fibre-optic technology to facilitate engine crankshaft orientation in engine assembly;

- photonic quality validation system: development of automated, in-process quality validation procedures; and

- automotive instrument panel: instrument panel related systems, heads-up display related photonics research.

What appears to be lacking in the Canadian manufacturing equipment industry is a strong capability to integrate the components and equipment produced primarily by small Canadian suppliers into turn-key systems needed by the manufacturers. A recent study[24] identified 49 systems integrators working in the field of advanced manufacturing technology, but most of them are very small companies doing custom work. The five projects above represent "door openers" and could possibly act as initial spurs both to the development of a stronger systems integration capability in Canadian manufacturing, and to the development of novel large-scale mass-produced products.

There is also a high cost and risk of market development and commercialization including the demonstration of working prototypes of advanced manufacturing technology equipment that contains photonics components. The photonics developers indicated that as a rule, they have more success in selling their products abroad than in Canada.

Canadian research capacity in photonics appears to be an under-utilized resource. Researchers have a strong interest in cooperation with industry in the development and application of photonics technology. Photonics technology researchers with relevant research and consulting experience and with excellent research facilities are urging Canadian companies to contact them with regard to specific projects or problems.

[24] See footnote 21.

2.5 The Oil and Gas Sector

The Canadian oil and gas industry had revenues in 1989 of $50 billion[25], or 12 per cent of GDP. The industry is dominated by major integrated multi-national firms, and 15 to 20 medium-sized firms. While Canada's high standard of living, cold climate, and great distances all combine to make it the world leader in per capita consumption of energy, it has the distinct advantage of self-sufficiency in oil and gas.

Photonics technology has not yet been applied to any great extent in the oil and gas industry. While it is therefore evident that the Canadian oil and gas sector is competitive in world markets, there are indications that feed stocks, refinery throughput and hydrocarbon transportation are all rapidly changing and evolving, which means increasing technical challenge to operators to manage these changes with economy and safety. Additionally, significant parts of Canada's oil and gas infrastructure are getting old, and companies have limited resources with which to upgrade their facilities owing to continuing low global oil and gas prices. The challenge to photonics is how to be relevant to all these issues.

There is consensus within the oil and gas sector that photonics could contribute to the industry's needs, although the issue of whether photonics would be the most cost/effective solution has yet to be determined. While photonics technologies look promising, and the industry as a whole has concluded that it is worth investigating, substantial R&D is required to define the potential.

Opportunities exist in the oil and gas sector for commercial application of photonics in the areas of exploration and process instrumentation. These are related to pipeline remote leak detection, just-in-time gas compressor maintenance, and possibly oil sands mining safety. Specific opportunities identified by the industry and elaborated on in Annex A are:

- Sensing: environmental monitoring, such as source monitoring, and ambient monitoring
  process control/monitoring/quality control

- Material Processing: metal protection, e.g. coatings; fabrication and repair, e.g. surface hardening, welding, laser cutting and surface build-up

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25 Science Council of Canada, Sectoral Technology Strategy Series No. 5, *"The Canadian Oil and Gas Sector"*, 1992.

- Measurement: physical properties measurement
  spatial measurement

The technologies required for these applications are already available at the conceptual stage, and the infrastructure to carry out additional development work exists at the Laser Institute, TRLabs and the National Optics Institute and possibly at the Oil and Gas Research Association. However, there does not appear to be a company that is willing to integrate the technologies into user friendly operational equipment.

In addition to these market pressures on the industry, much of Canada's oil and gas infrastructure, such as pipelines, is now showing signs of age. Even relatively new pipelines date from the 1970s - a throwback to the "oil crisis" of that decade. This aging infrastructure inevitably brings forth questions of safety and environmental instability.

The equipment used by the oil and gas industry is supplied in part by the oil and gas field equipment sector which encompasses manufacturers of geophysical prospecting equipment; drilling rigs and ancillary tools; pumping, cementing and well-fracturing units; and dehydrators, separators, treaters and other field processing components. It also includes drilling and processing equipment on offshore platforms. In Canada this sector is composed of approximately 200 small to medium-sized firms with a total production[26] in 1991 of $760 million. The principal markets for the sector are oil field supply houses, the majority of which are subsidiaries of U.S. supply houses. Over 40 per cent of the sector's output is exported.

Many of the Canadian-owned oil and gas equipment firms are relatively small and undercapitalized and lack the necessary resources to support extensive R&D programs. Many firms still carry heavy debt loads incurred during the mid-1980s. Consequently, they often lack the resources needed to carry out extensive research and export promotional programs. Although many firms are already successful in the export field, they are limited by a lack of working capital. Their financial vulnerability in times of industry downturn is the principal weakness of the Canadian oil and gas equipment industry. Foreign-owned firms in the sector have done very little R&D in Canada.

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[26] ISTC Industry Profile: *Oil and Gas Field Equipment*, 1993.

The development and application of enhanced technology will offer this sector the opportunity to maintain its competitiveness. Significant introduction and use of photonics technology within the oil and gas industry, however, is unlikely in the near future without substantial government assistance. In normal times, Canadian oil companies would have large enough cash flows to participate in the development of innovative equipment to meet their specific needs. With the current situation of the petroleum industry, this is not the case.

For the most part, incorporating photonics technology into the Canadian oil and gas equipment industry will likely require government funding, especially among the technology suppliers who will have to develop products needed by the industry.

2.6 The Forestry Equipment Sector

Canada's forest products sector supplies about 90 per cent of its own domestic market, yet still exports 80 per cent of its shipments. This sector accounted for 3.6 per cent of GDP, and is by far the most important net exporting Canadian industry, with $22 billion in foreign sales in 1990[27].

The Canadian forest-products sector is highly productive and has a strong, albeit recently diminishing, position in international markets. Productivity has improved in all areas but logging. Labour productivity, measured by the average annual rate of change in output per hour, rose by 3.5 per cent in the wood sub-sector and 2.5 per cent in the paper sub-sector in 1981-87. The average rise in productivity for all Canadian manufacturing was 2.5 per cent.

Canada has relative dominance in world trade in forest products - 60 per cent of newsprint, 43 per cent of softwood lumber, and 34 per cent of wood pulp. In 1990, Canada exported $15.2 billion of pulp and paper and $5.6 billion of lumber. In the world export market for forest products, the next largest players are the U.S., Sweden, Finland and the Russia.

27 Science Council of Canada, Sectoral Technology Strategy Series No. 9, "*The Canadian Forest-Products Sector*", 1992.

The Canadian sector has benefitted from access to vast areas of indigenous raw material. It has profitably served export markets with basic and intermediate goods, such as construction lumber and market pulp, as well as some relatively lower value-added paper grades. Now, there is a strong drive to improve quality, using raw materials and other resources much more productively. At a time when technological change is sweeping the world industry, and new market challenges are coming from substitute products and alternative production sources, Canada must produce higher-quality products, and make the most out of its current products, if it is to remain competitive.

Currently, Canada lags in integrating pulp-and-paper operations, compared with other leading nations, and has a low ratio of paper to virgin pulp production. It also has a problem with the large percentage of small-scale, older facilities in operation - something not found in competitor countries.

Canadian forest product companies spend less than 0.5 per cent of their sales on R&D. The Canadian sector has invested heavily in advanced machinery and equipment, but it essentially purchases its technology from equipment suppliers offshore, which do much of the R&D. While there is a strong drive within the forest products sector to improve quality and productivity, forestry companies appear to have little interest in developing their own equipment[28].

The forest equipment industry, which produces machinery, equipment and tools used by the forest companies, consisted in 1990 of 40 manufacturers with a total production of only $300 million[29]. The total Canadian production of logging, sawmill and woodworking equipment was $1.3 billion in 1988[30]. The industry is concentrated in Western Canada with the majority of photonics developers and integrators located in British Columbia.

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28 Science Council of British Columbia, *"Increased Value from a Changing Resource"* and *"Creating the Climate for Innovation"*, April 1988.

29 ISTC Industry Profile: *Forestry Equipment*, 1993.

30 The Science Council Study on the Machinery Sector (see footnote 16) included machinery for logging, sawmill and woodworking and pulp and paper as sub-sectors.

The industry can be separated into two main segments, the first related to solid wood processing and distribution and the second, to geographic information systems (GIS)-based volumetric surveying of standard timber. Among notable companies operating in the first category are Porter Engineering and Dynamic Control Systems, each with sales above $5.0 million per year. MacDonald Dettwiler and Associates has built a reputation as a world leader in GIS-based analysis. These companies have grown out of a base in the forest products industry and are now branching into other sectors of endeavour. It is important to note that unlike other sectors of photonics use, these Canadian companies currently have the world's leading technology related to softwood processing.

A new sector of photonics developers has emerged and applications of optical-sensor technologies can be found in almost every aspect of the industry, including:

- silviculture:
  - identification of not sufficiently restocked lands
  - monitoring of seedling growth
  - detection of disease/fire damage/blowdown
  - species breakdown/volume estimates
- harvesting:
  - remote sensing for cutting plans, road building,
  - environmental impact reviews
- transportation:
  - sorting/tracking of log booms
- manufacturing:
  - sorting and sizing of logs
  - scanning of log dimensions
  - laser guided head rig
  - re-saw operations optimization
  - colour sorting and matching
- quality control:
  - precise measurement
  - automatic grading
  - grade reading and marking
  - detection and trimming of defects
  - detection of dull saws, broken bits, worn guides
  - veneer profiling
- inventory control:
  - inventory aging/tracking
  - material tracking

- secondary manufacturing:
  - precision etching, cutting, grouting
  - other finishing techniques

Our examination of the forest products sector indicates very positively that photonics technology offers additional business opportunities, for example, three-dimensional profiling of logs through multiple-axis scanning.[31]

Our research also shows that these opportunities are not being pursued for a variety of reasons. The technologies required for these applications are available at the concept and component level. What appears to be missing in this sector, as in the previous one, is the key organization to pull it all together. The technical infrastructure exists in the form of the photonics organizations noted in the previous sub-section and on the sectoral side in the form of the Forestry Engineering Research Institute of Canada, Forintek and Paprican. Industry research institutes such as these have been shown to play an important role in improving the productivity in their respective sectors[32], but none of these have any photonics capability at the present time.

Other factors responsible for the commercialization gap which appears to exist with respect to the introduction of new forest photonics products include:

- imprecisely defined applied research that does not always meet the needs of the end user;

- lack of domestic opportunities to test and prove the technologies; and

- shortage of trained personnel and simplified operator interfaces.

Although Canadians have a current lead in the application of photonics technology in the solid wood forest industry, there is strong competition from larger, better capitalized, Scandinavian and German companies that are beneficiaries of government-encouraged, cooperative research efforts. Government action will be required to maintain this lead.

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[31] See Annex A.

[32] I.A. Litvak, *"Canadian Trade Associations and the Promotion and Diffusion of Innovation"*, prepared for the Department of Regional Industrial Expansion, May 1985.

The federal government recognizes the need for additional R&D by the sector and has made a commitment[33] to invest about $45 million in partnership with research institutes in the private sector, provincial governments and other government departments to promote the development of innovative products and processes in the forest industry.

2.7 Sectoral Characteristics and Common Denominators

Our examination of these sectors indicates very positively that photonics technology offers a number of business opportunities. Our research also shows that these opportunities for a number of reasons are not being explored. There appear to be certain themes that cut across sectors. In the following sub-sections, we further explore some of these themes.

A summary of selected characteristics of the sectors that were examined are shown in Exhibit 2-1. In all cases, the end user is a relatively sophisticated user, usually a large company that is in the business of providing products or services to the general public. Several of the end users are organized in industry associations or other groups that are concerned with industry-wide issues, for example, the Canadian Manufacturers Association (CMA), the Canadian Gas Association (CGA), and the Canadian Petroleum Association (CPA), the Canadian Pulp and Paper Association (CPPA), the Canadian Forest Industries Council (CFIC), and the Council of Forest Industries of British Columbia (COFI).

33 Industry, Science and Technology Canada and Forestry Canada, *"Follow-through for Prosperity: Canada and the Forest Industries"*, April 1993.

Exhibit 2-1: Summary of Selected Characteristics of Application Sectors Studied

Sector	Telecom	Aerospace	Manufacturing	Oil & Gas	Forestry
Users	telecom carriers CATV operators	aircraft mfrs airlines aircraft users aerospace contractors	manufacturing cos	petroleum cos pipelines refineries petrochemicals cos	lumber cos sawmills pulp & paper cos
Systems integration	large suppliers system integrators	large system suppliers	very few	none	none
Photonics components	many small niche companies	some capability in large & small cos	many small niche cos	very little	some specialized cos
Sector R&D centres	SSOC TRLabs CRC CITR TRIO others	IAR UTIAS	NRC	CGRI	Paprican Forintek FERIC
Sector groups	CTAC	AIAC	CMA MEMAC EEMAC	CGA CPA	CPPA CFIC COFI
Photonics application	well developed	good market potential	critical good market potential	good market potential	good market potential
Strengths	technology infrastructure	vertical integration		strong cash flow domestic user industry	strong cash flow
Weaknesses	no market pull weak system design capability in SMEs	defence orientation MNE dominance	weak cash flow weak system integration capability	lack of system integration	lack of system integration

There are also some organizations of the equipment manufacturers in these sectors, such as the Canadian Telecommunications Action Committee (CTAC), which is a group formed by telecommunications equipment manufacturers, the Aerospace Industries Association of Canada (AIAC), the Machinery and Equipment Manufacturers Association of Canada (MEMAC) and the Electrical and Electronic Manufacturers Association of Canada (EEMAC).

Telecommunications and aerospace, the two sectors in which the application of photonics is best developed in Canada, have certain characteristics. For example, both sectors have several large manufacturing companies, all of which embody photonics technology in a portion of their products that are sold to the end user.

In the telecommunications sector, which has the largest photonics-related production, there are a number of publicly funded laboratories, universities and government-industry jointly funded consortia carrying out applied research in photonics. In addition, this sector is characterized by the existence of a major industrial R&D organization, Bell-Northern Research, which conducts a significant level of photonics-related R&D and is also involved in funding additional activities in some of the publicly supported applied research consortia and institutes.

In the aerospace sector, most of the R&D is conducted by the companies themselves. On the publicly funded side, the University of Toronto Institute for Aerospace Studies (UTIAS), which is university-based, has some activity in photonics-based smart structures, while the National Research Council's Institute for Aerospace Research (IAR) has no photonics capability.

The resource based sectors are characterized by end users that are world class and are relatively cash rich. Although these sectors are significant consumers of equipment in their operations, there are not many Canadian equipment suppliers. These sectors have jointly funded R&D centres that are conducting pre-competitive R&D: the Canadian Gas Research Institute (CGRI), the Pulp and Paper Research Institute (PAPRICAN), the Forest Engineering Research Institute of Canada (FERIC) and Forintek. None of these has any photonics capability. It is probably no coincidence that, while some promising applications of photonics in these sectors were identified, the actual use of photonics is relatively limited.

The following sub-sections discuss some of the important issues that were identified above in greater detail.

2.8 Systems Integration

A common theme that runs through most of the sectors is the lack of a strong systems integration capability. Systems integration can take either the form of large equipment and systems suppliers that produce a line of products for a large number of customers or of specialized integrators who provide custom installations for a small number of customers.

In the five sectors listed in Exhibit 2-1, the aerospace sector is the only one with a strong integration capability, which exists primarily in the large companies in the first tier, many of which are foreign-owned. Many of the smaller companies in the sector are subcontractors to first and second tier companies.

In the telecommunications sector, a systems integration capability exists in the larger companies, but at present, the capability is by and large not accessible to the smaller photonics-based firms in the sector. The TECH TEAM study[34] proposed a possible solution to this problem.

A systems integration capability exists, but is not strong, in the manufacturing equipment sector, and is almost totally lacking in the other two sectors, oil and gas equipment and forest products equipment. These three sectors are essentially three sub-sectors of the machinery and equipment supply sector. In each case, the customer is a sophisticated producer of a commodity that is sold to the consumer. Although these customers are constantly looking for improvements in their equipment performance, they rely on their suppliers to develop and provide the advanced equipment that they need. Since Canada's strength in photonics in these three areas is in small, innovative manufacturers of components and small equipment, they are dependent on larger firms to provide the integration capability necessary to supply end users with fully integrated, operational and user friendly equipment and systems.

There is also a recognized need for equipment developers to work more closely with users in order to develop user friendly equipment. Technology has a tendency to run ahead of the work force's ability to use it. The very specific training that is required to use much of today's sophisticated equipment acts as a disincentive to the introduction of the even more sophisticated equipment that could be produced using photonics technology.

[34] See footnote 6.

2.9 Technology Diffusion

Our consultations with industry during the course of this study showed that, in several application areas, the technology required for some promising applications of photonics was already developed at the conceptual stage. User demand was not well developed, partly because the users, often large commodities producing enterprises, were not interested in becoming involved in the design and production of equipment to meet their own needs and partly because they were not aware of the real capabilities of photonics technology in their businesses. In other words, there was not a strong market pull for equipment embodying photonics technologies that have been and are being developed by innovative technology-oriented Canadian companies.

Much of the photonics technology that these industries require in order to become more efficient already exists, not only in Canada, but elsewhere in the world. What is missing is the willingness on their part to act. This reluctance is due not only to their attitude but also, as stated previously, because of the lack of information about what can be done and what the benefits would be in exploiting these technologies and access to a capability to supply the systems that they can use.

Dialogue between suppliers and users of equipment will be beneficial on two counts. Firstly, users will look for and insist upon higher capability and additional performance in their new equipment, and secondly, suppliers will be able to design and produce equipment that will more closely meet user needs and expectations.

Technology diffusion has been a concern for the federal government for the last decade, particularly after the Economic Council study[35] on this subject, which concluded that the diffusion of technology occurs more slowly in Canada than in most other industrialized countries. A study by the Canadian Chamber of Commerce[36] concluded that Canadian managers have been slow to embrace technology as an integral part of business operations, so that the introduction of new technologies has trailed international competition and productivity levels are lower than those in the U.S. It identified and examined a number of barriers and incentives that influence the role of technology in the process of innovation, and concluded that, if senior managers show a grater commitment in the user of technology, many of the barriers identified should not present a problem.

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35 Economic Council of Canada, *"The Bottom Line: Technology, Trade and Income Growth"*, 1983.

36 *"FOCUS 2000. Report of the Task Force on Technology and Canadian Business"*, The Canadian Chamber of Commerce, August 1988.

Some mechanisms have been put in place recently by the federal government to promote technology diffusion, for example, the Technology Inflow Program[37], the Technology Outreach Program[38] and the Advanced Manufacturing Technologies Application Program[39].

A study currently being conducted by the Massachusetts Institute of Technology indicates that many technology-based corporations are getting into trouble, because they are not very efficient in managing technology. "By specifically excluding technological savvy from the seats of corporate power, they have given too much influence to the thinking of short-term, quick-gain bean counters and sacrificed some of their competitive edge in the process."[40]

In Japan, the Optoelectronics Industry and Technology Development Association (OITDA)[41] was formed more than a decade ago by industry to promote the comprehensive development of the Japanese optoelectronics industry. It now has over 250 members from a wide range of industrial sectors, not only electronics systems and equipment manufacturers, but also from sectors such as chemicals, precision machinery, banking and advertising. Among its activities are studies of trends in optoelectronics technology and in the optoelectronics industry. Since these studies are carried out by large committees, they serve as effective vehicles for technology diffusion. The OITDA carries out a number of other activities that promote the diffusion of technology, such as symposia on optical industrial technology, a laser school to promote the introduction of laser equipment and to train operators, regional seminars, and InterOpto, a comprehensive optoelectronics equipment exhibition which has become one of the three major optoelectronics exhibitions in the world.

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37 The Technology Inflow Program helps small and medium-sized Canadian companies acquire technologies developed in foreign countries. See A. Couvrette and A. Watanabe, *"Report on the Acquisition of Foreign Technology"*, Dept. of External Affairs, November 1984.

38 The Technology Outreach Program provides financial support to specialized technology centres for national activities and services that accelerate the acquisition, development and diffusion of technology and critical management skills in industry.

39 AMTAP's objectives are to improve productivity and competitiveness in small and medium-sized companies by providing advice and identifying areas where new equipment or improved use of existing facilities and personnel.

40 *"Bringing Technology into the Boardroom"*, Photonics Spectra, May 1993, p. 11.

41 See Annex B for a more detailed description of practices in other countries.

Following the Japanese lead, U.S. industry recently formed the Optoelectronic Industry Development Association (OIDA) to improve the worldwide competitiveness of the North American optoelectronics industry. The OIDA's membership also includes both suppliers and users of optoelectronics equipment. One of OIDA's main current undertakings is the preparation of a technology road map for optoelectronics. The methodology used in the preparation of the road map included market workshops in six application areas, as well as six technology workshops.

2.10 Research and Development

Current annual funding for photonics R&D in Canada is of the order of $200 million, or about 20 per cent of current photonics-related production. The amount would appear to be reasonable, but a closer examination reveals that the bulk of the activities, particularly publicly funded activities, is in photonics research that is related to applications mainly in the telecommunications sector.

Industrial R&D activities are heavily concentrated in two sectors, telecommunications and aerospace. The fact that Canadian companies in these sectors have been able to maintain world-class status in no doubt due in large measure to the innovative R&D that they have carried out in the past.

It is probably no coincidence that the application of photonics technology in telecommunications has progressed at a more rapid rate than in other sectors.

Canada's major competitors are actively supporting R&D in photonics, particularly, collaborative R&D activities[42].

In the U.S., the Advanced Research Projects Agency (ARPA), the central R&D organization of the Department of Defense, is receiving about $75 million[43] annually for supporting pre-competitive technology consortia in areas chosen for their specific commercial importance. Photonics-related consortia supported by ARPA include the Consortium for Optical and Optoelectronic Technologies in Computing, the National Center for Advanced Information Components Manufacturing, the Optoelectronic Technology Consortium, the Optical Network Technology Consortium and the Ultra-Fast All-Optical Communications Systems Consortium.

42 See Annex B for a description of some foreign R&D support programs.

43 Converted to Canadian on the basis of US$1 = C$1.30.

The National Institute of Standards and Technology (NIST), which is the lead agency in the Clinton administration for accelerating the growth of civilian technology, will see its annual budget growing to about $1.8 billion by 1997. About half of this amount will go to NIST's Advanced Technology Program, a new program created to promote economic growth and to enhance the competitiveness of U.S. high technology businesses by accelerating the development and commercialization of pre-competitive generic technologies and refining manufacturing practices. Another of NIST's current programs is the Manufacturing Technology Centers Program, which has the objective of improving the competitiveness of U.S. small and medium-sized manufacturers through advances in their levels of technology utilization.

In Japan, the Japan Key Technology Center[44] is funding a number of photonics-related industry consortia, for example, the Optoelectronics Technology Research Center, the Optical Measurement Technology Development Co. Ltd. and TERATEC, a consortium established to develop ultra-high-frequency optoelectronic measuring technology. These three consortia will receive a total government subsidy of $240 million[45] during their lifespan.

In Europe, the EUREKA Project supported 15 projects in laser technology for a total expenditure of over $500 million by 1990[46]. There are no doubt photonics-related projects in other categories, such as material technology, robotics and production automation. The European Communities recognizes the strategic importance of generic technologies in enhancing European industry's competitiveness. Its new proposals reflect a greater concentration of research in generic technologies, such as photonics.

The Federal Republic of Germany is actively supporting collaborative research in photonics under the Photonik I project, which was started in 1990 and is scheduled for completion in 1994, and its successor, Photonik II, which will run for four years from 1994. The German government share of Photonik I was approximately $67 million[47], or 63 per cent of the total project budget. The budget for Photonik II has not yet been set, but the government's share will be about at the same level as for Photonik I.

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[44] See Appendix B.

[45] Converted to Canadian on the basis of ¥100 = C$1.29.

[46] EUREKA Annual Progress Report, 1991. Converted to Canadian on the basis of 1 ECU = C$1.48.

[47] Converted to Canadian on the basis of DM1 = C$0.77.

Canada must follow suit, and continue its support of pre-competitive R&D consortia, so that Canadian firms are not at a disadvantage compared to their foreign competitors. Most of the smaller Canadian companies in photonics are niche players that are highly export-oriented, and the only way that they can continue in business is to stay at the leading edge of technology.

Leading Japanese companies have found that money is not really the issue, rather, it is the way in which R&D efforts are organized. In the last decade, Japanese high-technology firms have gravitated towards something called "cross-industry" or "fusion" research. In other words, they are allying themselves with companies outside their own immediate sectors. By combining disparate technologies, they can create things that are completely new, or they can make significant improvements to existing products or processes[48].

2.11 The Special Needs of Small Companies

Many of the Canadian photonics companies are small. Approximately one quarter of the companies in the sector have annual sales of about $1 million or less, and another quarter have sales in the $1 to $5 million range. Less than 10 per cent of the companies in the sector have annual sales in excess of $50 million, and all but one of these is in the telecommunications or aerospace sectors.

Many of these small companies are reasonably strong in their innovative capability, but were relative weak in market research and in system design capability. As noted in Sec. 2.8 above, a common theme that runs through most of the sectors examined in this study is the lack of a strong systems integration capability.

[48] F. Kodama, *"Technology Fusion and the New R&D"*, Harvard Business Review, July/August 1992, p. 70. See also, *"Creative linking of industries creates good climate for R&D"*, Toronto Star, November 28, 1992.

Small companies the world over suffer generally from a lack of cash flow. The federal government recognizes that small companies have more difficulty than large businesses in obtaining financing at competitive rates, and, in the December Economic Statement[49], took steps to increase the availability of financing to small businesses.
The small companies in the photonics sector are no exception. For them, developing and selling prototypes of new products is tantamount to risking their future.[50] Very few of these companies have been able to enter into any sort of alliance with larger companies that use their products and which have sufficient cash flows to underwrite such prototype development projects.

2.12 The Global Photonics Market

Canada's small and medium-sized high technology companies are noted for their innovative capabilities in niche areas, with domestic sales usually constituting only a minor portion of their total sales; the companies in the photonics sector are no exception. A demanding domestic market can provide a good springboard for proving innovative products, but these companies must continue to compete, and be successful, in global markets, which are becoming increasingly competitive.

The ongoing trends to free trade and globalization of markets, as well as recent developments in North America, such as the Free Trade Agreement (FTA) and the North American Free Trade Agreement (NAFTA), are very positive factors for the majority of these companies. In particular, FTA and NAFTA provide access to much larger markets on much the same terms as the domestic markets. The relatively small size of the domestic market therefore should not be a significant deterrent to their chances of succeeding in global markets.

On the other hand, there are a handful of companies in the sector that are wholly owned subsidiaries of foreign multi-nationals. Their continued existence in Canada would not make sense unless they are able to develop and produce products for world markets, rather than mainly for the domestic market.

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[49] *"Economic and Fiscal Statement"*, delivered in the House of Commons by the Honourable Don Mazankowski, December 2, 1992.

[50] Science Council of Canada report. See footnote 19.

The global photonics sector is dominated by Japanese companies, with approximately two thirds of the current global production of photonics components, equipment and systems[51]. Much of this Japanese production, however, is generated by huge corporations, each of which has annual revenues that are an order of magnitude or more greater than the entire current Canadian photonics production. Accordingly, they may not choose to participate in medium-sized product niches that are not large enough for their scale of operations, but which, none-the-less, are very attractive to most of the Canadian companies. The current lead of Japanese companies should therefore not be a deterrent to Canadian companies. Indeed, there may be attractive niche opportunities even in Japan, as some Canadian companies are already discovering and which the Canadian photonics study mission to Japan was able to confirm.[52]

3.0 STRATEGIC APPROACHES FOR THE PHOTONICS SECTOR

Based on the strong potential for positive impact that photonics technology has on a number of important sectors of the Canadian economy, we strongly recommend that Phase III of the Photonics Sector Campaign be implemented following the action plan described below.

As stated in the Introduction, our vision is a strong and vibrant export-oriented photonics sector with $5 billion annual production of photonics components, equipment and systems by the year 2000. To achieve this vision, Canada must seize the opportunity presented by the unique capabilities of photonics technology to promote vertical integration in the Canadian machinery sector and to add significant value to a number of other important Canadian sectors, such as telecommunications, aerospace, oil and gas and forestry. The increase in productivity resulting from the innovative application of photonics technology will increase their competitiveness in spite of growing international pressures.

A number of potential business opportunities for the application of photonics were identified. Also evident was that, for a variety of reasons, these opportunities were not as yet being pursued. This section presents the elements of an action plan for achieving the vision and provides estimates of the funding required to carry out the plan over a five-year period.

By adopting the action plan described in this Section, we predict an increase in the Canadian production of photonics-based components, equipment and systems from the estimated 1992 production of $1.2 billion to $5 billion in the year 2000, or growth at an annual rate of 20 per cent. This performance would be needed to maintain Canada's share of world production in this high growth strategic sector at the current level of 1.7 per cent.

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[51] Elliott Consulting. See footnote 2.

[52] Industry and Science Canada, *"Canadian Photonics Mission to Japan"*, November 1992, unpublished.

3.1 Support for Vertical Alliances

This study recommends an action plan with two related elements, support for vertical alliances, which is described in this sub-section, and the formation of a photonics umbrella organization as described in the following sub-section. In simple terms, the following levels (the "supply chain") are required for a technology to be exploited successfully:

- *end users*: in the sectors examined in this study, they include manufacturers, forest products companies, sawmills, pulp and paper mills, oil and gas companies, pipeline companies, aircraft builders and users, governments, the military, etc.;

- *systems integrators*: this category includes manufacturers of equipment required by the users through the integration of pre-assembled and/or tested sub-systems, as well as stand-alone systems integrators who integrate available equipment into an operating system required by the end user in its operations, usually on a custom basis;

- *equipment manufacturers*: in this category we include the manufacturers, most of whom are small and medium-sized companies, of equipment that is usually not used on a stand-alone basis but in conjunction with other pieces of equipment;

- *component and device manufacturers*: this category is composed mainly of small and medium-sized companies, usually with a relatively narrow range of high performance niche products; and

- *technology generators*: this category includes applied research laboratories and consortia, such as the National Optics Institute, the Laser Institute, TRLabs, the various National Research Council laboratories, the Communications Research Centre, the Solid State Optoelectronics Consortium, provincial research organizations and university-based research consortia; and industrial laboratories, such as Bell-Northern Research.

These five levels are depicted in Exhibit 3-1. Canada is reasonably well represented at the three lower levels. At the lowest level (technology generation), however, Canadian strengths are concentrated in applications for the telecommunications equipment sector. There is therefore a need to strengthen Canadian applied research capability in the application of photonics to non-telecommunications sectors.

At the second and third levels, Canada has a number of small, highly innovative companies that produce leading-edge components and equipment. In spite of the outstanding ability of many of these companies to penetrate world markets, based on the superior performance of their products, they are at a disadvantage due to the lack of a vigorous domestic market which would allow them to test new products in collaboration with significant users. The majority of the small companies in the sector are export-oriented, with some of them having as much as 90% of their sales outside the country. Nevertheless, the importance of the first customer for a new application should not be underestimated.

Exhibit 3-1
Innovation/Supply Chain

One of the reasons for the lack of a strong domestic market is the weakness of Canada as a supplier of large equipment and systems used by its manufacturing and resource industries. Another contributing reason is the lack of interest of the leading companies in Canada's resource-based industries, many of whom are world-class, in getting heavily involved in the development of high performance equipment.

In order to rectify the weakness of vertical integration in the sectors studied, we recommend that government support be provided for photonics application projects according to the following guidelines:

- each project should be carried out by two or more unrelated organizations at different levels of the supply chain described above;
- support should be provided on a 50-50 cost sharing basis; and
- each project would be approved by a rigorous screening process, which must be industry dominated and must respond promptly on applications, to maintain maximum industry interest and participation.

We recommend that subsidies be at the level of 50 per cent in order to ensure industry's commitment to each project. Most support programs that we have examined provide this level of support. The Japan Key Technology Center[53] provides subsidies of 70 per cent, essentially for equipment purchases, with the private sector providing the remaining 30 per cent in the form of salaries for its own employees participating in the projects supported. Public funding for EUREKA projects has averaged only about 35 to 40 per cent.

The 50-50 cost-sharing formula could be applied on a participant basis, on a project basis or on the total funding provided. In the Swedish IT4 Programme[54], a 50 per cent cost sharing between the government and the private sector was achieved over the whole Programme, with up to 100 per cent of the cost of small feasibility studies being paid. The Programme could also pay the full costs of research centres and small firms, provided that the large participants paid a large enough share of the total costs, so that the 50 per cent guideline was achieved over the whole project. We recommend this last approach be examined more closely as the preferred mode of administering the proposed funding.

[53] See Annex B.

[54] Technopolis and SPRU, *"Final Report: Evaluation of the IT4 Programme"*, May 1992.

Our reasons for recommending some form of financial support include the following:

- small companies need cash up front to develop new ventures, and government can share the risk in the more promising areas;

- users need to be convinced to take part in specific projects, not withstanding the high degree of interest in the application of photonics that our surveys uncovered; and

- systems integration capability has to be expanded in certain domestic sectors on an urgent basis.

Although the main motivation for proposing this mechanism is to encourage greater systems integration activity, the mechanism could be used equally to support technology generation, so long as the activity involves another participant from another level. Support for small companies is also built into the mechanism, since many of the participants will be small companies. The support would increase user pull and as well, make the flow through of technology to the end user more effective.

As indicated in Exhibit 3-1, the infusion of the proposed funding would strengthen the following interactions in the Canadian photonics industry:

- technology developers would be coupled to component and equipment producers and to each other;

- equipment producers would be connected to end users directly or through systems integrators or large systems manufacturers;

- market-pull forces originating with the end users would be felt at all lower levels; and

- technology-push forces originating with the technology generators would be felt at all higher levels.

We are not recommending support for activities that are carried out on a purely horizontal basis, i.e., where all of the participants are at the same level in the structure depicted in Exhibit 3-1, particularly those involving mainly research institutes, for two reasons. Firstly, such activities are already being supported in Canada through other funding mechanisms. Secondly, evaluations of two European programs for supporting pre-competitive R&D[55,56] have shown that, while the programs were successful in increasing the level of R&D in the area of support, they were less successful in improving the competitive position of industry and that other actions were required to reach the international competitiveness goals.

There are some evident differences in priorities for the application of photonics in the sectors that were studied. We do not, however, recommend an *a priori* sectoral division of any funding approved for implementing the Photonics Sector Campaign. We recommend, rather, that the industry itself be permitted to determine which sectors will receive the greatest subsidies by the funding that it is willing to commit to support specific projects.

The TECH TEAM study[57] identified the need to make the systems integration capability that resides in the larger systems suppliers accessible to small and medium-sized niche product suppliers. The need that we have identified and the solution that we propose to help alleviate the problem here are similar to the findings and recommendations in that report. The most significant difference in the sectors examined in this study is the degree to which systems integration capability is missing in most of these sectors studied, and the urgency to create a capability that is nearly non-existent.

In the following sub-section, we propose a mechanism to manage the funds that would be set aside to provide the recommended support.

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55 University of Sussex at Brighton, Science Policy Research Unit Annual Report, 1991-1992.

56 See footnote 54.

57 See footnote 6.

3.2 The Canadian Photonics Corporation

The second element of the recommended action plan is the formation of a Canadian photonics umbrella organization, which we will refer to as the Canadian Photonics Corporation[58] or the Corporation for convenience in the remainder of the report. The Corporation would have the following features:

- the objective of the Corporation would be to promote the development and application of photonics technology in Canadian industry;

- it would serve as the funding body for supporting vertical alliances that are established to develop and/or apply photonics technology in industrial applications;

- it would be industry-led and not-for-profit;

- its membership would include a broad range of companies and organizations, including technology generators, suppliers of components, equipment and systems, integrators and users;

- it would work to the extent possible with industry associations, R&D consortia and existing photonics institutes, such as the National Optics Institute (NOI), the Laser Institute and the Solid State Optoelectronics Consortium (SSOC);

- depending on the willingness of its members, it would act as a forum for the supply of small quantities of devices or components for trial use by other members in the development of equipment; and

- to the extent that its membership would deem appropriate, it would carry out related activities, such as, monitoring and predicting technology and market trends in photonics; tracking photonics production statistics; providing a forum for the exchange of information on new developments in photonics; sponsoring meetings, conferences, seminars, equipment exhibitions; publishing newsletters and other information bulletins.

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[58] Several alternatives, such as consortium, association, institute, etc. were considered and rejected, because each had some nuances that we wished to avoid. The important consideration is the concept, which we believe to be new and for which there is no precedence, rather than what it is called.

We do not believe that the Corporation should carry on activities, such as R&D, which could possibly put it in a conflict of interest position with some of its members. The Corporation could encourage and support market-driven activities organizations, such as SSOC. We also recommend that the Corporation not retain any intellectual property rights for the fruits of any activities supported by it, which we recommend be owned by the funders and performers of the subsidized activities.

The Corporation would receive funding from the following sources:

- from its members, it would receive membership fees to cover its operating costs;

- from the federal government, it would receive, on a contribution agreement basis, a pool of funds to support activities carried out by vertical alliances, as described above; and

- from other sources, such as provincial governments and industry associations, it would receive, either on a project-by-project or on a pooled basis, funds to support activities carried out by vertical alliances that are of specific interest to those bodies.

In addition to membership fees, Corporation members would be expected to contribute to specific projects in which they participate, their contributions being "in kind" or in cash, as required.

Exhibit 3-2 depicts the interactions between the Corporation and the industry that we envisage with the establishment of the Corporation. The arrows are intended to illustrate the following:

- industry will provide leadership and advice to the Corporation and participate in the election of the Board of Directors;

- industry will participate in committee work and other activities as appropriate;

- membership fees will flow to the Corporation from all interested parties;

- funding will flow to the Corporation from the government and other sources;

- the Corporation will promote the further application of photonics technology by the user groups;

- industry will form alliances to develop and/or apply photonics technology in Canadian industry and will submit funding proposals to the Corporation;

- funds will flow from the Corporation to support collaborative activities carried out by its members and which pass the scrutiny of an appropriate screening process; and

- the Corporation will promote networking and information exchange among its members.

Exhibit 3-2
Dynamic Model of the Canadian Photonics Industry

The focus of the Corporation's efforts should be on the application and use of technology, supporting technology development mainly to meet identified needs. It is recognized, however, that exceptional cases can be made for funding the development of generic technologies in anticipation of future needs. The requirement that private sector participants provide their own funding and resources should be the ultimate criterion in determining funding priorities. It is important to keep in mind that, although government action was responsible for initiating this strategic thrust and government funding will be needed to sustain the effort, the specific thrusts must be industry-led, and a prudent selection of industry representation on the Board of Directors of the proposed Corporation will be an important determinant in its setting policy directions.

The following options were considered for the proposed organization:

- an existing organization that is involved in promoting or carrying out collaborative activities in photonics could have its mandate modified to carry out the additional functions required;

- an organization that is not currently involved in photonics, but whose mandate is otherwise similar to that of the proposed organization, could be modified to add responsibilities for the promotion of photonics; and

- a new organization could be formed.

The main advantage of modifying an existing organization would be the relative ease with which the organization could begin to carry out some of the new functions. The only photonics-based organizations that could possibly take on new functions are the Solid State Optoelectronics Consortium (SSOC) and OPCOM. The disadvantages that we see with SSOC playing the role of the Corporation are two-fold. Firstly, it is too closely identified with the telecommunications sector and particularly with Bell-Northern Research, and secondly, since it would be a potential user of the funds to be managed, there could be a potential conflict of interest. Similar disadvantages also exist for OPCOM.

As for existing organizations that are not specific to photonics, one possible candidate would be PRECARN. However, PRECARN's activities are restricted to the management of funds for pre-competitive R&D. Another possible candidate would be the newly established CANARIE Inc.; its disadvantage, as for SSOC, is a close identification with the telecommunications sector.

In balance, we recommend the formation of a new organization that is especially tailored to carry out the recommended functions.

The TECH TEAM study also made a similar recommendation with regard to the formation of a photonics consortium for promoting the application of photonics in telecommunications. We strongly recommend that, should both recommendations be implemented, only one organization be formed so that the efforts will not become fragmented.

To our knowledge, there are no organizations whose primary mandate is the promotion of vertical (as contrasted to horizontal) collaboration and which addresses the total spectrum of needs from the technology generation level to the user level and which covers such a broad range of application sectors and users. The type of organization and its operation would, however, be similar in many respects to other organizations that have been created in Canada for somewhat similar purposes in recent years, for example, the Strategic Microelectronics Consortium, PRECARN and CANARIE Inc.

CANARIE Inc., which is incorporated as a not-for-profit corporation[59] reporting to a Board of Directors and government funding flowing to it through a contribution agreement, would be a useful model to examine more closely in setting up the Canadian Photonics Corporation. The Board would consist of representatives of the founding members of the Corporation. Initially, the Corporation could consist of the Board of Directors, a President and an Executive Assistant. Other positions would be established and filled, as required, but functions should be contracted out to the extent possible. The President must be an experienced individual that is highly respected by both user and supplier companies and capable of promoting their participation in the activities of the Corporation.

3.3 Funding Requirements

In this sub-section, we estimate the funding required to implement the two measures in the recommended action plan: financial support for vertical collaboration and the formation and operation of the Canadian Photonics Corporation.

[59] See *"CANARIE Business Plan"*, CANARIE Associates, December 1992.

In order to estimate funding requirements for a five-year period, we found it expedient to estimate Canadian and world production, currently and over the next five years. In using these figures, it should be borne in mind that statistics for photonics production are highly dependent on the exact definition used for photonics and for the way in which the production of equipment and systems that included photonics content is counted[60]. The production figures that we have used are only very approximate and could change very easily depending on how these two factors are taken into account. Nevertheless, we believe that the estimates that we have arrived at for the funding required to implement the action plan are sufficiently accurate to make the necessary strategic decisions about the implementation of the Photonics Sector Campaign.

The estimates that we used for current and predicted Canadian and world production are shown in Exhibit 3-3. The production figures for the telecommunications sector were taken from the TECH TEAM study[61]. As noted in the above paragraph, these figures are strongly dependent on the exact definition of photonics used in arriving at the estimates.

We predict the greatest growth in photonics production in the area that we have labelled "Other", which includes equipment for manufacturing industries and for the resource-based industries. The output in this area is predicted to grow from about one-quarter of total Canadian production to approximately forty per cent of the year 2000 output, and it will be a challenge to accomplish such a target. As mentioned previously, this is area which has the greatest potential impact on other sectors of the Canadian economy. The enormous technological advantages presented by photonics can be viewed as an opportunity, for example, to promote vertical integration in the Canadian manufacturing and resource equipment industries, and if this is accomplished, the proposed target production figures should be achievable.

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[60] Definition of photonics used in this study is given in Sec. 1.2.

[61] See footnote 6.

Exhibit 3-3: Production Estimates for the Canadian and Global Photonics Industry ($ billion)

SECTOR	1992 PRODUCTION	2000 PRODUCTION	GROWTH RATE
Aerospace	$0.3	$1	16%
Telecommunications	$0.6	$2	16%
Other	$0.3	$2	27%
Total Canadian production	$1.2	$5	20%
Global production	$72	$300	20%
Canadian share	1.7%	1.7%	

One reason for the growth potential in this area is, of course, that the current production level is rather low, only $300 million in 1992. However, since the production will consist to a large measure of equipment and systems based to some extent on existing technology, rather than of components and devices, a total production of $2 billion should not be impossible to attain in the year 2000. It should also be kept in mind that this area accounts for half of the Canadian photonics companies, even though their combined output only accounts for a quarter of current Canadian production.

The target that we have proposed for overall production in the year 2000 would result in Canada maintaining its current share of global photonics production. In assessing whether such a target is too optimistic, or perhaps too pessimistic, the following factors should be considered:

- for many of the companies in the sector, the domestic market accounts for less than half of their total sales;

- much of the photonics technology required by Canadian industry is, or will be, available from foreign suppliers;

- about 40 per cent of photonics production is in consumer goods, an area in which Canada does not have much strength and in which Canadian companies would have difficulty competing when production volumes reach high levels; and

- even to maintain the current world position requires aggressive action, in view of current activities of competing nations.

Our estimates for the maximum funding required to achieve this target are shown in Exhibit 3-4.

Exhibit 3-4: Maximum Five-Year (1994-1999) Funding Requirements for the Photonics Sector Campaign Implementation ($ million)

ACTIVITY	FEDERAL FUNDING	OTHER FUNDING	TOTAL FUNDING
Support for non-telecom collaboration	$175	$515	$690
Support for telecom collaboration	155	245	400
Operation of Photonics Corporation[62]	10	10	20
Total	$340	$770	$1,110

In deriving these figures, we made use of the production figures shown in Exhibit 3-3 and the following additional assumptions:

- growth in the Canadian production of photonics components, equipment and systems will be smooth and exponential from the estimated 1992 level of $1.2 billion to the year 2000 target of $5 billion;
- technology development costs and systems integration costs together are twenty per cent of total production;
- government subsidies would be provided on a cost-sharing basis, which would average out at approximately 50-50 over all projects subsidized;
- about half of the total activities carried out would qualify to be subsidized (i.e. are carried out on a vertical alliance basis) and of these approximately half would apply for subsidies and would satisfy other criteria for funding;
- the operating costs of the Corporation has a variable part that is dependent on the level of funding that it is required to administer; and

62 We have not added the $5 million assumed for the operation of a consortium for the application of photonics to telecommunication proposed in the TECH TEAM study on the assumption that our recommendation that there be only one photonics promotion organization is adopted.

- approximately half of the costs of the Corporation during the initial five-year period would be provided by the government and the other half would be raised from membership fees.

We have assumed that membership fees should be sufficient to cover the Corporation's operating costs when it is fully operational, and that government subsidies would be required to help offset start-up costs and operating costs during the first few years until a sustainable number of members is recruited. Experience with other Canadian organizations, however, indicate that this assumption may be too optimistic and other methods of raising the operating costs of the Corporation may be necessary.

An evaluation of the Swedish IT4 Programme[63] found that the administrative capability needs to be "front-end-loaded" to cope with the influx of work at the beginning and reduce over time as procedures become fully routine. The evaluation also showed that the decision to spend only one per cent of the $175 million in funds managed over five years on administration resulted in inadequate management.

In estimating the operating costs of the Corporation, we have assumed that government funding would be transferred to the Corporation under a single contribution agreement and that government monitoring of the Corporation's activities would follow normal practices in the private sector. Depending on the burden for audit, evaluation, monitoring an evaluation that the government wishes to impose on the Corporation, its operating costs could be substantially higher and the government funding for operating costs would have to be increased accordingly.

For the non-telecommunications applications of photonics examined in this study, government expenditures would total $185 million, or approximately one quarter of the total costs, with industry picking up the remainder. The TECH TEAM study[64] recommended the infusion of $155 million of government support (not including operating costs for the consortium) for photonics development, application and demonstration in the telecommunications sector over the same five-year period. Together with the additional funding mentioned here, the maximum support required for the Photonics Sector Campaign is therefore $340 million.

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[63] See footnote 54.

[64] See footnote 6.

The figures provided above were derived on the optimistic assumption that about half of the technology development and systems integration activities of the Canadian photonics industry would be carried out on a collaborative basis and that about half of these activities, or a quarter of the total activities would be subsidized. In reality, some companies will choose to do it alone or to collaborate with non-Canadian organizations. Others may not wish to apply for subsidies from an outside organization.

In addition, it may not be politically possible to allocate this level of funding to one technology area in spite of its strategic importance. Also, the growth of the industry may be somewhat lower than the assumed rate of 20% per annum, in which case the industry's ability to take on the activities may be a limitation. Notwithstanding, we believe that funding levels approaching about one-quarter of those shown in Exhibit 3-4, or approximately $85 million over a five-year period, are required as a minimum if a serious Photonics Sector Campaign is to be mounted.

Under the assumptions made about the growth in the industry production, the production in non-telecommunications applications of photonics during the first year of the proposed Sector Campaign, 1994, will be approximately $900 million, or thirteen per cent of the five-year estimated total production of $6.9 million, which was used as the basis for estimating the five-year funding requirements presented in Exhibit 3-4. It is expected that the fraction of projects that would qualify for support during the initial year would be somewhat lower than the average level assumed of twenty-five per cent for the five-year period, perhaps about twenty per cent. The amount required in the first year will therefore be about ten per cent of the five-year total. The minimum amount required in the first year of the proposed Sector Campaign, 1994, will therefore be $8.5 million.

Current Canadian photonics activities, particularly in the "other" area, are heavily concentrated in the lower levels of the technology hierarchy triangle presented in the Elliott Consulting study[65], shown in Exhibit 3-5. As you proceed up each level of the hierarchy, the added value on the product increases by roughly one order of magnitude, and correspondingly, so do the development costs and the associated business risks.

Exhibit 3-5
Technology Hierarchy

[65] See footnote 2.

One of the effects of the Photonics Sector Campaign would be not only to increase the total activity in photonics in Canada, but also to increase the proportion at the higher levels of the hierarchy, probably bringing in as participants existing companies that do not have any photonics capability at present. Accordingly, the ability of the industry to generate and to absorb a higher level of funding in photonics activities should increase significantly.

Total production during a five-year period with a two-year time lag (assuming a lag between the activities to be supported and production) will be over $18 billion under our assumptions for production. There could therefore be a significant return on the proposed government expenditures for the Photonics Sector Campaign.

It should be emphasized that, in any finished equipment or systems, photonics would be only one of the technologies required, and the successful outcome that we are predicting may not be realized fully unless the other essential ingredients, such as signal processing, microelectronics and electronics, systems design and manufacturing technologies, are also developed in the same time frame. Nevertheless, according to our study, the return on government investment in photonics will be sufficiently high to warrant positive action at this time.

3.4 Support for Specific Business Opportunities

During the course of this study a number of specific business opportunities for the application of photonics were identified, and these are described in detail in Annex A. Many of the ideas are application concepts originating from technology generators. These concepts, nevertheless, serve the purpose of indicating the degree to which photonics could have application in the sectors studied, once the action plan is put into place and when realistic business opportunities will be pursued by companies that have to put some of their own funds at risk to pursue the ideas.

Some of the opportunities are better developed than others, and a few of them have an urgent time frame. Ideally they should be passed through the recommended funding mechanism along with all other proposals. Since the Photonics Sector Campaign, and in particular the Corporation, may take some time to become fully operational, we recommend that some of the proposals be put on a "fast track", to be funded as soon as the Sector Campaign is approved.

Three proposal were selected for fast tracking using the following criteria:

- the project has sufficient economic benefit and leverage not only to the participants but also to other Canadian parties to warrant special action; or

- the project involves participants from different levels, as described above, and they have confirmed their willingness to proceed; and

- the opportunity for the project is time sensitive.

We recommend that the following proposals[66] be considered for fast tracking:

- the laser material processing centre
- the Bragg diffraction grating demodulation optoelectronic chip
- the automated integrated imaging system

The merits of the laser material processing centre proposal are:

- It will provide a systems integration function for the products of a number of Canadian component suppliers to produce advanced laser-based materials processing systems that can be sold worldwide.

- It will provide a facility for manufacturers requiring access to fast turn-around, cost effective solutions to advanced materials and manufacturing problems.

- There is a well established need for such a centre, and it will no doubt be established elsewhere within the next year or so, to the detriment of Canadian users and Canadian component suppliers, if support for it does not materialize in Canada.

Listed below are the merits of the Bragg grating demodulation optoelectronic chip (BDOC), which is an integrated optoelectronic device to provide an interface between Bragg grating fibre-optic sensors surface-adhered to or embedded inside structural materials and external measurement systems.

- Interface chips are among the key missing components required for the application of smart structures in a number of application areas.

- The BDOC, which is a an intermediate stage towards the full optoelectronic smart structure interface chip described in Annex A, has the potential to be developed into the chip required to demodulate an array of sensors.

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[66] See details of these proposals in Annex A.

- The development of a BDOC would give Canada technological leadership in the new field of structural sensing.

- A prototype of the system has already been demonstrated in the Calgary bridge project, in which some of the girders are instrumented with structurally integrated fibre-optic sensors.

The merits of the automated integrated imaging system proposal are:

- Automated imaging can be applied across a very broad spectrum of applications.

- Canada has expertise in the area at the component and equipment level but is not particularly strong at the systems level.

- Several participants, including at the user level, have indicated their interest in the project.

The estimated total costs of these three projects are:

- the laser material processing centre: $5 million over three years

- the Bragg grating demodulation optoelectronic chip: $3 million over three years

- the automated integrated imaging system: $5 to $10 million over three years

The total cost of these three projects is $13 to $18 million for three years, so that the government's support would be no more than $2 million per year during the first three years, leaving plenty of funding for the support of other worthwhile projects.

Some of the details of these proposals are commercially confidential and cannot be disclosed in a report such as this. The originators of these proposals should be encouraged to submit detailed proposals as soon as funding becomes available. Final approval of funding would, of course, be subject to the submission of an acceptable business plan and the commitment of matching funding from the participants.

There is a danger that a decision to fund specific projects in this way could be viewed as by-passing the mechanisms that are about to be set up. On the positive side, however, it would send a strong signal to the private sector immediately that the government is serious about photonics.

4.0 SUMMARY OF RECOMMENDATIONS

We recommend that the Phase III of the Photonics Sector Campaign be implemented in terms of the following two elements:

- the approval of government funding to support the activities of vertical alliances formed to develop and/or apply photonics technology in Canadian industry; and

- the formation of an industry-led, not-for-profit Canadian Photonics Corporation to promote the development of the Canadian photonics industry and the use of photonics technology by Canadian industry.

The maximum government funding required to carry out the recommended action plan over the 1994-1999 period is estimated to be $345 million, of which $36 million would be required in the first year. A realistic lower limit to the funding required to mount a serious Photonics Sector Campaign would be about one-quarter of this level.

As a result of implementing the action plan, we envision the development of a strong and vibrant, export-oriented Canadian photonics sector, whose production will grow at an annual rate of 20 per cent from the current annual production of $1.2 billion to $5 billion by the year 2000, maintaining its current market share in this high growth strategic area.

Canada's current strengths in the application of photonics technology to telecommunications and avionics would be maintained, and at the same time, photonics technology would add value to a number of sectors of importance to the Canadian economy. The increase in productivity resulting from the innovative application of photonics technology will increase their competitive in spite of international pressures. A window of opportunity exists for using the unique capabilities of photonics to promote the vertical integration of Canada's machinery industry.

ANNEX A

BUSINESS OPPORTUNITIES

FOR PHOTONIC TECHNOLOGIES

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BUSINESS OPPORTUNITIES FOR PHOTONICS TECHNOLOGIES

This annex covers findings on business opportunities in non-telecommunications applications correlating to the industry sectors discussed in the main body of this report. The information for this annex was gathered at separate Industry Working Group meetings for several sectors, and numerous one-on-one meetings between the specialized sectoral consultants and relevant industry executives.

The formal Industry Working Group meetings were held as follows:

1. Oil and Gas Sector, Edmonton, May 19, 1993
2. Oil and Gas Sector, Calgary, May 20, 1993
3. Forest Sector, Vancouver, May 21, 1993
4. Small-scale Manufacturing Sector, Mississauga, May 28, 1993
5. Avionics Sector, Montreal, June 1, 1993
6. Large-scale Manufacturing Sector, Toronto, June 11, 1993

As well, several meetings were held during June and July 1993 in Ottawa, Toronto, Montreal, and Calgary, which identified and investigated "other applications": medical devices, smart construction, office furniture systems, mining and raw material extraction, military projectile guidance and bomb disposal systems.

1.0 MANUFACTURING EQUIPMENT

1.1 Industry Environment

The opportunities for Canadian collaborative projects based on photonics technology in equipment manufacturing are particularly significant. They represent a major opportunity for developing and deploying new, high-productivity technology in Canada - provided adequate financial encouragement can be deployed between, and among, all relevant parties (including governments), in order to focus photonics as a leveraging technology that would allow Canadian photonics firms to develop their core technologies to the systems integration level. It would encourage more small-scale manufacturers and users to incorporate photonics technologies into their processes as well as into large-scale manufacturing, e.g. automotive.

Photonics as an enabling technology, and through systems integrators, provides a threshold for Canadian sources to access the international marketplace with critical technology. There are a number of existing factors encouraging more widespread use of photonics within the equipment manufacturing industry.

First, Canada has systems integration capabilities in the equipment manufacturing sector. Although the relevant Canadian firms are currently limited in scale, they are not negligible. Canada is a world leader in certain niche specialties such as mould making - where photonics-based rapid imaging and adaptive machining technologies can play significant roles in maintaining our international competitiveness. Canadian firms have also pioneered in the development of flexible manufacturing systems. These Canadian systems integrators are very good at the key creative elements - the sensors and controls (including photonics), the system and control software and the workpiece fixturing - used with the imported machining centres.

Second, an industry consensus exists within Canada that photonics represents a promising competitive technology for both large scale and small scale manufacturing applications. This is because photonic-based systems, such as imaging systems, vision and guidance systems and power laser systems, offer the kind of precision and quality that, when combined skilfully with mechanical and electronic apparatus, are required for leading-edge competitiveness in flexible manufacturing systems. This consensus also means a willingness to engage in collaborative projects.

Third, the process of equipment manufacturing is changing. Often the endless variety of new products today rely just as much for their existence on the flexible machinery upon which they are produced, as on their process of design and development. Accordingly, many new market opportunities for developing innovative manufacturing equipment.

Fourth, global competition in both large scale and small scale manufacturing is now so intense that manufacturers themselves are seeking out innovative machinery. This is broadens the market prospects for new technology in both product and process applications. Automotive is an example; this industry is re-structuring into the so-called "tier system", whereby suppliers take much greater responsibility for new product development. This means not only superior quality derived from the methods and machinery of production processes, but also better consumer.

Fifth, the Canada-U.S. Free Trade Agreement makes available the large U.S. market, alleviating the historical limits of the small Canadian market.

These five factors, along with focused initiatives to expedite and coordinate the effective integration of various photonics technologies in flexible manufacturing systems and in specialized manufacturing equipment can provide Canadian equipment manufacturers with a powerful competitive advantage in the growing worldwide market.

1.2 Methodology

Five projects and their overall photonics context have been developed from the May 28th, 1993 Industry Working Group meeting on small scale manufacturing and the June 11th, 1993 Industry Working Group meeting on large scale manufacturing, as well as numerous one-on-one meetings and telephone conversations between the two relevant consultant specialists (J.R. Technologies and J.C. de la Riviere and Associates) and industry executives.

The following industry representatives were involved:

- small scale manufacturers (such as custom-product electronics firms) and large scale manufacturers (such as automotive) with the potential to use photonics technology, products or components;

- suppliers of equipment that either does or might potentially incorporate photonics technology or components;

- developers of photonics technology or components that might be incorporated in small or large scale manufacturers' products or processing equipment; and

- research institutes, associations, government departments, and university faculty with an interest in industrial applications of photonics technology.

1.3 Industry Consensus

During the course of these business consultations, a consensus of opinion as reached with respect to photonics technology potential in large scale and small scale manufacturing in Canada.

Most Canadian manufacturers appear to be interested in using photonics as critical enabling technologies in their manufacturing activities, for such operations as laser welding and machining, in-process inspection, bar-code tracking of components and products, etc. Moreover, some large scale manufacturers are also interested in incorporating photonics in the products they manufacture. A good example is the automobile instrument panel.

The manufacturing equipment suppliers (which include some limited systems integrators in manufacturing machinery) contacted in this research study generally indicated that they would like to acquire photonics technology on a "black-box" basis, by purchasing proven photonics components or sub-systems from reliable suppliers. A handful of the equipment developers indicated that they had received some informal small scale funding of photonics technology application projects from their customers in large scale manufacturing. The equipment suppliers clearly follow the lead of their manufacturing industry customers rather than initiating any development in this area. Yet there is considerable opportunity for development of advanced manufacturing technology equipment that incorporates photonics-based components, both for domestic and export sale.

1.4 Opportunities

The five projects identified by the industry representatives have been divided into near-term and long-term opportunities. The near-term projects are essentially ready to implement. However, the longer-term opportunities represent promising openings for future industry-led developments.

Near-term opportunities:

Project 1: Automated Integrated Imaging System - DALSA Inc.

Automated imaging is currently applied across a very broad market. Included in this market are inspection systems for film, paper, and steel, where one looks for deviation against the norm in a continuous medium, and also for individual characteristics versus a standard. These areas are the most common applications. Many different applications could use the same camera systems; however, the output material would have to be adapted to the particular industry requirements. The ability of an integrator to provide more depth in camera systems would accordingly create both vertical and horizontal new market opportunities.

There exists the technical challenge to integrate the components into an imaging system. The act of becoming a systems integrator would essentially shift both the client base and the market base - maintaining technical superiority in camera systems, while at the same time developing all the attendant technical links required in integrating a complete automated imaging system.

A vital component in any imaging system is the camera sub-system. The Canadian company, DALSA Inc. of Waterloo, Ontario, is a world leader in that business. Growing an integrated imaging system would enhance their core business as it would permit access to product capability currently served at arm's length through their customers. It is recommended that DALSA serve as the core business unit in such a project.

DALSA itself has suggested that being a systems integrator would be advantageous to the company. The extent of this advantage is readily apparent when one considers that any given individual sale would be an approximate tenfold increase in revenue, and that many of the components and systems capabilities required by any imaging systems integrator could be made more readily available. This is the powerful leverage a systems integrator has, over merely a component or sub-system supplier.

DALSA has created special products on occasion on a contract basis for particular clients. In these situations, they function as an integrator taking full responsibility for the delivered system. These undertakings have required particular specifications in camera technology, favouring their status as a technological leader. Hence internally, they have benefitted in direct camera system developments and in specific R&D direction through creating and adapting their technology into a real time imaging solution, of the type that their product is applied to resolving in each application. DALSA has proven capability in R&D, in related core product development, and in international market development. While DALSA is an Ontario-based company, it should be noted that such a system as proposed here would have application all across Canada, and would have major export potential, particularly to the U.S.

Total overall market potential is believed to be the same for both the component supplier and for the integrator. The imaging market is in the range of US$350 million in the U.S. in 1992. The future trends are for a 250% growth in the current applications market by Year 2000. Current production of camera systems is sold to numerous small integrators scattered across the applications market. There are regional concentrations of integrators serving regional market applications, however, these applications are becoming more standardized, offering the potential for the emergence of larger integrators, and integrators with a product and applications mix.

If one assumes that current imaging systems technology can be applied to inspection in designated major process industries, i.e. manufacturers who require 100% product inspection, then it is possible to assume a quick potential market of some 250 companies alone in Canada as part of that market. The average price of an integrated system is in the range of US$50,000 to US$100,000. Using US$75,000 figure, the Canadian manufacturing market holds a potential of some C$50 million (at two imaging systems per manufacturer, as an average). The U.S. by comparison has a market size of 12 to 15 times larger.

Systems integrators have to look to many more variables in their product and market equation than do specialty product houses with a core technology. While the core business may be built around one technology base, the integrator must also become expert in those complementary technologies that create the integrated system. This means growing expertise in related areas. Core capabilities would require on-going R&D and integrated systems will require research, product and market development, and "prototype to production" investment.

At this stage in the development of the business opportunities, some assumptions are necessary. Assume the mission is to create a systems integrator with a core based on DALSA. Camera-related systems sales should grow tenfold in the next seven years.

Assume revenue of $10 million today, hence the core would generate a total of $70 million during the 1993-2000 period. To achieve $100 million in annual revenue by the year 2000, sales would have to grow at 50% per year, hence 7 years sales would gross approximately $304 million, or $234 million over the core. It one assumes 10% of annual revenue for reinvestment, and six turn-overs per year (working capital needs), the company would on the basis of this simplistic model have a realizable goal. However, the company has to put in place the infrastructure to deliver an integrated package, and it must also "front fund" this activity and develop a user (new) market. This would require from $5-$10 million over the next three to four years, much of it up front.

Over the first few years there would be insufficient contribution from operations therefore, capital would have to be available from outside. The market and the product capability would have to grow simultaneously due to the nature of this type of commitment.

The lead times for introducing a new integrated product are estimated to be 2-3 years. The impact that introducing a significantly higher cost capital item has on the current business methods and capital structure are unknown, but they will require a financial off-set equivalent to the fresh capital requirements.

There would be major pay-backs to this investment if DALSA's overall market share within the automated imaging sector would shift from 1/40 ($10 million over $400 million) 1993 basis to 1/11 ($100 million over $1,100 million) year 2000 North American market. Over 500 skilled jobs would be created directly with such growth and another 1,500 might be created indirectly.

Moreover, if one assumes that 250% growth is the forecast in the period 1993-2000, then DALSA as the camera system supplier would grow to $25 million equivalent ($10 million 1993 basis) if it were to remain in its current mode. This would hold DALSA to perhaps 25% of the North American camera systems market. On the other hand, if it pushed for dominance in the industry as a camera systems supplier, it would need about 100% of the camera market to achieve the same type of absolute dollar growth that could be theirs if they became integrators. This is not feasible. Only the systems integration route provides the necessary dollar opportunities.

DALSA requires near-term funding to support growth to the systems level. Some of this would have to be contributed by a user-industry partner. However, some would need to be contributed by a source willing to accept technical risks in light of potential national needs.

Project 2: Technology Centre for Laser Manufacturing - Lumonics Corp.

Starting from its Canadian roots in 1971, Lumonics has established itself as the world's leading supplier of industrial lasers, with annual sales in the range of $100 million, and manufacturing operations in Canada, the U.S. and Europe. Throughout this period, customer interactions have changed from the sale of stand-alone lasers to the supply of complete laser-based solutions and systems. It is recommended that Lumonics be the core business unit in an industrial laser systems integration facility.

The proposed facility is aimed at providing a means of expanding Canadian capabilities in the areas of on-line industrial applications of laser-based solutions by linking the capabilities of Lumonics and relevant and interested Canadian suppliers. Its objectives would be to provide short/mid-term laser-based solutions to the Canadian manufacturing sector, improving the understanding of "real world" industrial laser processes relevant to Canadian industry, and establishing a "world-best" database for laser materials and interactions as a means of facilitating future commercial growth. The facility would bring together customer needs and supplier capabilities for a common objective: increased sales, both domestic and export, of advanced, laser-based manufacturing systems.

As a starting point, Lumonics would provide the existing skill/knowledge base from which candidate applications and cost of the relevant laser technologies would be explored. Initial emphasis would be placed on establishing a rapport with relevant Canadian manufacturing sites and job shops in a variety of key industrial sectors, thereby ensuring the direction of the facility's activities remains strongly user-driven. From this, the supplier base could be developed, for both the short-term and mid-term horizons.

Although the facility would maintain a strong commercial focus, actual sales and supply of systems would revert back to the supplier base which would include Lumonics, Canadian job shops, and Canadian suppliers of systems and peripherals.

Owing to the expanded breadth of potential laser applications, it is becoming increasingly important to link together evolving customer needs, process knowledge and development, appropriate laser sources, and systems technologies such as workpiece manipulation and controls capabilities. The proposed facility would provide precisely this type of environment, with Lumonics taking the lead role in laser-related issues while forming alliances with suppliers of the various systems technologies. The availability of photonics sector funding would greatly increase the attractiveness of locating this type of facility in Canada, thereby benefitting not only the Canadian operations of Lumonics, but also Canadian-based manufacturing sites as customers in terms of increased global competitiveness and Canadian suppliers in terms of increased sales and international presence.

A key aspect of the proposed effort is to provide faster access to information relating to the use of the rapidly growing number of "advanced materials" available to industry today, e.g. ceramics, plastics, composites, etc. Many of these materials are well suited to laser processing and yet existing databases are small compared to more traditional laser applications involving metals.

Although Canadian capabilities in technologies relevant to advanced manufacturing solutions have improved dramatically in recent years, much of this increased knowledge base remains in the hands of relatively small companies which, by themselves, have limited means to access the full scope of the industrial marketplace. The proposed facility would provide a vehicle for such suppliers, particularly in areas such as controls systems, motions systems and computer-aided manufacturing (CAM) to expand their market presence and/or market scope.

Although Lumonics would play a central role in the facility, the nature of the facility does not limit the end result to sales of Lumonics-based systems or even Lumonics lasers. Indeed, it is envisioned that, depending on customer needs and system composition, another Canadian supplier or job shop may become the integrator of the overall systems.

Laser-based solutions have proven to be a sound basis for many advanced manufacturing techniques now in use in the electronics, aerospace and automotive sectors. However, due to the limited R&D resources available at many Canadian-based manufacturing sites, laser-based solutions often cannot be home grown and must await being imported. The proposed facility would provide an economically viable route for Canadian manufacturers to develop new, cost-effective production techniques and thereby improve the global competitiveness of Canadian-based manufacturing sites. This facility would be relevant to industrial applications throughout Canada. Thus, all Canadian manufacturing would be the market for the products of this project. Total potential market in Canada for laser-based industrial systems is estimated to be at least $60 million by year 2000 and could be as much as $200 million.

It is intended that job shop services will not be part of the facility's mandate. Rather, the facility will work with existing Canadian job shops on precisely those applications which, although potentially attractive from the commercial standpoint, require more process or systems development work that can be provided within the technological and economic constraints of existing job shops. In this manner, job shops are intended to be one beneficiary of the facility's efforts, again from both the domestic and export perspectives.

The nature of the proposed facility, as currently envisioned, would require start-up funds in the range of $2.0-$2.5 million, with an annual operating budget in the order of $1 million.

There would be major benefits. A technology centre could help Lumonics grow into accompany of $250-$300 million in sales internationally by the year 2000. The Canadian operation would grow from the current $20 million to about $60 million by year 2000. This would provide about 400 high-skilled new jobs directly.

The proposed facility would be located in the Ottawa area, thereby allowing maximum synergy with the Canadian operations of Lumonics, while at the same time providing ready access to Canadian customers and suppliers of associated equipment. Overall management of the facility will be provided by Lumonics, with active participation from Canadian industry on both the customer and supplier sides.

It should be noted that the proposed facility is not planned to duplicate the capabilities of existing Canadian research facilities or that of the existing supplier base. On the contrary, the facility would form linkages with institutes such as the National Research Council (Ottawa), the National Optics Institute (Quebec), the Centres of Excellence program in Ontario, and the Laser Institute of Alberta. The mandate of the facility being proposed here is based on a strong commercial orientation aimed at moving quickly from a feasibility study to on-line use at the customer's site.

The final objective in all cases, is the commercial exploitation of laser-based solutions for he benefit of Canadian manufacturing sites and the growth of sales, both domestic and export, for Lumonics (Canada) and related, Canadian high-technology industries.

Long-term opportunities:

Project 3: Fibre-Optic Location, Orientation and Compensation- Ford Motor Company of Canada, General Motors/Sensor Adaptive Machines Inc.

Ford Motor Company is well known as one of the U.S. "Big Three" assemblers. The company has already successfully undertaken engine-related research in Canada and as a result, has a new engine plant under construction in Windsor. There is potential to expand on preliminary work using fibre optics technology to facilitate engine crankshaft orientation in engine assembly to further pursue photonics-related techno-business opportunities. This could be conducted in conjunction with ISC's Advanced Manufacturing Technology Institute, and the University of Windsor.

Two other companies are currently collaborating on a related automotive research project. These are General Motors of Canada and Sensor Adaptive Machines, Inc. (SAMI). There are profound implications to this project with regard to the "down time" for machine tool maintenance. With vision-guided machine compensation, it could be virtually eliminated.

GM and SAMI are already collaborating on a research project (the Smart Lathe) with support from McMaster University and the University of Windsor, which uses miniature video cameras mounted inside the lathe to provide real time adaptive tool management in precision machining operations. GM and SAMI are also working closely with the U.S. National Centre for Manufacturing Science in Ann Arbor and there is the possibility to be involved incrementally in a major new photonics-related project, possibly with the technical collaboration of the University of Waterloo. SAMI indicates flatly that the basis for their R&D relations with GM has been government support.

This project is relevant to the automotive industry across North America, possibly representing a market in the tens of billions of dollars. Within Canada, it would have major significance to Ontario and Quebec.

Project 4: Photonic Quality Validation System - Ortho-McNeil Inc.

This company is a large scale manufacturer of health-care devices and pharmaceutical products that is currently developing new products as well as reviewing its current manufacturing processes. Ortho-McNeil would like to implement a range of advanced manufacturing technologies in order to achieve world leadership as the highest quality, lowest cost producer of several large volume products. A critical element of the company's continuous improvement program is the development of automated, in-process quality validation procedures. Such procedures will incorporate photonics technologies, one example being the use of infrared thermography to determine the wall thickness of a molten ultra-thin wall product as it is being formed. Ortho-McNeil has worked with the Universities of Waterloo and Windsor and is exploring a further project in cooperation with the Ontario Laser and Light Wave Research Centre and an equipment supplier. In view of the applicability of the proposed photonics-based automated inspection procedures to other manufacturing operations, this project seems worthy of further development and support.

The market implications of such a project are substantial. The value of pharmaceutical production is tens of billions of dollars annually; yet quality and purity are vital and photonics technology can ensure these.

Project 5: Automotive Instrument Panel - Chrysler Canada

Chrysler Canada recently announced that the next generation mini-van will be manufactured in its Windsor assembly plant, following on the recent successful introduction of the "LH" sedans assembled in Bramalea. Product engineering for the LH vehicles has been carried out completely at Chrysler's Auburn Hills, Michigan Technical Center.

With the aforementioned strengths of Canadian companies in instrument-panel-related systems, the concentration of instrument panel mould makers in Windsor and the interest of the University of Windsor in heads-up display-related photonics research, this would be a strategic photonics initiative worthy of support. Participants in this project might logically include the Tech Centre group of companies in Windsor responsible for the design and building of the instrument panel moulds for the current mini-van.

The potential market for this sort of automotive product is enormous, amounting to several billions of dollars annually. However, an even more profound benefit would be the opportunity for Canadian auto parts firms to reach so-called "Tier 1" status through such a project.

1.5 Recommendations for Strategic Approaches

Successful responses to the above photonics-related business opportunities can have considerable impact on the international competitiveness of Canada's equipment manufacturing sector and on the further strengthening of the country's equipment suppliers, photonics technology developers and research institutions.

There appears to be considerable scope for government to play a strategic role in facilitating the development of photonics-based business opportunities. The successful commercialization of this photonics-based technology, however, will require the development of links and the coordination of activities among the participants to a much greater degree than has been, and is now, the case.

In the present world wide climate of corporate fiscal restraint occasioned by the prolonged recession, there is a greater willingness on the part of multi-national corporations to enter into strategic alliances with public research institutions and with small, technology-based, entrepreneurial-owned companies in order to achieve technologically-driven business opportunities. In other times, such projects would likely have been pursued in-house, typically in the multi-national corporation's home country. It is noteworthy that each project listed above, involves joint small company/large company linkages, regardless of the size and scope of the initiative.

In light of Canada's significant dependence on its large scale manufacturing sector on foreign-owned multi-national companies, this situation is an opportunity to strengthen the relationships between these companies, Canada's research institutions and the Canadian-owned small, technology-based, entrepreneurial equipment suppliers and technology developers.

Support from government for the implementation of a business-oriented photonics sector strategy and the facilitation of cross-linked activities in support of this strategy will be vital to the large scale manufacturers, the equipment suppliers and the technology developers in overcoming the current fragmentation of the industry.

Over a longer time frame, a photonics sector initiative could play a key role in assuring Canada's large scale manufacturing competitiveness. It will strengthen the strategically important equipment supplier and photonics developer industry sectors with their knowledge-intensive, high value added exports.

It is recommended that consultations continue for further collaborative project definition and planning.

2.0 AEROSPACE

2.1 Industry Environment

Taken as a group, the aerospace community has an experienced marketing capability with excellent linkage to the customer base. There does exist a core competence in the technological areas that have been chosen for further market exploitation. The participants individually and as a group can demonstrate current competitive activity in photonics on which further estimates of success can be measured e.g. Litton, Spar, CAE, etc.

2.2 Methodology

This sector information was developed from first-hand interviews with senior executives from Canada's leading aerospace electronics companies with combined annual revenues in excess of $2 billion and substantial global export sales and market penetration. AlliedSignal, CAE, Canadian Marconi Company, Litton Systems Canada Limited, Spar and CRL provided the majority of industry input, while other organizations such as the Federal and Quebec Departments of Industry and Science and provided additional sectorial data.

An Industry Working Group Meeting was held in Montreal on June 1st, 1993. A subsequent meeting was also held in Montreal on June 30th, 1993, to allow participation by a major aerospace company in the study process, which had been unable to attend earlier.

In addition numerous journals and publications were consulted in order to provide further information on technological trends and market trends in a global environment.

2.3 Industry Consensus

Firms contacted in the course of this research agreed that a photonics sector campaign would be industry strategic, and although elements of the campaign have been addressed, along with other projects, through specific MOUs with ISC, this sectorial initiative offers an opportunity to bring together the best industry has to offer in one focus, reducing duplication and thereby maximizing the impact from limited Canadian resources.

2.4 Opportunities

In aerospace, photonics can be used essentially as an enabling technology, with significant opportunities existing in upscale high technology, high reliability, high performance specialized niches such as specific aerospace and defence programs, as well as in selected individual projects.

For example, imaging systems could tie together helmet display virtual reality interfaces and integrated human-machine interfaces. Sensors could be utilized in specialized vision systems as well as in surveillance and robotics and smart structures. In addition, guidance, control and communications functions could become more accurate and economical through the use of photonics-based systems.

As a result of surveying a cross section of the Canadian aerospace and defence sector, and reviewing the summary findings of the participants in the focus group, the following broad projects/applications were proposed as the basis for viable collaborative programs.

<u>Flat Panel High Definition Displays</u>

- Very high resolution, colour, wide range of environmental performance such as vibration, temperature and, brightness.
- Displays may be transmissive or emissive-based technology.
- Applications include aircraft, simulators, ground stations, ship-borne and space.

<u>Imaging and Sensing Systems</u>

- Night vision, thermal imaging, for navigation/guidance/targeting/robotics, etc. based on the processing and use of specialized materials and electronic digital processing and pattern recognition algorithms.
- Applications include weapon guidance, civil and military navigation, and numerous civilian spin-off applications.

<u>Virtual Reality Interfaces</u>

- Based on classical optics, in combination with dedicated high speed computing engines, creating appropriate imagery and sensory interfaces.

- Applications include simulators, large-scale entertainment, educational systems including both military and civil training, R&D process enhancements and telecommunications.

<u>Smart Structures</u>

- Photonics-based materials used to detect changes in physical structures, etc.

- Applications include flying airframes, maintenance systems, civil engineering structures, etc.

<u>Human-Machine Interfaces</u>

- Display-based interface systems to improve the efficiency of the human-machine interface e.g. the reduced use of moving data entry keyboards, etc.

- Applications range from aircraft pilot stations to the "office of the future".

2.5 Recommendations for Strategic Approaches

The size of the photonics market is expected to grow to a value in excess of $200 billion over the next five years. The flat panel market alone is expected to grow at a rate of 14% per annum to $9.4 billion by the year 2000. Despite the current recessionary environment, the aerospace photonics market is expected to grow 2-3 times faster than the rate of the global economy.

Product sales could surpass $200 million per annum within the next five years. Average start-up and sustaining development funds required are in the range of twenty per cent of sales and may be in the region of $40 million annually. A work force of 500 to 1,000 additional highly skilled jobs would be directly required by this program. Moreover, up to three times this number of jobs would be created indirectly.

Risks are primarily financial rather than technology based. For example, foreign governments may opt to support critical technologies used within their own technology infrastructure rather than subject embryonic projects to the fate of market forces. Canadian government support has been deemed essential in a start-up and growth phase in order to allow industry to compete on a level playing field. Previous experience of collaborative effectors between industry and government have proven very successful.

Funding is required for high-risk collaborative R&D. Aerospace firms in Canada should be encouraged to make proposals to ISC provided at least two participants are willing to share in the risks also.

It is recommended the existing consultations continue. Nevertheless industry representatives have made it clear that government funding of R&D is a sine qua non of the existence of this industry in Canada.

3.0 OIL AND GAS EQUIPMENT

3.1 Industry Environment

A number of opportunities exist in the oil and gas equipment sector for the commercial application of photonics. These are related to pipeline remote inspection, pipeline remote leaks detection, just-in-time gas compressor maintenance, and possibly oil sands mining safety.

Significant parts of Canada's oil and gas infrastructure are getting old, and companies have limited resources with which to upgrade owing to continuing low global oil and gas prices. The challenge to photonics technology is how to be relevant to all these issues.

3.2 Methodology

Meetings were held in Edmonton and Calgary in May, 1993. All operational aspects of the oil and gas industry were represented, including representatives from two large integrated oil companies, a major gas pipeline and an oil sands extraction company, along with technology suppliers, such as the Laser Institute and TRLabs.

3.3 Industry Consensus

A consensus did emerge that photonics could contribute to the industry's needs, although the issue of whether photonics would be the most cost/effective solution is not yet determined. While photonics looks promising, and there was industry consensus this technology is worth investigating, substantial R&D is required to define the potential.

The opportunities for the application of photonics technologies within the oil and gas equipment sector were segmented into the following three areas:

Sensing

- Environmental Monitoring, e.g., source monitoring and ambient monitoring
- Process Control/Monitoring/Quality Control

Material Processing

- Metal Protection (Coatings)
- Fabrication and Repair, e.g., surface hardening, welding, laser cutting, surface build-up

Measurement

- Physical Properties Measurement
- Spatial Measurement

3.4 Opportunities

Specific projects identified by the industry for collaborative photonics R&D include:

Heavy oil processing

- image analysis of texture of the froth created during the process; and
- reflective analysis of the oil sand on a belt to determine water content, oil content and some composition information.

Keys to success in heavy oil processing are productivity, machine monitoring, and fugitive emissions from the process. A major ongoing issue in the industry is wear and abrasion resistance.

Oil and gas processing

- replacing gas chromatographs with Fourier transform IR sensing

- there are currently many gas detection sensors scattered throughout gas plants - replacing them with a laser scanner/sensing system to achieve distributed sensing vs. point sensing of fugitive emissions.

- in-site coating and refurbishment of flow lines/pipelines

Pipelines

- requirement for a faster gas stream measurement system and the ability to measure more constituents at once. There is value in selling each hydrocarbon separately, therefore real time measurement of precise gas composition in the flow stream is more important.

- requirement for improved remote sensing of compressor operations and incipient failure detection. The key to success in gas pipeline operations is to keep the compressors running with least cost (fuel and labour).

- requirement for improved techniques for leak detection. The infrastructure is getting old and diverse techniques are used for gas detection from trained dogs to hydrophillic plastic coaxial cable. (The microwave energy passed through the coax is attenuated as the coax absorbs hydrocarbon).

- requirement for a solution to pipe internal surface pitting measurement despite heavy wax residue.

- requirement to better discriminate bottom solids from low viscosity materials (to recognize the sludge from good low viscosity product in oil storage tanks).

- requirement of optical techniques to measure surface storage tank volumes (so-called "tank strapping") and to measure the volume of tank contents (tank gauging).

Drilling

- "down hole" trajectory measurement

- image analysis of surface roughness of cuttings; porosity and permeability measurements of the cuttings

- sensing to assist in core analysis conducted at the temperatures and pressures found in-site

Offshore applications in particular are sensitive to the contaminants associated with the drill cuttings and discarded mud returned to the ocean.

<u>Environmental</u>

- oil spill clean up and separation of oil from water, sand and soil.

<u>All Operations</u>

- wear and corrosion reduction/prevention

3.5 Recommendations for Strategic Approaches

<u>The Petroleum Photonics Sensor Consortium</u>

A strategy to improve the "Canadian content" of new oil and gas technology, successful in other situations, has been to create a consortium of industry and local/regional Canadian expertise to develop and commercialize technology. A number of industry participants responded favourably to the suggestion of a consortium dedicated to the exploitation of photonics technology in the petroleum industry. Such a consortium, if established in Western Canada would likely include the Laser Institute, the Centre for Frontier Engineering and Research (CFER), an existing petroleum industry consortium, TRLabs,a telecommunications consortium with a distinct emphasis on photonics-based sensor development, a number of universities, and regional, national and international petroleum producers and service companies.

The Petroleum Photonics Sensor Consortium could be effectively sustained within existing facilities, such as TRLabs, the Laser Institute. The industry could be organized to lead the planning for and participate in photonics-based R&D programs of high priority to the industry, addressing such activities and technical challenges as outlined above.

It is recommended that the Laser Institute, based in Edmonton, Alberta, be the lead business unit in forming such a consortium. At present, the Institute has 25 people (of which 12 are in laser job shop), and a total budget $2 million annually of which 30-40% is recovered by commercial control. In order to fulfil such a mission, the Institute would need a core funding increase of $1 million annually to develop more home-grown (systems) technology.

ISC would have to provide an IRAP-like grant/support for oil patch to use on R&D. There could be matching grants, e.g. photonics in resource industries.

While the possibilities for photonics certainly do exist in the Oil and Gas equipment sector, more R&D work is required. It is likely this means ISC funding for photonics, especially among the technology suppliers who will have to develop products from scratch. Generally, photonics can help resource industries in exploration, and process instrumentation. Sensors can give productivity gains at low costs, but it is a "hard sell" as yet. Also environment problems are a promising market: note "fugitive emissions" e.g. from valves, etc.

4.0 FOREST PRODUCTS

4.1 Industry Environment

There are excellent opportunities for photonics technology in one of Canada's largest industrial sectors, forest products. Moreover, there is a major opportunity to export this technology to the large export markets if the existing commercialization gap can be overcome. This barrier can be overcome with a collaborative, pre-competitive R & D program.

Over the past 15 years, the Canadian forest products industry has undergone a quiet transformation from labour intensive manufacturing to highly efficient. This progression was necessary to withstand increased foreign competition from regions with low wage rates and fibre costs. As well, domestic costs rose rapidly due to increased stumpage rates, power and transportation costs.

As a result, photonics-based products can be found in almost every aspect of the industry including R & D, silviculture, harvesting, transportation, manufacturing, quality control, grading, inventory tracking, remanufacturing and distribution.

Silviculture:
- identification of not sufficiently restocked lands
- monitoring of seedling growth
- detection of disease/fire damage/blowdown
- species breakdown/volume estimates

Harvesting:
- remote sensing for cutting plans, road building, environmental impact reviews

Transportation:
- sorting/tracking of log booms

Manufacturing:
- sorting and sizing of logs
- scanning of log dimensions for precise bucking and optimized headrig cutting programs (i.e. recovery optimization)
- laser guided headrig (sawyer guide)
- resaw operations optimization (edger, trimmer, cant)
- colour sorting and matching

Quality Control:
- precise measurement
- automatic grading
- grade reading and marking
- detection and trimming of defects
- veneer profiling

Inventory Control:
- inventory aging/tracking
- material tracking

Secondary Manufacturing:
- precision etching, cutting, grouting and other finishing techniques

4.2 Methodology

The information gathered in this report was collected directly from interviews with executives of leading forest products companies, equipment manufacturers, photonics manufacturers and integrators and from leading researchers. These companies represent an industry with combined annual revenues of over $10 billion per year.

The working group consisted of the senior executives of two major producers - MacMillan Bloedel Limited and Canadian Forest Products Ltd.; two research centres - University of British Columbia and Forintek Canada Ltd. (with over 150 sponsoring companies); an association which represents equipment manufacturers, photonics developers and integrators - Western Canadian Wood Machinery & Services Export Association (with over 50 sponsoring companies); and the CEOs of three photonics development companies - VisionSmart, Dynamic Control Systems and SOFTAC Systems Canada.

In addition, ten other photonics companies were canvassed by telephone as were officials from the B.C. Wood Specialities Group (an association of 75 secondary manufacturing operations), ISC, the Advanced Systems Institute, and the Science Council of B.C.

4.3 Industry Consensus

There exists overseas a negative impression that Canadian forest machinery suppliers are opportunistic with respect to overseas markets, only wooing these markets when the economy at home is depressed and then leaving them as the domestic situation improves. Greater market research related to these markets and a stronger presence in these markets formed through strategic alliances will improve the Canadian image.

A sectorally integrated approach is necessary to be successful. Most of the photonics developers and integrators are SMEs that expressed desire to see cross-sectoral applications for their forest industry photonics technologies. Many forest industry photonics-based process controls have applications to general metal processing and materials handling technologies.

Proprietary interest in research is important to those participating in collaborative research, at least over a two-to-three year time frame.

There is an immediate need for operator interface-related research. Currently the technology available is running ahead of the work force's ability to use it. Operator interfaces are often quite complicated and forest products companies are experiencing staff mobility problems associated with "deep" or very specific training. Key staff are recruited by competitors shortly after they are trained, discouraging these companies from introducing even more sophisticated photonics technologies.

Canadians have a lead in solid wood forest industry photonics technology but cooperative research will be required to maintain this lead. There is strong competition from larger, better capitalized, Scandinavian and German companies that are the beneficiaries of government encouraged cooperative research efforts.

The Canadian pulp & paper process control industry was in a similar lead position 15 years age. A small but growing number of SMEs had developed a series of technological innovations. Today, all of these companies have fallen prey to Scandinavian and German interests who bought the companies up and, for the most part, exported their technologies. The success of these foreign interests was due partially to cooperative research efforts sponsored by their domestic governments. Participating companies were able to reduce the risk and cost associated with new development through joint R&D cooperation, subsidies, purchase of foreign technologies, and commercialization and debugging of new technologies in participating domestic pulp and paper operations.

A commercialization gap with respect to the adoption of new forest photonics technologies exists. This gap results from a number of factors including:

- lack of available funding for pre-competitive research;
- lack of coordination of government funding for the photonics sector;
- imprecisely defined basic research that does not always meet the needs of the end user;
- lack of coordinated or collaborative efforts to define the needs of export market segments;
- lack of domestic opportunities to test and prove the technologies; and
- shortage of trained personnel and simplified operator interfaces.

4.4 Opportunities

The working group was unanimous in support of one multi-faceted project which would help the industry overcome the lack of pre-competitive R & D. They felt there were large opportunities for Canadian forest photonics technology in export markets if the domestic developers and users could work together to overcome the commercialization barrier posed by a lack of market intelligence and applications data. Data acquisition and technology interfacing were the two areas the industry expressed an interest in supporting.

<u>Data Acquisition</u>

- Part of further introducing the application of sensor (photonics) technologies to new domestic and export markets includes gathering data related to specific wood characteristics:
    - colour sorting for grade and matching for edge-glued components;
    - shape (3-D profiling of logs through multiple axis scanning for grade and maximum recovery);
    - quality (analysis for strength and appearance characteristics);

- marking/grading (automatically grading and marking lumber given a complex set of variables related to grain, compression, warp/wane, knots, stain and discolouration, etc.);

- species characterization (separating species characteristics from defects, especially for non-domestic species).

Technology Interfacing

- This would include studies to improve:

  - user interfaces

  - training

  - machine-to-machine interfacing (the accuracy of the processing equipment must match that of the scanning optimisers)
  - cross-sectoral interfacing

  - real time use of complex data sets

Both of these endeavours would require significant payback or market research entailing:

- Cost benefit studies and international market intelligence are required to encourage the purchase and adoption of Canadian forest photonics technology.

- Payback studies are required to illustrate the usefulness of the various sensors technologies. Such work could lead to the leasing of equipment with payments made from increased revenues.

- Export target market niches should be defined by local customer requirements. Possible alliances required to deliver the technologies should be explored as well as any particular sales or distribution strategies.

Products sales now total $15+ million per annum for photonics components, $400+ million per annum for forest machinery and services, and several billion dollars in forest products. Sales of photonics components alone could surpass $45 million over the next 5 years given continued growth. A new breed of equipment manufacturer would develop their own photonics components (e.g. Newnes Machines) are leading growth in Canada's forest machinery sector.

The individual studies encompassed in this project would be prioritized according to need and risk. The total project budget is estimated to range from \$2.0 to \$5.0 million.

A likely organizational structure for a collaborative group to carry out the research proposed above would include a project committee, a champion organization and a project manager to coordinate the efforts of the various contributors.

The project committee would be made up of participating forest products companies and equipment manufacturers, photonics companies, and various participating government agencies. Both the forest products companies and the government would contribute money toward the project while the mostly small and medium-sized photonics companies would make in kind contributions. The lead government agency, ISC, would be responsible for 30% of the total project costs and would play a catalytic role, funding most of the preliminary stages of the project.

There would be a neutral champion organization to coordinate the project. Both the Council of Forest Industries (COFI) and the Science Council of British Columbia (SCBC) would be excellent candidate organizations. The SCBC has stated that it is willing to fund one half the cost of a Forest Technology Champion and this person, or someone designated by COFI, could play the role of project manager. The manager would initiate and coordinate the consultants, researchers and companies participating on each of the specific studies over the proposed two year time frame for the project.

4.5 Recommendations for Strategic Approaches

Several consensual conclusions and concerns were voiced during the meeting held in Vancouver on May 20th. One specific concern expressed was the perceived image that the federal government feels the forest products sector is a "sunset" industry. This perception could hinder the efforts of the industry to continue its rapid absorbtion of technology and have a negative effect on the growing forest photonics sector.

Specific conclusions resulting from the working group session included:

- Need for cohesive action on behalf of the government as photonics sector is often defined and classified differently by various federal and provincial government agencies, creating "islands of support" and overlapping research initiatives.

- Non-competitive, cooperative research should be emphasized as it is difficult to joint fund "applied" projects where most photonics developers compete.

- Research projects should be driven by user need. Most participants felt that the photonics sector had experienced "several technical successes that were commercial failures".

- A global focus is necessary to be successful. Even though 80% of forest products output is destined for export, most research effort to date in forest products photonics has concerned domestic issues.

- A sectorally integrated approach is necessary to be successful.

- Proprietary interest in research is important to those participating in collaborative research, at least over a two to three year time frame.

- There is an immediate need for operator interface-related research. Currently, the technology available is running ahead of the work force's ability to use it. Operator interfaces are often quite complicated and forest products companies are experiencing staff mobility problems associated with very specific training. Key staff are recruited by competitors shortly after they are trained.

- Canadians have a lead in solid wood forest industry photonics technology but cooperative research will be required to maintain this lead.

- Funding sources exist for most types of research, however, there is a need for collaborative or pooled research efforts at the pre-competitive stage where the return to any one company does not usually warrant the research effort.

5.0 OTHER APPLICATIONS: SMART MATERIAL INTERFACE CHIP

In the course of this project, a number of other applications of photonics were identified and investigated: medical devices, smart construction, office furniture systems, mining and raw material extraction, military projectile guidance and bomb disposal systems. All of these applications could be made into viable photonic collaborative research projects.

The most promising technology, which is highlighted in this section is "smart construction". Experimental development of the "smart construction interface chip" would represent a major advance for the Canadian technology industry. Specifically, the product discussed here is an integrated circuit device (chip) which will consist of optical and electronic components and will provide information on the stresses of structural materials.

5.1 Proposed Product and Participants

This new multidisciplinary branch of engineering termed "Smart Materials and Structures", represents a merger of photonic technology with advanced materials and is as likely to be found in future aircraft as in new bridges. Improvements in safety, reductions in operating and maintenance costs, and enhancement of the environment are some of the benefits expected from this technology.[67]

The proposed product which is the subject of this business plan is an integrated circuit device (chip) which will consist of optical and electronic components. The chip will provide an interface between optical fibre strands buried inside of structural materials or bonded to their surface (i.e. prestressed concrete forms, steel tubes, metal or plastic containers, etc.) and external measurements systems.

The chip will provide information on the stresses and aging characteristics of the structural material, based on changes experienced by the embedded fiber-optic strands (and/or sensors). The chip will essentially "shine" light into the embedded strands, and based on reflections (and other characteristics) received, relay information to the outside world.

The product has a number of potential benefits:

- providing "early warning" signals of impending breaks, cracks, etc., in structures such as bridges and pipelines;
- enabling new materials to be used for structural components, such as composite materials[68] to be used for natural gas tanks; and
- supporting integrated management of stresses and strains in large, complex structures, such as buildings.

The chip itself will be an integral part of the structural component. For example, it could be embedded directly into a prestressed concrete form, or composite pressure vessels.

[67] Measures, Raymond M., "The Development of a Canadian Optoelectronic Smart Material Interface Chip and its Role in Smart Structures", position paper to ISC, University of Toronto Institute for Aerospace Studies, March 1993, page 1

[68] Composite materials are made from fibres such as glass, carbon, and graphite mixed with plastic resins.

The challenges in designing such a chip are many, including:

- robustness - the chip must operate in harsh environments both during the construction of the structure in question, as well as in ongoing operation;

- ease of use - the interface (interconnect) to the outside world must be simple and easily usable by construction personnel;

- ease of powering - the chip is an "active" component and relies on being fed power to work; several modes of powering the chip and communicating with it are possible and need to be explored; and

- low cost - there are many individual structural components in any large structure; to meet high volume applications, the chip must be low cost and manufacturable in large quantities.

Similar chips could also be used for application in the aerospace industry for monitoring of aircraft.

Experimental development of the smart material interface chip would represent a major advance for the Canadian technology industry, bringing the following benefits:

- provides a new advanced technology that can be applied in many Canadian industry segments, including aircraft, bridges, pressure vessels, pipelines, ships and storage tanks;

- stimulates development of innovative designs in the structural materials industry;

- reduces the cost of technology and make it more rugged, compact and user friendly;

- stimulates the electronics and photonics sectors, strategic areas of industrial development in which Canada is generally less competitive than other countries; and

- addresses a growing market for advanced materials, potentially increasing Canadian industry competitiveness and providing value-added in Canadian exports of semi-finished goods (e.g. tanks and containers).

Development of the chip requires participation of a variety of industry participants and user organizations. Base technologies have been developed through programs at the University of Toronto Institute for Aerospace Studies (UTIAS); patent applications have been made for aspects of the multi-sensor signal processing technology and other aspects of the design.[69]

EG&G Canada Ltd. has been identified as an appropriate manufacturing company to explore this opportunity. Other companies that have expressed an interest in manufacturing this chip are MPB Technologies Inc. and Seastar Optics Inc.

Several "user" organizations have been identified as potential participants in the development program, notably:

- EDO Canada Ltd., a joint venture of the Alberta government and EDO Corporation of New York (a defense contractor), a maker of gas tanks and other products from composite materials (plastic resins);

- The Alberta Gas Transmission Division of NOVA Corporation of Alberta, a builder and operator of gas pipelines; and

- CON-FORCE Structures Ltd., based in Calgary, a maker of architectural pre-cast concrete units and concrete beams for bridges.

ISC's participation, combined with the UTIAS and the user organizations, will assist in realizing the potential benefits of developing the interface chip. The viability of the chip will depend on having the widest possible application in industry, with the needs of a variety of users "built-in" from the beginning of the development program.

[69] Measures, page 2

5.2 Strategic Market Analysis

Target market segments, trends and market size

This business plan addresses three target market segments for the smart material interface chip:

- bridges and buildings
- pipelines
- gas tanks

There is hope that a common chip can be designed for these three applications, thus sharing the development cost over a wide range of user organizations and potential markets. To gauge the size of the potential market that the chip addresses, the size of the Canadian industry for structural components related to these areas can be identified, as shown below:[70]

Iron or steel containers for liquefied or compressed gas:	$ 34 million
Concrete pipe, reinforced or prestressed:	$ 27 million
Custom design concrete precast structural or architectural components:	$ 340 million
Bridges and bridge sections made from iron or steel:	$ 58 million
Total of these markets:	$459 million

Thus the chip can address shipments of product of $459 million in these four categories. There are clearly other categories for which statistics are not explicitly reported, such as containers made from plastic resins, or steel or iron tubing, which may add another ~ $100 million in shipments, for a total of roughly $550 million. The interface chip adds value to the shipments of these products, and would be considered an incremental market to the base of $550 million (Canada only).

The application of the chip to the three market segments will depend on a number of factors:

- the rate of growth in construction of structures such as buildings, bridges, pipelines, etc.;

[70] Statistics Canada catalogues, 4-251, 44-250 and 43-250, 1989

- the rate of acceptance of new technologies in these applications (e.g. composites for natural gas tanks); and

- the rate of diffusion of smart structure technology into the structural materials.

Trends, assumptions and preliminary market estimates are described below for the target market segments.

Precast concrete application

Custom design concrete precast structural or architectural component total product shipments were 979,500 cubic meters in 1989 (Canada only).[71] Although this was about double the 1988 figure, it will be assumed that subsequent growth will simply follow GNP growth. By knowing roughly the number of interface chips that would be required per cubic meter, a rough estimate of market size can be determined.

If it is assumed that one interface chip might be required for every ten cubic meters, (an assumption which requires verification), the addressed market size in Canada for interface chips would be about 97,950 per year, for the precast concrete application. Assuming North America is about 11 times as big as Canada, the North American market would represent a potential for about 1.1 million chips per year.

The resultant market for the chips will depend on the rate of adoption of the new technology by the precast and prestressed concrete industry. For study purposes, it is assumed that use of the chips will reach 15% of the market by the Year 2000, resulting in potential sales in the Year 2000 of about 180,000 chips.

Gas Tank Application

Gas tanks today are generally made of metal. To power automobiles, the metal tank format of natural gas tanks is too heavy to support the amount of natural gas required for the automobile to be competitive with liquid gas automobiles (on a "miles travelled per tank" basis). New composite materials are being used on a limited basis for natural gas applications due to their much lighter weight. EDO Canada Ltd. recently announced the "world's first government certified all-composite lightweight cylinder for natural gas vehicles".[72]

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71 Statistics Canada catalogue 44-250, 1989, page 27; the figure for 1988 was 435,000 cubic meters

72 EDO Canada Ltd. News Release, April 1, 1993

One of the problems limiting industry acceptance of composite material tanks is that they are more prone to cracking than metallic tanks. For this reason composite material tanks are generally over-designed. Even when over-designed, there is often a lingering perception that the tanks are unsafe.

Another problem with natural gas tanks is periodic inspection to ensure ongoing reliability and to verify that cracks are not developing. Currently this would be done by taking the tank "out of service" (i.e. removing it from the vehicle) so it can be pressurized to a level suitable for testing (10,000 psi, for example). This process would clearly be too inconvenient for the mass market of automobile purchasers.

The use of smart materials could be a key enabling technology in overcoming these problems since stresses and strains could be monitored and reported before cracks develop. This "feature" of composite material tanks would reduce the amount of "over-design" required (hence reducing costs) and would provide an added level of comfort for automobile manufacturers in supporting a switch to natural gas powered vehicles.

The North American automobile market represents about 10 - 12 million units shipped per year. There are currently about 70,000 natural gas vehicles operating in Canada and the U.S. It has been forecasted that by the Year 2000, the total shipments in the U.S. market will be about 10 million natural gas vehicles.[73] The resultant market for chips will depend on the rate of adoption of the new technology for natural gas tank applications.

For study purposes, it is assumed that use of the chips will reach one third of the market by the Year 2000. It is also assumed that there would be only one chip required per natural gas cylinder (cylinder). With these assumptions, and assuming sales of six million natural gas vehicles in the Year 2000, there would be a potential of two million chips.[74]

[73] Information supplied by EDO Canada, based on conservative predictions done in the U.S. regarding the impact of the Clean Air Act.

[74] It is assumed here that there would only be one "cylinder" needed per natural gas vehicle. If more than one cylinder were required per vehicle, the market for the chips would increase in unit terms, but not necessarily in $ terms.

Pipeline Application

Pipelines require ongoing monitoring to ensure structural integrity. This is particularly important in areas of unstable or unfriendly terrain (muskeg, river banks, etc.). "Just in time" monitoring, which could be facilitated by the use of smart materials, would greatly reduce maintenance costs, while increasing the safety of pipeline operations.

In Canada and the U.S., there are currently about 10,700 miles of oil and gas pipeline under construction (new and replacement lines).[75] It is assumed for analysis purposes that projects generally last from one to three years. If the average project duration is two years, there would be an annual activity level of about 5,350 miles of pipeline being built. For study purposes, it is assumed that pipeline construction grows at the rate of GNP growth. Assuming there would be 15 chips per mile of pipeline (i.e. about one every 100m; an assumption that requires verification),[76] and that by the Year 2000 the chips are used in 30% of the projects, the resultant potential sales would be 27,000 chips.

Market Size Estimation

The trends in the market segments and the assumptions discussed above thus lead to a Year 2000 market for the chips of 2.2 million units, broken down as follows:

Prestressed concrete forms	180,000
Gas tanks for natural gas	2,000,000
Pipelines	27,000
Total Units	2,207,000

An estimate of the market size (in unit shipments of chips) for the years 1996 to 2000 is shown in Figure 1.

Assuming products start becoming available in 1996, the cumulative sales between 1996 and 2000 could be about 3.6 million chips.

75 Based on a compilation of reported projects in "Pipeline - World Construction", published in OGJ Special Issue, Oil & Gas Journal, April 12, 1993, pp. 87-89

76 Per NOVA Corporation, "conventional" sensors require three sensing elements per monitor point in order to cover three dimensions. With the Smart Material Interface Chip, it is assumed that only one chip per point would be required as each chip would contain multiple active sensing elements.

Note: These figures are only tentative, and are subject to further study. They are presented here to demonstrate that a significant market could exist for a chip of the nature being described herein. One critical element the analysis also points out is the potential importance of natural gas vehicles to the viability of the market.

Figure 1 - Market Estimate (units)

Current Level of Technology in the Marketplace

This business plan addresses three target market segments for the smart material interface chip:

- bridges and buildings
- pipelines
- gas tanks

The idea of integrating electronic sensors into these structures is relatively new. Thus there is little technology "in place" which would be directly comparable to the capabilities defined for the interface chip.

Sensor technology now being considered, aside from the "smart materials" technologies, are:

- Mechanical strain gauges and add-on fiber optic sensors: These technologies involve mechanically attaching sensors to a structure over the sections which need monitoring (i.e. areas of shifting terrain, areas of severe freeze/thaw characteristics, etc.). Deflections which occur in the structure are also evident in the attached sensor. This information can be remotely recorded and appropriate maintenance action taken. The typical application for this technology is in pipelines.

- High frequency echoes and infrared tomography: These techniques work like a sort of X-ray for the structure. The reflection patterns (in the case of high frequency echoes), or received variations in radiated energy (IR tomography), indicate possible presence of structural weaknesses.

  In the case of the echo technique, a device emits high frequency sound over the surface of a structure. The waves travel along the structure and some of the sound energy is reflected back. Applications have typically been in the analysis of metal tendons forming part of pre-stressed concrete components, and in analysis of metal rock/soil anchors (the alternative technique used in the past involved removing a section to be measured; i.e. it involved "destructive testing").

Table 1 provides an overview comparison of these two techniques relative to the "smart material" approach.

The Smart Material technique has the most capability in terms of the range of the different parameters that can be monitored, in terms of reliability and other attributes. In addition it provides greater long-term potential in terms of structural control in addition to monitoring.[77] Furthermore, much of the optoelectronic sensing technology could also be used with surface-adhered systems and could therefore be retrofitted to structures such as aircraft. In these cases, the chip would serve to keep costs low and would provide compact rugged systems.

The level of technology in the marketplace can be summarized as follows:

- Bridges and buildings: Would use external monitoring systems such as high frequency echoes (or techniques such as Richter scale measurements); the main consideration is to monitor structures already in place which is a much larger market than new construction.

- Pipelines: Current activity is based on add-on strain gauges and fiber optic sensors, again the main consideration being that the existing pipeline base to be monitored is far larger than the pipeline under construction.

- Gas tanks: These currently do not require monitoring; natural gas tanks made from steel are robust and do not crack. This would be a new emerging market for the embedded sensor technology as gas tanks made from composite materials gain acceptance.

Apparent Opportunities/Market Gaps

Based on this analysis, the best opportunities for the chip would appear to be:

- applications in new structures (bridges, buildings and pipelines) which are made of prestressed concrete parts or other materials. In this application, the chip will compete with other technologies such as high frequency echo techniques, and add-on sensors and gauges.

- applications to composite material gas tanks for natural gas powered vehicles, an emerging market, which the existing technologies have difficulty in addressing because they require the tank to be taken out of service for testing.

[77] For example, in the case of vibrations, counter-vibrations could be generated to offset the noise of other effects.

Table 1
Comparison of Sensing Techniques for Structural Integrity Monitoring

	Smart Material (embedded fibers and interface chips)	Add-on fiber optic sensors, strain gauges	High frequency echo, infrared tomography
Potential for monitoring effects of: - wind - temperature - thermal expansion - load deflection - ground movement - vibrations - material defects	HIGH potential for all measurements as long as build into structure at outset; however, many measurements also possible if surface-adhered	HIGH potential for measurement of mechanical stresses; less for material defects (corrosion)	HIGH; records "after the fact"; mostly for results of aging, etc.
Continuous monitoring and remote access to "live" data	YES	YES	NO; requires site visit, or out of service test
Suitability for hostile environments	HIGH; system can be integral part of structure being measured	HIGH; within the constraints of mechanical attachment system	Possibly; difficulty of access for site visit?
Sensitivity and reliability of sensor	HIGH	HIGH, but may be limited by mechanical attachment used	Less direct measurement; may require more interpretation
Potential to "control" aspects of the structure	HIGH; system is an integral part of structure	LIMITED; system is attached to, not part of structure	LOW; external measurement only
Potential for application to existing structures	LOW; system is embedded	HIGH	HIGH

Competition and Expected Market Share

More analysis would be required to determine all the players who may be active in the Smart Material field.

The following organizations have been identified to date:

- G2 Systems Inc., a California-based company making an optical sensor system for pipeline applications based on the "add-on" sensor approach (to be verified);
- Smart Structures Ltd., affiliated with the University of Strathclyde, Scotland;
- Cordec International Inc. of Ottawa, Ontario, which provides a "Reflectometric Impulse Measurement Technique" service for measurement of structural integrity (high frequency echo approach);
- Institute for Intelligent Structural Systems, University of Vermont, which is involved in integrating fiber-optic sensors into buildings and dams; and
- Center for Intelligent Material Systems, Virginia, which specializes in actuator and control systems.

The chip does not have any direct competitors based on this preliminary list. For analysis purposes, it will be assumed that, on a 5-10 year horizon, there will be at least two other developers of a similar device in North America.

The Canadian chip maker is assumed to attract 40% of the potential market, based on an assumption of early entry into the market due to the advanced work completed to date, combined with the expected ISC program support.

Key Success Factors

Table 2 summarizes some of the parameters of the Smart Material application by the three market segments (gas tanks, bridges and buildings, pipelines).

Table 2
Parameters and Key Success Factors by Market Application

	Monitoring of Gas Tanks of NG-Powered Vehicles	**Monitoring of Buildings and Bridges**	**Monitoring of Pipelines**
Market Parameters Market Size for new Construction	Large	Large	Relatively Small
Growth in market	High, emerging	Stable, with GNP	Relatively low (expansion with use of nat. gas)
Alternatives - technologies - competitors	Acoustic echo IR tomography ?	Acoustic echo Cordec Int'l	Add-on sensors G2 Systems
Need for real-time information, measurement	YES	Somewhat (more in high earthquake areas)	Somewhat (depends on terrain)
Cost sensitivity	HIGH - gas tank is a low-dollar item ($600-$800)	HIGH - need low cost to make cost effective	HIGH - need low cost to apply many chips to long pipeline projects
Success Factors Critical factors for acceptance of the technology	Acceptance of NG-powered vehicles	Introduction of composite materials as a replacement for steel in bridges, etc. Construction in earthquake zones	Growth in pipeline construction
Timing of application (if chip were available)	Year 2000?	Now	Now
Relative market risk	HIGH	LOW	LOW

The main considerations can be summarized as follows:

- Bridges and buildings: These have a large potential market for the chip in new construction applications; growth would come first in areas of high earthquake activity. There is relatively low market risk (large, stable market), but may take some time for acceptance of the technology. A low cost chip would likely be a stimulating factor due to the high number of chips which would be required in any given application.

- Pipelines: There is a smaller potential market here than that of bridges and buildings. Growth could be stimulated by increased use of natural gas. Other considerations are likely similar to those of bridges and buildings.

- Gas tanks for natural gas: This is a potentially large market which will emerge later in the decade as natural gas vehicles gain acceptance by the automotive industry. While there are no immediately evident substitute products, this market would be high risk (large, but uncertain).

Overall the key factors for success will center on being able to produce a chip which is based on a solid user definition of functionality (i.e. to ensure the widest possible applicability to build volumes), combined with low overall cost (i.e. including the device itself as well as its packaging, powering, installation, etc.).

Program Risks

The key elements of risk, which would require further analysis, are:

- Timing of the introduction of the chip is sensitive to be competitive with alternative technologies; a number of alternative sensing technologies are available now or sooner than the chip. These technologies may address a large part of the market before the chip can be made widely available.

- There is risk in the relative rate of acceptance of the new technology by the industries related to the three market segments. Makers of concrete components and pipelines are not usually thought of as being "high tech". While this is changing as new technologies migrate into their industries, the rate of acceptance may be slow. This favours more conventional monitoring techniques, which again may reduce the market addressable by the chip. A major breakthrough by UTIAS in installing a fiber-optic sensing system in a road bridge in Calgary could help facilitate acceptance of the technology by the civil engineering community.

- The rate of introduction of natural gas powered vehicles is risky. This is the largest potential market segment. If natural gas powered vehicles do not gain market acceptance (because of relative energy costs, due to limitations in speed, distance, etc.) the potential market for the chip would be significantly smaller.

- Technological complexity is a factor. Current devices built in Canada (by the SSOC, for example) consist of a small number of components grown on wafers using a single growth technique.[78] The OEIC technology to produce the chip would be far more advanced (requiring VLSI circuitry on the same substrate as optoelectronic components) and may not be accessible in a near-term time frame (three to five years). This risk may favour development of a simpler chip with more limited capabilities, or consisting of fewer components. An intermediate chip could be developed with current technology that would allow cost reduction and other improvements.

- There is system level complexity.[79] The need to power many points in a large structure, and to access these points on a permanent or periodic basis, creates a level of complexity at the "systems" level. For example, if a fiber is used to power all the chips, the way the fiber is routed through the structure and how the system is laid out will be a significant design issue. At a components level, there is complexity in the large-scale pigtailing of the chip to single-mode fiber, and in the techniques required to embed the chip into the structural components. The level of complexity at the systems level may also limit the chip's applicability.

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[78] Based on conversation with the Solid State Optoelectronics Consortium of Canada

[79] Preliminary input from EG&G; letter dated August 9, 1993

- Product proliferation has to be considered to achieve low unit costs, a single version of the Chip would address many applications. Given the diversity of the potential applications, the differing user needs may create a proliferation of product types, thus reducing the possibility of a low cost chip thereby limiting its applicability.

- The investment required for the machinery to produce an OEIC would be very high ($50-$100 million - to be investigated). This level of investment supports the idea of creating a "foundry" for OEICs. It is unlikely that one application device could support the investment required. Thus the lack of a foundry capability limits the potential to produce the chip on a near term horizon (except perhaps by going to the U.S. or Japan).

These risks need to be explored more fully in a feasibility study of the chip, prior to moving into a full R&D program.

5.3 Product Description

The proposed product is an integrated circuit device (chip) which will consist of optical and electronic components. The chip will provide an interface between fiber optic strands buried inside of structural materials (i.e. prestressed concrete forms, steel tubes, metal or plastic containers) and external measurements systems.

The chip will provide information on stresses and aging characteristics of the structural material, based on changes in the embedded fiber optic strands (and/or sensors). The chip will essentially "shine" light into the embedded strands and, based on reflections (and other characteristics) received, relay information to the outside world.

An overview of the chip is shown in Figure 2. The key elements of the system are described briefly below:

- Optical fiber architecture: The layout and design of the fibers that are embedded in the structure being monitored. The devices could also be surface adhered.

- Bragg grating sensors: These are built into the fibers which are embedded in the material and serve as part of the lasing cavity of the devices built into the chip. The combination of the Bragg grating and the lasers on the chip creates the sensor.

- Laser diode array: Multiple laser diodes would be present on the chip, interfacing into multiple fibers embedded in the material being monitored. This provides for the monitoring of the structure at many points by the chip.

- Wavelength demodulation system: - The laser array emits energy of different characteristics depending on the properties of the reflections between the laser diodes and the Bragg gratings. The demodulation system reacts to these properties (through comparisons with reference wavelengths, for example) providing an electronic output signal.

- Output transmission system: The electrical signal received from the detectors requires interpretation and formatting for transmission to the outside world. This is done on the electrical parts of the chip. Actual transmission to the outside world could be accomplished using radio-frequency waves or other techniques (possibly infrared?).

- Input power and laser driver system: The chip is an "active" component and thus requires powering. This could come from a direct electrical connection to the chip, or optically via a "return fiber".

Product Cost

The cost of an integrated circuit component depends largely on the production volume. The higher the volume, the lower the cost. The basic raw materials which comprise an integrated circuit are inexpensive. It is the machinery to process the chip (i.e. to grow layers of semiconductor on substrates, to etch channels, etc) which is expensive, along with the initial R&D required to develop it. There is thus a very high "fixed cost" to produce an integrated circuit; the higher the volume, the lower the unit cost.

The cost is also highly dependent on the yield which results from the manufacturing process used. The Smart Material Interface Chip is complex, containing many different components and types of components (waveguides, optics, electronics). One could assume that yields initially will not be very high.

Based on very preliminary discussions with EG&G, it is felt that the cost of an unpackaged chip (assuming it is based on GaAs technology) could fall in the $50 to $100 range. To this cost would have to be added the cost of packaging and pigtailing the chip so that it can be used in the desired applications. Low unit costs could only be achieved by the mass production of one product. This reinforces the need for detailed up front analysis of the market and user considerations.

For analysis purposes, it will be assumed that the initial cost of the chip will be about $100, and that with cost reductions and improvements in yield, that this could decline to $50 after three years.

Figure 2
Basic Elements of the Smart Material Interface Chip[80]

80 Measures, page 10

5.4 Financial

Development Funds Required

It has been estimated by UTIAS that development of the chip will require a five year program with a total funding of approximately $15 million. This is a very preliminary estimate, subject to further study.

Sales Forecast and Financial Ratios

Based on the analysis shown in Figure 1, and assuming a market share of 40% for the Canadian manufacturer, the sales forecast for the chip would be for at least one million units per year after the Year 2000.

The exact nature of the price (based on the users' expectations) and the cost (driven by potential volumes and yields) should be the subject of further study. If one assumes that for the initial years, a gross margin of $5 per chip sold can be achieved (on average),[81] the initial $15 million R&D cost would be "paid back" after three million chips sold; i.e. after about three years of production.

A major issue impacting the cost of production is the availability of a "foundry" to produce the final chip, once the design is proven. This initial investment is assumed to be shared by many industry users as it is unlikely that a single chip, such as the Smart Material Interface Chip, could support it alone.

Financial questions should be addressed more fully as part of an overall feasibility study for the chip.

81 Note: while this does not sound like much margin, the price that the buyers are willing to pay is likely to be in the $20 to $30 range, based on preliminary discussions. Achieving $5 margin on the chip at this level would be a major accomplishment. If the buyers are willing to pay more for the chip, due to the benefits they get from using it, the price could be higher. However, it should also be borne in mind that costs could be significantly higher, particularly in the early years of production.

5.5 Program Development and Milestones

The program requires a high investment up front in order to have the capability to produce the chips. In order to de-risk the development program, it can be divided into several phases, with a "gating" decision made after each major step:[82]

Phase	Gating Criteria
Phase 1 - Feasibility Study	Financial, market and technical decision criteria.
Phase 2 - Demonstration System	Technical success of discrete prototype, Field acceptability of concept.
Phase 3 - OEIC Development	Producibility of component.

A description of each of the phases follows.

Phase 1 - Feasibility Study

This phase would investigate in greater depth the marketing, technical and financial issues associated with the development of the Smart Material Interface Chip.

Key elements of the study would be:

- Analysis of user segments: "value-in-use" of the chip for the various buyers, key factors for market success, target price objectives by segment, expected quantity usage, possible spin-offs and alternate uses;
- Competitor analysis: both for competing technologies (relative strengths and weaknesses) and competing organizations developing similar chips;
- Commercial specification for the chip: a set of requirements as defined by the marketplace that will ensure commercial success of the chip, including expected product lifetime, and market homogeneity (i.e. requirements for product variations);

82 Note: this sequence of events is for the development program; after Phase 1 a parallel set of activities would be required to "commercialize" and bring to market a finished product. The steps, tasks and activities associated with this would be identified during Phase 1.

- Investigation of novel techniques and technologies for the chip: etching/growth of various component types, available materials (InP or GaAs), connection and coupling of fibers, packaging, thermal issues, powering, connection to external systems;

- System level design considerations: number of chips required per structural component, interworking of chips in large structures, permanent attachment versus periodic testing;

- Product specification: based on the results of the market and technical analyses identified above, a "firm" product specification should be written;

- Assessment of technical feasibility, R&D cost and personnel requirements; coupling with SSOC resources/members, time frame and schedule, target production costs; and

- Financial assessment: projected market share, pricing strategy, market development strategy, investments required, sales forecast, profitability projections (payback, rate of return, etc.). Identify potential financing sources.

Based on a "positive" outcome of the feasibility study, the project would move to Phase 2. The feasibility study would require about six months to complete.

Phase 2 - Demonstration System

The next step in the development of the chip would be to build a prototype based on discrete components. This would be identical to the final version of the chip except that it would not be integrated onto a single substrate. Thus the prototype would be larger, more expensive and have less long term reliability than the ultimate product.

The prototype could be built using GaAs-based external-cavity tuned lasers and would take about six to nine months to produce. The expected unit price at this level (for the laser components only) would be about $7,000 - $8,000 for small quantities (10 units), or about $1,000 - $2,000 in quantities of 1,000 units.[83] Other electronic components needed (for digital signal processing, demodulation, communications) would add to this cost. Building a prototype of discrete components would provide the following benefits:

- de-risk the final integrated circuit by being able to test all the functionality of the chip; and
- conduct field level evaluations of critical factors "around" the chip: handling, installation, powering and connection to external systems.

Part of this phase of the project would also be used to explore options for design and production of the integrated circuit itself, including closer examination of issues such as appropriate growth and etching technologies and the expected yield. Phase 2 would be expected to last about two to three years.

Phase 3 - OEIC Development

Phase 3 would be for the design of the optoelectronic integrated circuit itself; i.e. moving the discrete-component level demonstration system onto a semiconductor substrate. The main elements of this phase would be:

- Basic R&D on OEIC integration;
- GaAs VLSI circuitry design based on the results of the discrete component design;
- Thermal, optomechanical, optoelectronic and electrical design of the chip package;
- Qualification and testing; system level design;
- Fabrication/adaptation of production facilities; limited runs of prototype wafers to test for producibility, yields;

[83] Based on preliminary input from EG&G, August 9, 1993

- Field measurements where the IC replaces the discrete-component device;
- Incorporating changes into the design; and
- Initial runs and production testing.

For a final product, fully qualified for field use, approximate requirements would be: 5-10 scientists and 15-20 engineers over a three year period. Costs could be minimized by transferring OEIC technology developed for other uses to the Smart Material Interface Chip project. Potential Canadian sources for this technology in SSOC and the BNR Advanced Technology Lab.[84]

5.6 Development of an Intermediate Device

The project described above represents a quantum leap in smart structure technology, including a number of critical advances needed to make this technology practical and cost effective. This sub-section proposes an intermediate stage, the development of a Bragg grating demodulation optoelectronic chip (BDOC), shown schematically in Fig. 3.[85]

This past summer a bridge was built in Calgary using carbon-fiber prestressing tendons in the deck support concrete girders and instrumenting some of the girders with a state-of-the-art structurally integrated fibre-optic sensing system. The BDOC would reduce the cost and size of the prototype Bragg grating sensor demodulation system for the Calgary bridge.

The advance represented by the BDOC is required to develop sensor interrogation systems that are low cost, rugged, compact, portable and consistent in order to commercialize this technology. As a result of the experience gained on the Calgary bridge project, a new company, ElectroPhotonics Corporation, was formed to commercialize the technology.

Figure 3
Passive Wavelength Demodulated Chip for
Multiple Bragg Grating Laser Sensing System

[84] Based on preliminary input from EG&G, August 9, 1993.

[85] Measures, Raymond M., "Development of Bragg Grating Fiber Optic Sensor Optoelectronic Demodulation Chip", Proposal to the ISC for Study II of the Photonics Sector Campaign, UTIAS Fiber Optic Smart Structures Laboratory, October 1993.

The development of a BDOC would give Canada technological leadership in the new field of structural sensing. The development of this intermediate stage device has been made possible for the following reasons:

- A simple wavelength demodulation system has been devised for the intracore Bragg grating and a prototype version of this system has been demonstrated in the Calgary bridge project.

- This system has the potential to be developed into an optoelectronic chip that would demodulate an array of such Bragg grating fibre-optic sensors.

- A patent application has been filed to cover certain aspects of this technological advance.

Merits of the BDOC

The laser diodes and the detectors that are required for demodulating Bragg grating sensors in the manner indicated in Fig. 3 are available on an individual basis. However, the wavelength-dependent splitter will require some research to optimize its design. The important advance needed to produce the BDOC is the integration of these components onto a single chip, probably with a thermoelectric cooler. Although this chip is far less sophisticated than the optoelectronic smart structure interface chip (OSSIC) proposed above, it nevertheless requires the type of component integration likely to be very important in the next decade.

The advance represented the BDOC would enable the ElectroPhotonics Corporation to commercialize the Bragg grating-based sensing technology. It should be recognized that the BDOC cannot perform all of the function ascribed to the OSSIC and is therefore only one of the steps towards the development of a full function chip. Nevertheless, the fact that the BDOC could be implemented in a relatively short period and that it will not require any major breakthroughs in optoelectronic technology is a factor in the probability of its successful commercialization.

Project Goal: The development of an optoelectronic chip that can demodulate the optical signals from an array of fibre-optic Bragg grating sensors and serve as the heart of a commercial system for interrogating structurally integrated Bragg grating sensors.

Project Elements:

- Develop a semiconductor laser demodulation system for Bragg grating sensors;
- Characterize and test a range of potential applications;
- Optimize the system, including a design that can be produced on an optoelectronic chip;
- Work with major potential users of the technology to define market requirements for the BDOC;
- Design and build a BDOC in collaboration with a manufacturing partner;
- Characterize and demonstrate the range of applications for which the BDOC is suitable;
- Work with major potential users of the technology to demonstrate that sensing systems based on BDOC meet market requirements.

Project Budget: $3 million over three years

Project Proposer: ElectroPhotonics Corporation

ANNEX B

COLLABORATIVE R&D PROGRAMS

AND

PRACTICES IN OTHER COUNTRIES

TABLE OF CONTENTS

1.0 INTRODUCTION

This Annex contains descriptions of a selection of funding mechanisms, practices and industry associations in several countries, the U.S., Japan, the Federal Republic of Germany and Sweden, as well as the European Communities, where the development and application of photonics technology has been given priority. In addition, there are brief outlines of evaluations that were conducted on two non-photonics R&D funding programs.

2.0 THE U.S.

Some significant changes are occurring in U.S. government funding of R&D. For example, there is a shift from defence industries to non-defence industries and increased support for R&D activities carried out by the private sector. In the following subsections, some of the activities and projects of the two main current agencies for funding R&D, the Advanced Research Projects Agency of the Department of Defense and the National Institute of Standards and Technology, are described.

Descriptions are also given of two non-government organizations that promote the application and use of photonics technology.

2.1 Advanced Research Projects Agency

The Advanced Research Projects Agency (ARPA), formerly known as DARPA, is the central R&D organization of the Department of Defense, with a primary responsibility to maintain U.S. technological superiority over potential adversaries. ARPA functions around ten technical offices, for example, the Microelectronics Technology Office, which develops and demonstrates electronic and optoelectronic components and associated manufacturing processes for general purpose computing, special-processing and sensors and sources.

Most of ARPA's activities are dual-use in nature. In recent years ARPA has sponsored the development of technologies chosen for their specific commercial importance. Congress provided US$50 million in 1991 and US$60 million in 1992 to ARPA for pre-competitive technology consortia. Some of the consortia supported by ARPA are described below.

2.1.1 <u>The Consortium for Optical and Optoelectronic Technologies in Computing</u>

The Consortium for Optical and Optoelectronic Technologies in Computing (CO-OP) was formed in 1992 under ARPA sponsorship to promote the development of optical and optoelectronic platform technologies by making them widely accessible and by a cooperative sharing of test data and design methodologies among the Consortium members.

In the interest of being complementary to existing R&D efforts in technology development, the Consortium's primary emphasis will on existing technologies rather than on developing new technologies or improving their performance. It will augment the R&D activities in optical architectures, applications and systems development by making state-of-the-art device technologies more readily available to system developers.

To date over 20 institutions (government, universities and industry) have joined the CO-OP and the transfer of devices from providers to users has already begun. CO-OP is designed to benefit both users and technology providers; there is easy access to the latest devices and materials for users and providers can access a pool of potential users.

The transfer of technology from device and materials researchers to systems developers will be accomplished primarily through the publication of catalogues. A preliminary catalogue was published in August 1992, and the first official one was published in February 1993.

Working groups are being established for each technical area, the first of which are for smart pixel and diffractive optics.

2.1.2 National Center for Advanced Information Components Manufacturing

The National Center for Advanced Information Components Manufacturing (NCAICM) is a new venture that will be operated as a partnership between ARPA and the Department of Energy (DoE). It will be located adjacent to Sandia National Laboratories, which will provide scientific know-how and laboratory facilities to the Center, along with two other DoE national laboratories, Los Alamos and Lawrence Livermore.

NCAICM's priorities will be the development of advanced manufacturing techniques for large-area flat panel displays and photonics. The Center will consolidate work on several flat panel supporting technologies, including package interconnects, inspection and repair at a single site. Other research will focus on agile manufacturing technologies for flat panel components, such as silicon integrated circuits, high-speed optoelectronics and electronic subsystems. Another thrust will be on photonic components for fiber-based communication networks.

The Center will receive US$60 million this year. Sandia will receive about 20 per cent of this amount to equip and staff the Center. The remaining funds will be concentrated on joint research projects between private industry and the three DoE laboratories. The exact nature of the research projects and the relationship between private companies and federal scientists has yet to be defined.

Photonics Spectra[86] describes the new Center as "a mini-MITI for the U.S. photonics industry", noting that "whatever form the final venture takes, its mission is clear: to help U.S. industries that are being squeezed by foreign competition".

2.1.3 The Optoelectronic Technology Consortium

The Optoelectronic Technology Consortium (OETC) was formed by GE, AT&T, IBM and Honeywell to develop optical backplane interconnects for information processing systems. The Consortium has received US$8 million in funding from ARPA. In what the participants call a "pre-competitive industrial alliance", its objective will be to develop a manufacturable backplane interconnect system with a bandwidth of 64 Gb/s, accomplished through 128 parallel 500 Mb/s lines.

Newly developed transmitter array, receiver array and array connector technology will be used to brassboard a prototype by the end of 1994. The key to the program is the development of producible, low-cost components and subsystems. Since the emphasis is on manufacturing a workable system, the consortium is using technology that is already reasonably well developed.

All participants see the ultimate benefit of the project as yielding technology that they could use in their own systems. A larger users application group is also being formed, including companies such as Boeing and Cray. The intent of this group is for companies who have an interest in the technology to have a say in defining the requirements for what the consortium does, like inputs on operating specs and different configurations of interconnections.

2.1.4 The Optical Network Technology Consortium

The Optical Network Technology Consortium is developing technology for all-optical communications networks capable of three orders of magnitude improvement in throughput and integrated optoelectronic switching networks to interconnect next generation high-performance computers. The participants are Bellcore, Northern Telecom, Hughes Aircraft and Columbia University.

86 *"A Mini-MITI for the US Photonics Industry is in the Works at Sandia National Labs"*, Photonics Spectra, March 1993, p. 46.

2.1.5 The Ultra-Fast, All-Optical Communications Systems Consortium

The Ultra-Fast, All-Optical Communication Systems Consortium will work to eliminate data flow bottlenecks and develop efficient wide area networks and long-haul communications systems capable of 10 Gb/sec data rates. An all-optical communications system, with its huge bandwidth, is recognized as the only approach for handling his speed and density. The consortia will address both components and architecture and culminate in a demonstration of an ultra-fast optical network.

2.2 National Institute of Standards and Technology

The National Institute of Standards and Technology (NIST), which was set up in 1988 from the former National Bureau of Standards, is the lead agency for accelerating the growth of civilian technology in the Clinton administration's game plan.

NIST manages the Advanced Technology Program (ATP), a new program which was created to promote economic growth and enhance the competitiveness of U.S. high-technology businesses by accelerating the development and commercialization of pre-competitive generic technologies and refining manufacturing practices. This year, NIST has received a total funding of US$501 million. It is predicted that by 1997, NIST's budget will reach US$1.4 billion, of which ATP will receive US$750 million, or more than 1000% above the current US$68 million. Several features make ATP unique among U.S. federal programs, including the following:

- focus on pre-competitive generic technologies
- direct funding of industry only
- priorities set by industry
- promotion of cooperative research and strategic alliances
- substantial support to small businesses

Another of NIST's current programs is the Manufacturing Technology Centers (MTC) program, which has the objective of improving the competitiveness of U.S. small and medium-sized manufacturers through advances in their levels of technology utilization.

NIST also has a strong photonics program centred at its facilities in Boulder, Colorado with an annual budget of about US$5 million.

2.3 New York Photonics Development Corporation

The New York Photonics Development Corporation was established in 1989 with a mission to create and implement programs to stimulate and foster economic development throughout the State by providing technical and business assistance in the field of photonics to companies and entrepreneurs through linkages to universities, federal laboratories and economic development organizations. Its activities to date have focused on the transfer to small and mid-sized companies in New York State of photonics technology developed by the Rome Laboratories of the USAF, which has responsibility for all Air Force photonics programs. Another of its functions is the brokering of cooperative R&D agreements.

The Corporation receives some funding from the State, but is attempting to become self sufficient. It has established the New York Photonics Consortium, in which companies can become members by paying a fee, ranging from US$4,500 for large companies to US$450 for small companies. In return the members are able to receive some free or discounted services.

2.4 The Optoelectronic Industry Development Association

The Optoelectronic Industry Development Association (OIDA) has the mission to improve the worldwide competitiveness of the North American optoelectronics industry. Its distinguishing features are that it:

- includes both users and suppliers of optoelectronics components and systems;
- works in partnership with the U.S. Government; and
- is vertically integrated and covers a wide range of activities, including telecommunications, computers, data communications, industrial, military and consumer electronics.

OIDA was formed in response to a request from the Japanese during discussions for joint R&D activities. Current membership consists of 10 voting members (including Bell-Northern Research) and 12 associate members (including Waterloo Scientific).

OIDA's main undertaking at present is the preparation of a technology road map for optoelectronics. The methodology used in preparing the road map included a review of the foreign literature, market workshops in six application areas, a market forum, six technology workshops, a technology workshop, and report preparation. The draft report is scheduled to be released in late 1993.

3.0 JAPAN

The Japanese government has played a small but significant role in the development of photonics-related businesses in Japan. This role is manifested not only in the provision of modest amounts of funding, but more importantly, in the leadership that the government provided in identifying promising technologies and in serving as the catalyst to generate a national vision.

The amount of government funding in photonics-related activities is dwarfed by the expenditures of the private sector. Government expenditures in photonics R&D estimated to represent no more than 10% of the amount spent by the private sector. The modest government expenditures have served to focus private sector attention on photonics technologies and markets.

3.1 Applications Programs

The Ministry of International Trade and Industry (MITI) has been funding photonics activities on a continuing basis since 1973, when it started the Hi-OVIS (Highly Interactive, or Higashi Ikoma, Optical Visual Information System) Project, which provided fiber optics links to a number of homes in the community of Higashi Ikoma, just east of Osaka. This initial experiment to provide a range of services to home was MITI's answer to the CCIS (Coaxial Cable Information System) project of its rival, the Ministry of Posts and Telecommunications, which oversees the operation of the Nippon Telegraph and Telephone Corporation. Funding for the two phases of Hi-OVIS was about $100 million[87] over a ten-year period from 1973-1983. The main industrial participants in Hi-OVIS were Matsushita Electric, Sumitomo Electric and Fujitsu.

A subsequent applications program funded by MITI is the Interactive Basic Information System Development Corporation (IBIS), which was established in 1986 to develop and apply a highly advanced information system. The total budget for IBIS during its four-year lifetime was $48 million, 70 per cent of which was provided by the Japan Key Technology Center. The industrial participants in IBIS were Matsushita Electric, Sumitomo Electric and Fujitsu, who were the main participants in Hi-OVIS. IBIS designed and installed the system and operated it on an experimental basis until 1990. It was then passed on to its successor corporation, New IBIS.

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87 Converted from Japanese yen at ¥100 = $1

The real purpose of New IBIS appears to be to study which of the services being offered can be provided on a profitable basis. It has a staff of 16 people, 11 on loan from the member companies and 5 permanent staff. New IBIS occupies spacious quarters in a building owned by its largest shareholder, the city of Osaka, who owns 40 per cent of the corporation. The other shareholders are the regional government of Osaka, Sumitomo Electric, Matsushita Electric and Fujitsu, each with a 10 per cent share, and 46 others, who own the remaining 10 per cent, including the Mitsubishi Research Institute and the National Institute for Research Advancement, 7 banks, 32 apparel manufacturers, C. Itoh Co., NTT Data Communications Co., etc.

New IBIS provides visual and data information services to businesses located in the Semba area of Osaka. At present there are 143 subscribers, most of whom subscribe to the visual services and about 70 of whom also subscribe to the data services. The Semba area was formerly the centre for textile manufacturing in Osaka, and is now a business area with a high concentration of fashion stores. Many of the stores subscribe to the visual services to provide background images for the sales areas. These images show world-wide fashion trends from both Japan and overseas.

The data services consists of four components:

- business software
- ordering and distributions support system
- transactions among the users of the system, including banking services
- gateway services to data systems outside IBIS

The subscription fees for the service are high; for example, for the combined image and data service, the joining fee is $5,000 in addition to the monthly fee of $1,200.

Other significant MITI-funded projects include the Optical Measurement and Control System, which was funded to the level of $157 million over 1979-1985.

3.2 The Japan Key Technology Center

The Japan Key Technology Center (key-TEC) is a government organization under the joint supervision of MITI and the Ministry of Posts and Telecommunications. It is funded by dividends flowing from government corporations, such as the Nippon Telegraph and Telephone Corporation (NTT) before its privatization in 1986 and Japan Tobacco Inc., as well as contributions from government financial institutions and funds from teh Japan Development Bank (a MITI organism) and from the private sector. A total of $180 million was received from these sources in 1985 and an additional $217 million in 1986.

Key-TEC provides 70 per cent funding industry R&D consortia (of two or more companies). Examples in the photonics area include the following:

- the Optoelectronics Technology Research Center ($70 million from 1986-1995), a consortium of 13 companies that is developing basic optoelectronics materials technologies for applications in information processing;

- the Interactive Basic Information System ($35 million from 1986-1990), which is described above;

- the Optical Measurement Technology Development Co. Ltd. (OMTEC) ($42 million from 1986-1992), a consortium of five measuring instrument manufacturing companies, established to perform research on the fabrication of high-quality photonic devices for measurement use; and

- TERATEC ($75 million from 1992-2001), the successor to OMTEC, a joint venture of five measuring instrument companies to develop ultra-high frequency (up to the terahertz range) optoelectronic measuring technology for future high-speed IC and optoelectronic IC testing.

3.3 Research and Development Program on Basic Technologies for Future Industries

The Research and Development Program on Basic Technologies for Future Industries (JISEDAI), a MITI-sponsored program that was initiated in 1981, focuses on R&D of innovative basic technologies necessary to establish future industries and to upgrade present industries, such as aerospace, information processing and biotechnology. Several projects sponsored under this program fall into the category of photonics:

- non-linear photonics materials (1989-1998): development of photonic materials which exhibit high non-linear optical susceptibilities and short response times for application of optical information systems (1991 budget $5 million);

- photo-reactive materials (1985-1992): Development of photo-reactive materials, which characteristically exhibit a reversible change in the structure or arrangement of molecules in response to a light stimulus (1991 budget $4 million); and

- quantum functional devices (1991-2000): development of control technology of new device functions based on such quantum effects as wave properties for the purpose of developing ultra-high-speed multi-functional electronic devices (new project launched in 1991).

3.4 Real World Computing Program

MITI has embarked on an ambitious program, known as the Real World Computing Program, to lay the technological foundation for the advance information society of the 21st Century. The program is still in its very early stages and support is still being solicited for it, both in Japan and internationally. An organization known as the Real World Computing Partnership (RWCP) was established last year to act as the secretariat for the program, to manage sub-contracts and to establish a central laboratory. No solid figures are available for the planned expenditure level, but numbers of the order of $1 billion over a 10 year period have been bandied about.

Among the proposed research topics is optical computing, including optical interconnection, optical neural systems and optical digital systems.

3.5 Other Government Programs

In Japan, there are three science and technology support ministries, MITI, the Ministry of Education, Science and Culture (MESC) and the Science and Technology Agency (STA). In addition to the specific programs described above, MITI carries out research at institutes in its Agency of Industrial Science and Technology. One of them, the Electrotechnical Laboratory, carries out basic photonics research in materials and optoelectronics devices.

MESC supports photonics-related research at several Japanese universities, the most significant of which is the work in the Research Center for Advanced Science and Technology (RCAST) of the University of Tokyo.

STA's only significant involvement in photonics is through the Exploratory Research for Advanced Technology (ERATO) Program, which was created in 1981 to foster the creation of advanced technologies and advancing future interdisciplinary scientific activities. Current photonics-related projects include the Sakaki Quantum Wave Project, which is studying quantum wave effects in advanced quantum microstructures, and the Masuhara Micro-photo-conversion Project.

3.6 Optoelectronic Industry and Technology Development Association

The Optoelectronic Industry and Technology Development Association (OITDA) was formed in 1980 by a group of Japanese manufacturers to "promote the comprehensive development of the optoelectronics industry". The real impetus for its formation was to monitor progress and developments in a government-funded project, the Optical Control and Measurement Systems (OCMS) Project, which was started in 1979 to run for eight years and funded at a level of $150 million, was a demonstration of a total sensor system for instrumenting a petroleum complex.

OITDA now has 257 members from a wide range of industrial sectors, including not only 91 electronic and equipment manufacturers, but also companies from sectors such as chemicals, precision machinery, banking, trading and advertising. OITDA is a secretariat for the assembly of intelligence on the optoelectronics industry in Japan and the identification of opportunities for it.

The headquarters is operated by about 30 staff members, largely seconded from sponsor companies. The total annual budget of OITDA is about $7 million. Membership fees constitute the major source of funding: one unit of membership is ¥360,000 ($3,600) per year. The 11 founder companies pay 15 units each. Other major companies may pay two or three units. The major benefit of membership, both to manufacturers and consumers of optoelectronics, is information. OITDA also receives contributions from bicycle racing associations. This support seems to be analogous to support from a Lottery in Canada.

There are 35 committees to conduct the overall activity. These fall into the following general categories:

- research on trends in industry and in technology
- feasibility studies
- system development
- standards
- specific technology surveys

Committee meetings are held three times a year. Committee members are from research staff of sponsors and universities. Committees are reconstituted yearly. There may be up to several meetings per month. Reports issued by committees are not available outside sponsor group. It is noteworthy that a large proportion of these committees are chaired by university professors or by the staff of government research institutes, such as the Electrotechnical Laboratories.

The "production scale survey" has been produced yearly for the past ten years. These data on the optoelectronic industry are collected only by OITDA. MITI does not collect this information. Feasibility studies are carried out on about four themes every year to explore the possibilities for optoelectronic technologies. Subjects are selected from proposals and requests from members. The secretariat makes a preliminary selection, then a committee makes a final choice. This year, surveys were carried out on "Overseas Optoelectronic Systems", "Optical LANs for Marine Environment Measurement", "High Sensitivity, High Resolution Optical Measurement Technology".

The Systems Development activity is unusual in that it consists partly of international projects which lead to the donation of results to other countries. The aim is to promote optoelectronic technology both in and outside Japan. There is operational support for this activity from MITI but not from the foreign ministry. Systems supplied are not competitive with commercial offerings from Japanese companies. Examples of this activity include a rural optical transmission system for India and a fibre trunk for Hungary.

The first year of a systems development activity involves a feasibility study. The following two years work is carried out by consignment to a member company, with an assessment conducted by a committee. The development department of OITDA is staffed with seconded personnel from private companies. The work on these projects is consigned to sponsor companies.

Communications systems were developed successfully for several EXPO's (i.e. regional fairs) with budgets of the order of $10 million. These were commissioned to the OITDA by the EXPO's.

About 70 draft JIS Standards have been developed based on proposals from the OITDA. OITDA also participates in the Japanese National Committees of IEC and ISO. In addition to these activities, OITDA operates a Laser School to promote laser equipment safety standards and ensure the safety of operators. It is working toward formal recognition of its laser equipment operator's licence, and has requested MITI approval for this similar to pollution-prevention managers' licences.

OITDA publishes books, and holds seminars, as well as sponsoring symposia, notably the large exhibition InterOpto, the flagship activity of the organization, receiving 100,000 people in four days.

Future activities of the OITDA include:

- activities under Overseas Development Agency budgets, which may decrease in future because of an anticipated drop in bicycle racing revenues;

- detailed research on optical communications/optical information processing technology, which remains the major focus of the activities of OITDA;

- detailed research on optical interconnect, optical neural computing and similar subjects, which relate to MITI's Real World Computing project, which contains an optoelectronic component;

- research on entertainment video, which has the potential for stimulating the development of a new industry.

In its earlier days, the OITDA played a key role in bringing photonics equipment manufacturers together with potential users of their equipment and in aiding in establishing a national vision of the general direction in which industry should go. Currently, it plays a role in compiling industry data and in standards setting.

It also has committees looking at technology and market trends. However, these committees do not appear to be playing effective roles. From the point of view of the large Japanese equipment manufacturers, there may no longer be a need for such committees, since the companies are very well equipped to carry out such studies on their own.

The role of OITDA in the future is uncertain. It is still supported by some of its founders, such as NEC and Matsushita, and appears to be well regarded by most of its members. There were some indications, however, that the effectiveness of the OITDA is waning.

4.0 THE FEDERAL REPUBLIC OF GERMANY

The Federal Republic of Germany is one of the world's leading countries (after Japan and the U.S.) in the production of photonics-related components, equipment and systems. There is no industry association of other such organization specifically for photonics, but most of the companies in the photonics industrial sector in Germany are members of the Zentralverband der Elektrotechnischen Industrie e.V. (ZVEI), which translates in English as the Central Association of the Electrotechnical and Electronics Industry). ZVEI publishes a number of market survey for its members.

One of the main vehicles for the dissemination of technical information in Germany is the trade fair. There are a number of well attended trade fairs, for example Laser/Optoelectronik (biennial), Produktronica, and events taking place within the Hannover Fair, such as Optec and Optronic.

The German government recognizes the importance of photonics to its economy, and has had a number of support programs, mainly for collaborative R&D. German research is focused in materials processing, measuring technology, waveguides, laser medicine, analysis techniques and photometry. Most of the government's support of collaborative R&D is centred on the Photonik I and II programs.

4.1 Photonik I

Photonik I, which was started in 1990 and is scheduled for completion in 1994, is organized into two collaborative projects, one focused on optical interconnects, based on GaAs technology, and the other on optical signal processing, based on InP technology.

The optical interconnects project, which is coordinated by the Fraunhofer-Institut für Angewandte Festkörperphysik (IAF), is organized into the following research themes:

- lasers
- detectors, modulators, switches
- passive components
- systems and system theory

Participants include Daimler-Benz, Siemens, SEL-Alcatel and MBB, along with six universities and three government institutes.

The optical signal processing sub-project, which is coordinated by the Heinrich-Hertz-Institut für Nachrichtentechnik, is exploring the potential of optics in communications systems, particularly the switching of optical communications channels at a wavelength of 1.55 microns. The technical approach used includes the improvement of materials and current technologies, development of system-oriented components and subsystems and demonstrators for new system concepts. Industrial participants include ANT Bosch, SEL-Alcatel and Siemens.

The projects were organized in such a way that each of the participants worked more or less independently in the area of interest, and from time to time status seminars were organized in which each partner reported on its results. Special interest groups were also formed for more detailed discussions. There is a general feeling that cooperation and the transfer of results should be improved, and the follow-on program (see below) will be organized somewhat differently.

4.2 Photonik II

The Photonik II Program is the continuation to Photonik I. It is scheduled to start immediately after the termination of Photonik I on April 1, 1994 and will run for four years. At present, only general objectives are known, with all interested participants having submitted proposals to the project management agency. It is anticipated that specific information about projects to be funded will be available early next year.

Photonik II will continue to fund collaborative R&D, both horizontal (for component development) and vertical (for system development). At the end of Photonik II, prototypes and demonstrators should be available for short-term development, and these prototypes should be transferred to manufacturers.

4.3 Other German Government Programs

In addition to Photonik I and II, the German government and other organizations are supporting some related program, for example:

- BMFT: micro systems technologies (sensors, housing packaging, interconnecting, integrated optics), 1994 to 1999;
- BMFT: laser technologies (high power laser diodes);
- DFG (Deutsche Forschungsgemeinschaft, the autonomous research association of the German universities and scientific institutions): optical signal processing (basic research in the field of epitaxy, structuring, novel effects and circuits, theoretical aspects);
- Stiftung Volkswagenwerk (VW Foundation): photonics (basic research in materials, physical and chemical fundamentals); and
- Deutsche Bundespost-Telekom: optical communication systems, 1994-1996.

5.0 SWEDEN

Sweden is not one of the world's leaders in the development and application of photonics technology. Nevertheless, it may be interesting to look at Swedish approaches, since Sweden is a country very similar to Canada from the standpoints of its size and the make-up of its industry.

5.1 Swedeoptronics

Swedeoptronics is an industry association within the Swedish Federation of Manufacturers with a mandate to create conditions for improved growth and profitability with the optronics sector and to lobby for issues of common interest that are difficult for single companies to handle successfully. Examples of activities that it has undertaken to improve the conditions in the sector for increased effectiveness and competitiveness are:

- to work for increased supply of educated personnel by stimulating better education in optronics;
- to act for improved development of the domestic market by dissemination of information on the applications related to optronics; and
- to work towards better and more competitive products through initiatives and support for basic research.

Swedeoptronics is a fairly small organization with about 26 members at present. Its members include manufacturers of products and components, as well as resource companies, consultants and research organizations. It is organized into three sections divided by application type: measuring/analysis, image processing and optical communications.

5.2 Other Swedish Organizations

The Institute of Optical Research, which is partly funded by government grants and partly by the private sector, acts as a link between industry and researchers for collaborative research. The Foundation for Swedish Optronic Research is responsible for raising industry funding for collaborative research and is also involved in technology transfer.

6.0 EUROPEAN COMMUNITIES

This section describes a selection of R&D programs that are carried out on a cooperative basis within Europe.

6.1 EUREKA

EUREKA was launched in 1985 to establish high quality, high technology, market-oriented international collaborative research projects in Europe. Although it involves many of the countries of the European Community, it is not a program of the Commission of the European Communities. In the period 1985-1991, there were a total of 505 projects sponsored under EUREKA for a total expenditure of 8.38 billion ECU (1 ECU = $1.5 approximately). The largest share of these expenditures were in information technology (69 projects, 1.82 billion ECU) and communication technology (32 projects, 1.54 billion ECU).

There is no breakdown of the amount spent on photonics. Laser technology accounted for 15 projects and a total expenditure of 344 million ECU. There were no doubt other photonics-related projects in communication technology and in information technology, as well as in other categories, such as material technology, robotics and production automation, etc.

6.2 RACE

RACE, which stands for Research and Development in Advanced Communications Technologies in Europe, is an initiative of the Commission of the European Communities that was started in 1987 to develop key technologies required for the introduction of an integrated broadband communications network in Europe by 1995. The total planned investment of the Commission is about $700 million, with a matching investment to be made by the private sector.

One of the interesting features of RACE is the involvement in the program, not only of equipment manufacturers, but also of service providers.

6.3 The Fourth Community Framework Programme

In September 1992, the Communities presented its proposal for the Fourth Community Framework Programme to cover the Community's efforts for the years 1994 to 1998. This proposal reflects the Community's new approach to R&D policy. For example, the proposal envisages greater concentration of research effort on a number of generic technologies, the mastery of which is essential to European industry's competitiveness. This approach recognizes the strategic role of generic technologies, which can have a bearing on a number of industrial sectors. While generic technologies will continue to be covered by conventional programmes, they will also be at the core of a number of "technological priority projects" proposed by businesses on their own initiative.

7.0 AN EVALUATION OF TWO EUROPEAN COLLABORATIVE RESEARCH PROGRAMS

This subsection describes the results of the evaluations of two programs to promote pre-competitive research, one in the U.K. and the other in Sweden, by Ken Guy of the University of Sussex at Brighton. It should be noted that the term "pre-competitive" is quite often very loosely defined. In effect, the willingness of two parties to collaborate is often used as the primary criterion for deciding that an activity is pre-competitive" collaboration.

7.1 The Alvey Programme

An evaluation[88] of the British Alvey Programme, which supported collaborative R&D in information technology showed that, while Alvey was successful in boosting R&D levels, expanding the population of researchers, uniting fragmented resources, nurturing links between academia and industry, it was less successful in improving the competitive position of the UK IT industry. Limiting factors included inadequate management of the R&D/production interface within firms and the limited availability of investment capital. The conclusion was that Alvey was a necessary although insufficient mechanism.

7.2 The Swedish IT4 Programme

An evaluation[89] of the Swedish IT4 programme, the Swedish national programme of pre-competitive collaborative R&D in industrial information technology. IT4, which had a total budget of SEK 1000 million ($175 million) over a period of five years from 1987 to 1993, had similar goals to Alvey as well as to the Photonics Sector Campaign (promote industrial capability to develop and produce IT, access international developments in the technology, secure international competitiveness in selected IT areas), showed that it made a significant impact on the national base of IT R&D capabilities, but that other actions are also required to reach international competitiveness goals.

The study also concluded that some aspects of programme management could have been improved. Among the comments:

- IT4 efforts focused strongly on big collaborative projects, involving relatively large numbers of participants, which tend to be hard to manage;

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[88] University of Sussex at Brighton, *Science Policy Research Unit Annual Report*, 1991-1992.

[89] Technopolis and SPRU, *Final Report: Evaluation of the IT4 Programme*, May 1992.

- the implementation was slowed by lack of clarity about strategy;
- the management and decision structure probably was more complex than was necessary;
- the process of establishing an administrative capability was inadequate;
- the bureaucracy was probably too "thin" (it was decided to spend not more than 1% of the budget on administration); and
- the administrative capability needs to be "front-end-loaded" to cope with the influx of work at the beginning, reducing is size over time as procedures become fully routine and the balance of the work shifts from decision and implementation to monitoring.

In the IT4 Programme, the 50 per cent cost sharing between government and the private sector was achieved. The programme was prepared to pay up to 100 per cent for small feasibility studies, but main projects had to be at least 50 per cent funded by the private sector (which included state-owned enterprises). The 50 per cent rule applied to whole project, not to individual participants. This meant that the program could pay full costs of universities, research centres and small firms, provide that the large participants paid all or most of their own costs.

ANNEX C

PHOTONICS TECHNOLOGY ASSESSMENT

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1.0 INTRODUCTION

Broadly speaking, photonics is a term used to describe technologies which guide, process, manipulate or amplify "light" (or energy in frequencies close to those of light). Photonics is a parallel technology to electronics, except that it is concerned with photons rather than electrons.

Photonics was born in 1960 with the invention of the ruby laser. A laser is a device which emits coherent (single frequency) light when "excited". In the case of the ruby laser, an electrical charge to the ruby crystal causes pure red light to be emitted. The purity of the light emission (its coherence) allows it to be processed, guided, amplified and essentially treated like an electromagnetic wave. Hence the term laser, which is an acronym for "light amplification by stimulated emission radiation". A laser is a device which amplifies light when excited by an electrical charge (or by another light source).

Photonics technologies, in theory, can have all the same "generic" applications that electronics has - optical transistors, optical "wires", optical amplifiers, optical switches, optical integrated circuits, etc. Some of these are more realizable than others, since photons and electrons do not behave entirely in the same manner. Many generic applications also combine photonics and electronics components; for example: optoelectronic integrated circuits, which combine tiny optical and electrical semi-conductor devices on the same chip.

The purpose of this document is to provide an overview of photonics components and generic applications, including an assessment of photonics technologies to identify their relative importance and whether they are emerging, declining, etc.

This document can then be used as a basis for reviewing the activities of Canadian industry in the industrial application areas. Figure 1 illustrates the analytical model which underlies the analysis presented in this report.

Figure 1
Analytical Model

2.0 OVERVIEW OF PHOTONICS COMPONENTS

There are numerous photonics components. In photonics, most components are either created from man-made materials which are not naturally occurring (e.g. indium phosphide used to make semiconductor lasers), or by "doping" certain materials in order to obtain desired photonic characteristics (e.g. doped silica glass which becomes "fibre").

Since it would be virtually impossible to catalog all the possible materials which make up the photonics technology "family" this section is focused at the components level; devices which result from the use of many materials. Since there is vast number of components which exist, or which are conceivable, it is useful to group the components into a number of categories. In this way the attributes of each "class" of component can be understood, and the key developments, materials and trends identified.

Photonics components have been grouped for analysis purposes into four generic categories:

A. Light sources - active devices which, when stimulated, produce optical or near-optical emissions; i.e. light. They generate photons, the optical equivalent of electrons. The primary components in the light sources category are lasers, light emitting diodes and high powered lamps.

B. Detectors - active devices which, when stimulated by photons (i.e. when light is shone on them) produce an electrical charge. Detectors convert photons into electrons. Detectors include semiconductor photodetectors, array sensors and solar cells.

C. Passive components - the physical medium which is used to store optical information or direct, guide or transmit photons between two points (for e.g. from a source to a detector). Passive components include compact disks, waveguides (fibres), lenses, gratings and connectors.

D. Active components - the devices which can modulate, switch, store or process photons (the transistors of the photonics world). Active components include spatial light modulators, optical switches, liquid crystal displays, optoelectronic integrated circuits, and other devices.

Figure 2 shows how each of these four categories breaks down to specific components. Some examples of components are shown within each category (not an exhaustive listing). The following sections discuss the major base technologies grouped into the four generic categories.

Figure 2
Components

2.1 Light Sources

2.1.1 Semiconductor Laser/LED

Lasers emit pure (single wavelength) photonic emissions at or close to frequencies detectable by the human eye. Since lasers can be "switched" on and off, or modulated, at very high speeds, they can be used as optical transistors.

A class of lasers made from the material yttrium aluminum garnet (the YAG laser) emits light at near visible wavelengths, which can be transmitted over an optical fibre. These high power lasers have many applications in machining (cutting, welding, etching, etc) as well as in communications (splitting a broadcasted signal over many paths).

Semiconductor lasers are generally made from materials such as indium phosphide or gallium arsenide, possibly doped with other materials to produce desired characteristics. Depending on the material composition, semiconductor lasers emit light at several different frequencies. The most common commercial semi-conductor laser is the one used in the compact disk player (made from aluminum-gallium arsenide). This laser is very inexpensive to produce, but emits light which will not travel very far over optical fibres (hence its application in the CD player, as well as in computer interconnects).

Commercial lasers, other than the CD laser, emit light at either 850 nm, 1310 nm or 1550 nm (near infra-red) wavelengths. These are used in most industrial applications (other than applications requiring high power which use the YAG).

Fabry-Perot lasers are "bistable", meaning that they can be designed to switch from one type of light output to another. This characteristic can be used to create wavelength converters (shining light of one wavelength into a device produces a different output wavelength), filters and logic gates.

"Vertical cavity" lasers are being designed so that the light is emitted perpendicular to the layer of semiconductor material that creates the light (the "cavity"). This structure has advantages in packing density where multiple lasers are used; i.e. supports greater density of lasers arrays which would be useful in interconnection and logic applications.

Other current developments in semiconductor laser technology include: higher power, visible light sources, two-dimensional arrays and new wavelengths. Laser light can be modulated in many ways. For example, interferometric (creating an interference pattern) and acousto-optic ("vibrating" the light directly with sound waves) can have important applications in imaging, scanning and other vision systems.

Light emitting diodes (LEDs) produce light which is less coherent than that of a laser and which is less powerful. LEDs emit visible or near infrared light, depending on the material used. An LED is a photo-diode - it has an on state and an off state depending on the bias current (like an electronics diode which emits light). LEDs are very inexpensive and have been traditionally used in displays (on calculators prior to the LCD display) and for replacing incandescent lamps where their small size and relatively high intensity are advantageous (e.g. indicator lights on electronic equipment, rear warning lights of some automobiles).

2.1.2 Gas and Solid State Lasers

Numerous lasers are commercially available covering a wide range of the wavelength spectra and power levels. The recent technology evolution can be categorized as follows: higher power, improved beam quality, compact packaging, and shorter wavelength.

The power of CO_2 laser can be as high as 14 kw. As described in the industrial material processing section, the necessary power levels for most of the applications are available in today's technologies. A good beam quality is necessary for precision metal cutting and metal welding for packaging of electronics components where well defined and small spot size is essential. Compact packaging not only reduces the power consumption but also opens the door to new applications, e.g. robotics, military, metrology, etc. An example of compact packaging will be a slab Nd:YAG laser.[90] By changing the shape from the conventional cylindrical form to that of a slab, the Nd:YAG can be used in high power laser diode arrays for pumping as an alternative to lamps. Consequently, manufacturers claim high brightness, peak power and repetition rates, in addition to the size reduction.

The practical realization of blue LED and laser diodes has been a dream of researchers for some time. The applications will be full colour displays, higher density optical disk memory, high resolution printing and high resolution photolithography. A blue LED has been realized using silicon carbide and a blue laser has been demonstrated by using either parametric frequency doubling or up-conversion techniques. Recently, the last technique is drawing attention because of the high efficiency and also the availability of rare earth ion doped fibres which have been developed for optical amplifiers.

Excimer lasers extended the laser wavelength to ultraviolet (UV) by stimulating different combinations of gases. The applications of shorter wavelength lasers in the UV and soft x-ray regions include biomedical, material processing, high resolution microscopy, high precision interferometer and high resolution photolithography.

[90] Nd - the rare earth metal element Neodymium

The recent advent of EDFAs (erbium-doped fibre amplifiers) for telecommunications applications has stimulated the development of other types of rare-earth-doped fibres and their application to fibre lasers. A laser is created within the glass fibre by doping it with elements such as erbium. This has the effect of "confining" active ions in the fibre core over a relatively long guided path (long relative to semiconductor lasers). A laser is thus created "within" the fibre.

Miniature fibre lasers can be distributed along the length of an optical fibre. From the application viewpoint, the advantages of fibre lasers are their coupling compatibility with optical glass fibre and their compact package. The size of fibre lasers will be substantially smaller than solid state lasers but somewhat larger than semiconductor diode lasers. The applications of fibre lasers will include test equipment, range finders, compact and coherent blue light sources for display and photolithography.

2.1.3 Other Light Sources

In spite of many advantageous features of laser light sources, the classic high power Hg or Xe lamp[91] can still generate more total power especially in the visible to UV region. This feature has significance when industrial material processing demands a high total power rather than a high power density. An Ontario-based company, Solarchem, has been pursuing a toxic material treatment based on a photochemical processing using such a light source.

Photolithography is another example where a coherent laser light source is not a necessity. An incoherent excimer lamp and laser-produced plasmas have been proposed as UV and x-ray light sources, respectively. Synchrotron radiation is the most powerful light source in the x-ray region. The wavelength of 1 nm or 0.001 μm can be exploited for the realization of ultra super LSI considering that UV light with a wavelength of 0.4 μm is already the limiting factor for the current VLSI.

2.2 Detectors

2.2.1 Semiconductor Photodetector

The semiconductor photodetector is the counterpart to the semiconductor laser, i.e. it is a device (a diode) which generates an electrical current when stimulated by "incoming" coherent light. The detector's output is the analog of its light input; if the light is going "on and off", the electrical current output will be replicated.

91 Elements: Hg - mercury, Xe - xenon

Detector characteristics vary depending on what wavelengths of incoming light they will respond to, and depending on what their noise characteristics are. Detectors with high background noise will require higher levels of input signal in order to assure a consistent, error free, electrical output. Detectors are commonly made from doped silicon or germanium, and other materials such as gallium arsenide. As with lasers, detectors can also be designed in arrays. Depending on the application, detectors are sometimes custom-designed (for example, to meet specific temperature or noise environments).

2.2.2 CCD Arrays

A "charge coupled device" (CCD) is an image sensor - a silicon-based device which detects a wide spectrum (bandwidth) of visible light received in free space, generating a charge, or electrical current. This property of CCDs (along with their small size and cost) led to their use in small hand-held cameras.

CCDs can be grouped in arrays that support their use in industrial imaging applications. The more CCDs per given area, the higher the resolution of the image. CCD arrays are thus useful in applications such as medical imaging, where small device size and high resolution are important factors. Since high resolution images require many "pixels" to be accurately stored and reproduced, a single CCD array could consist of many thousand individual devices.

Developments in CCD arrays for industrial applications are thus focused on miniaturizing the components, on producing components in a square format (square formats provide better resolution since there is no "empty" space between pixels), and on reducing the noise per pixel.

2.2.3 Solar Cell

A solar cell is a type of photo-detector which reacts to light in the solar frequencies producing electricity (the photo-voltaic cell). A panel with dimensions of 1.2m x 2m can generate over 200 w of electrical power. One application is to power lighthouses, an application reported from Japan. Diesel engines, normally used to generate electricity for the lighthouse, are replaced by 6 panels of solar cells which generate a total power of 1.5 kw. Photonics in this application has the advantage of lower maintenance and of being environmentally friendly.

2.3 Passive Components

2.3.1 Optical Components

For any photonics applications, classical optical components such as lens and mirrors are an absolute necessity. The lens design for photographic cameras used to take years of laborious calculations, and at the end it was an art to make an optimal compromise taking the technical limitations into consideration and to accomplish an aesthetically satisfying quality in the final product, photos. Now, the same calculations can be performed instantaneously and more optical materials are available. Consequently, the quality of optical components has improved and the cost has been reduced. One of the driving force for the improvement of lenses has been photolithography for LSI chips which has been pushing towards shorter wavelength for the higher resolution. The wavelength has already approached the limit of the transparent window of quartz lenses and will have to be replaced with mirrors with higher precision polish and suitable materials in the x-ray region. Also, new types of optical components have emerged, e.g.:

(a) a plastic lens which is being used for the disposable camera;

(b) a GRIN (graded refractive index) lens which is extensively used in passive components for telecommunications, in endoscopes arranged in series, and in photo copiers and fax machines arranged as an array;

(c) computer generated hologram, which are opening the door to a series of optical components which have not been available in the classical optical technologies and are expected to find various applications starting from beam splitters and gratings to more sophisticated technologies such as pattern recognition, optical interconnect, and optical computing;

(d) temperature stabilized lenses;

(e) optical components for high power lasers;

(f) special mirrors to improve laser beam quality;

(g) protection coating with the hardness of diamond, etc.

Miniaturization of classical optical components has been one of the essential requirements for photonics applications.

To date, the technology has reasonably matured at the level of "micro optics". Here, the optical components deal with millimetre beam size with cylindrical beam shape. Most of optical components which have been known in classical optics are now commercially available or at least realizable in the form of micro-optic components. It should be noted that the beam size of the signal transported within a single-mode fibre is about 10 μm. The beam size has to be enlarged in order to use the micro-optic components. This is where GRIN lenses are being used. The following examples list three different approaches which are currently being used for commercially available micro optic components:

(a) Between two GRIN lenses, a neutral-density filter can be inserted to make an attenuator, or a filter to transmit only a selected wavelength. The other wavelength can be reflected back and captured by another output fibre. The device is a wavelength-division multiplexer (WDM) or demultiplexer.

(b) Fibres can be fused together side by side and elongated. The size reduction due to the elongation causes leakage of power and distribution of the power among the fibres. The device is a splitter.

(c) A fibre is impregnated into a block and a slot is cut through the fibre and a micro optic element such as a filter can be inserted.

Micro-optics technology can be compared to a radio assembled by soldering copper wires. The next generation of the photonics technology which is equivalent to the integrated circuit is known as integrated optics or OEIC. The evolution of the technology towards integration has been recognized from the early stage of the photonics history. However, the commercialization of such technologies has not yet been accomplished. In this section, only the passive part of integrated photonics technology is discussed. Inevitably, integrated photonics components will have a planar shape. Therefore, the interconnection between the planar waveguide and the outside world which consists of a lens or optical fibre is a technical challenge. In addition to semiconductor materials which can form an active device, silica-based glasses are also being used for planar optical passive components with limited active capabilities. Some of the commercially available or demonstrated components are briefly described:

(a) 1xN splitter with a maximum N of 8 to 16. These devices are being manufactured from glass substrate either by diffusing an element to form a waveguide with the necessary pattern or by depositing a waveguide layer followed by photolithography and etching.

(b) Mach-Zehnder interferometer made from silica-based material. The device was demonstrated as a DEMUX for FDM (frequency-division multiplexing) which is nothing other than WDM with very small channel spacing. If such a device can be mass-produced, it will find numerous applications for sensors and instrumentation.

2.3.2 Waveguides for Power Transport

For industrial material processing and for medical applications, a flexible means of transporting high power laser light is essential. Silica fibres are most commonly used for this purpose, and work over the wavelength range from UV to near infrared (IR). They cannot be used in the extreme UV where some of the excimer lasers can reach, i.e. 193 nm of the ArF laser.[92] To date, no alternative material has been demonstrated for this wavelength region. Unfortunately, the most commonly used wavelength range for high power industrial material processing is the IR region where silica fibres are no longer transparent, e.g. 10 μm of CO_2 laser and 2 μm of Ho:YAG laser.[93]

Alternative materials have been investigated but the maturity of the technology cannot be compared with that of silica fibre. Fluoride glass fibres can transmit in the 2.5 μm range and they are becoming commercially available but their power handling capability has not been fully investigated and peripheral technologies have not yet matured such as connectors, cabling, etc. Beyond this wavelength, especially at 10 μm of the CO_2 laser, hollow core waveguides have been demonstrated but their practical application is limited due to their inflexibility and difficulties in coupling with the laser output beam. 1.06 μm of Nd:YAG laser can be handled easily using silica fibre and is commonly being used for packaging or sealing of electronics components.

2.3.3 Waveguides for Signal Transport

The technology for silica-based optical fibre has matured because of its extensive application for telecommunications. The fibre material is suited for signal transport from UV to near IR. However, large core fibres made of plastic material are also suited for visible to near IR regions and are used for low cost sensors and displays.

92 Elements: Ar - argon, F- fluorine

93 Ho - the element holmium

Beyond 2 μm, where silica fibre is no longer transparent, fibre availability is limited. Fluoride glass fibre is becoming commercially available as discussed previously. Chalcogenide glass fibre and crystalline fibre have been demonstrated for their capability to transmit IR in the 5-10 μm region. To date, the availability of such fibres is very limited.

2.3.4 Waveguides for Image Transport

Coherent fibre optic bundles are commonly used for endoscopes but their resolution is limited by the fibre core size, which is typically 10 μm diameter. Image quality is better with a rod consisting of GRIN lenses. The disadvantage of this device is its inflexibility. One of the most advanced coherent fibre optic bundles is being used in some flight simulators which are being manufactured by CAE Electronics. Their helmet mounted display has a future potential to evolve into remote piloting, or more generally, virtual reality applications.

2.4 Active Components/Equipment

2.4.1 Optical Switches and Modulators

Light beams in free space or guided light in a planar waveguide can be spatially directed, switched on and off or intensity modulated. The most rudimentary photonics switches consist of a mechanical device which moves one port of guided light relative to the others. It is analogous to an electric rotary switch. Such a switch is commercially available and is actually being used for test equipment.

Acousto-optic modulators can be used to deflect light beams in space as well as in guiding media. Lithium niobate or semiconductor-based devices are most commonly used for experimental demonstration of a system which requires switches or modulators. The reason for the lack of commercialization of such a device can be attributed to technical problems such as temperature instability, polarization dependence, power requirement, and difficulty in coupling the signal into the device.

The most exciting applications of optical switches and modulators are optical signal processing, optical computing, and optical interconnect based on a two-dimensional spatial light modulator. Device research to perform such functions is currently driven by application opportunities. For this reason, this subject is covered in the "Applications" section.

2.4.2 Optical Amplifier

Any laser can be made into an amplifier by suppressing the lasing action. The highest end in terms of power is the large solid state lasers/amplifiers for nuclear fusion. Spin-off technologies from such a project are optical components for high power lasers, enhancement to optical glass quality and new types of glasses.

More practical development activities are actively taking place for telecommunications applications using semiconductor materials and rare earth ion doped fibres. Because of the coupling compatibility as well as other features required for telecommunications applications, the fibre amplifier is drawing more attention. However, it should be noted that currently fibre amplifiers are available only at 1550 nm. Recently, a 1310 nm fibre amplifier has been demonstrated in the laboratory and worldwide research competition is taking place. It remains to be seen whether its efficiency can be improved to make it a practical technology and whether a powerful pump laser diode can be made for the amplifier.

Other than telecommunications applications, the significance of the fibre amplifier is that the output power from a pigtail fibre can be readily enhanced by using the amplifier. This approach is easier than the development of laser diodes with higher brightness and development of more efficient laser-fibre coupling methods. Possible applications of a high output power pigtail fibre are range finders, machine vision, and communications in free space such as ship-to-ship, and various test equipment. It should be noted that the importance of the 1550 nm wavelength is not only its low loss but also its eye safety.

The semiconductor amplifier may become a key component for OEIC in order to recover the loss associated with each building block within the OEIC.

2.4.3 The Optoelectronic Integrated Circuit (OEIC)

The OEIC is a device which integrates a semiconductor light source, modulator, planar waveguide, and detector. Functionally the circuit replaces an optical set-up which may be found on an optical bench. It should be noted that a relatively simple optical set-up can be assembled at low cost by using micro-optic components. To be "competitive", OEICs have to be sophisticated and involve extensive active functions, relative to micro-optics techniques. It is inevitable that all the building blocks cannot be made from one type of material.

An optical hybrid circuit has been proposed and development work is taking place. Using a micro machining process, a micro-optical bench can be formed using silicon as the substrate. The components made of optimum materials are placed on the micro bench which is pre-aligned in terms of the optical axis.

To date, no optical circuit has been identified guaranteeing a market size which can support the costly development work. A laser doppler velocimeter may be one of the candidates. This lithium niobate based device integrates an optical heterodyne detection scheme on a chip. Applications includes blood velocity measurement and robotics arm velocity measurement as it approaches the target.

Lastly, it is worth noting that the OEIC consists of waveguides which have to guide a light with the wavelength of about 1 μm with minimum loss. Consequently, the size of the waveguide cannot be too small and the bends in the waveguides have to be gradual. These requirements imply a fundamental limit in reducing the size of the OEIC.

2.4.4 Liquid Crystal Devices

Substantial improvements have been made in the quality of liquid crystal materials, primarily driven by their application in flat displays as well as the previously described two-dimensional spatial light modulator. The technology may also find application in active micro optic components.

3.0 GENERIC TECHNOLOGY APPLICATIONS

3.1 Industrial Material Processing

Photonics technologies are used in a wide variety of industrial material processing applications:

- Micro-electronics packaging: metal cutting, welding, and sealing;
- Treatment of surfaces: applying coatings, removing paints, engraving, marking, coding;
- Etching: photolithography of micro-circuits;
- Machining: precision machining and cutting of parts and "micro-parts";
- Moulding: curing of plastics, selective sintering of powders; and
- Welding: an alternative to plasma or tungsten arcs and electron beams for joining metals.

The biggest current application of industrial lasers is cutting (45%), followed by welding (23%), marking (12%), drilling (8%) and other (12%) including surface treatment, etc.[94]

Photonics technologies have several key attributes which support their use for industrial material processing:

Focusing high energy on very small areas. This supports cutting, marking, etching, etc. where the surface or package being worked on is very small. This has major application in sealing of microelectronic packages. Light beams can be made much "narrower" compared with the electrical arcs traditionally used for these applications.

Precisely guiding high energy beams to accurately reproduce, or cut, patterns. This supports engraving, coding, photolithography, sintering, etc. where high precision is required. Photonics technology outperforms traditional mechanical techniques (cutting or etching tools made from metal or plastic, masking, moulding) which are less accurate, and electrical beams or arcs which are more difficult to control.

Focusing energy on a point without coming into contact with it; i.e. as with electrical arcs, but more precise and "distortion free". This supports its application in welding (joining) of metals. Because the delivery mechanism is often a fibre, the photonic energy can be precisely directed. Multiple welds can be performed at once by using multiple fibres. Because of photonic's precision, joints can be smaller (reducing the overall weight of assembled parts) and trim reduced.

These properties of photonics technologies also support their use in sintering and curing applications where parts can be made more precisely (and be readily repeated) by selectively focusing the photonic energy. A computer model can guide a laser which selectively "moulds" the parts required. This technique enables, among other things, rapid prototyping of parts. The part can be created in three dimensions on a computer work station, and then transmitted, via the laser energy, directly to the material to be moulded into a prototype.

Photonics systems have a high cost relative to traditional technologies for doing the same thing. Costs are overcome where photonics can outperform the traditional technology, for example, where very high precision is required, or where a very small surface is being worked.

94 Industrial Laser Review, February 1993, page 12

Due to its potential speed and efficiency relative to traditional techniques, photonics technology will see growth in welding applications (automobiles, aircraft). Smaller joints also help decrease overall assembled weight, further favouring laser welds. The use of multiple beams will increase welding applications in three dimensions, something virtually impossible with traditional welding technologies.

Photonics technologies are also more environmentally friendly than many traditional material processing technologies. Laser light can replace solvents in paint removal or replace etching chemicals in lithography. These attributes will stimulate the use of photonics in applications which replace dangerous or environmentally unfriendly chemicals.

3.2 Communications and Control

The advantages of optical communications (high capacity, long distances between repeaters, and immunity to electro-magnetic interference), which have stimulated the use of photonics technology in telecommunications applications, also translate into benefits in industrial communications and control needs. Industrial environments are often hostile (in terms of temperature, noise, humidity, etc.) and so photonics (particularly the "passive" elements - glass wires don't corrode, for example) can often outperform traditional electronics.

Photonics technologies play a key role both in communications of information (in the form of shop-floor local area networks) as well as in providing signalling paths for control of machines and robots. As manufacturing is becoming more and more automated, individual machines or robots are becoming more "intelligent". Photonics technologies provide a means of quickly addressing large numbers of machines which may be operating in environments hostile to other technologies.

3.3 Biomedical

Biomedical photonics applications can be divided into three areas: diagnosis, surgery and therapy.

Photonics technologies enable biomedical sensing "in vitro" and "in vivo". In other words, a patient's condition or biochemical reaction can be monitored real-time and within the biomedical environment without disturbing biochemical processes. This compares with prior technologies which require sample extraction from the bio-environment and laboratory testing. The above mentioned advantages of photonics technologies approach have been accomplished primarily by miniaturizing the sensing heads. The following examples are only a few of the numerous feasibility demonstrations:

(a) Blood velocity monitor using a laser Doppler velocimeter. The laser output/monitor port of a velocimeter is connected to an optical fibre and the tip of the fibre is inserted into an artery.

(b) Fluorometric sensor. The excitation light is guided through an optical fibre to the site and the tip of the fibre is a sensitized to specific biochemical substance in such a way that the concentration of the substance is translated into the fluorescence intensity. The light signal is guided back to the signal processing instrument via optical fibre.

Surgery can be performed using medium power lasers for eyes as well as general tissues. For eye surgery, the transparency of the cornea and lens at the visible wavelength allows direct access to the retina. It has also been demonstrated that laser illumination can cure cataracts and vision disorders. With respect to tissue surgery, the laser approach is known to minimize tissue damage and bleeding, and to sterilize as it vaporizes the tissue. Consequently, rapid post-operative recovery with fewer complications and less post-operative pain with earlier mobilization have been reported.

Optical fibres are also used for coronary laser angioplasty. In order to access the point where an artery is blocked, the power delivery fibre and the endoscope can be combined within a catheter, taking advantage of the small size and the flexibility of the photonics approach. Plaque and healthy tissue can be distinguished when they are illuminated by UV light and a medium to high power laser light can be used to dissolve the plaque.

The endoscope is the most common commercial application of coherent fibre optic bundles. However, a series of GRIN rods is also used for a straight endoscope, providing better image quality than the fibre optics bundle whose image resolution is limited by the size of the fibre core, which is typically 10 μm.

Lastly, tissue is known to be relatively transparent in the wavelength region of red to near IR. This permits direct absorption spectroscopy for diagnosis and also phototherapy. An example of phototherapy is a light induced chemical reaction of an injected chemical substance by externally illuminating the tissue. This approach was pioneered in Japan more than a decade ago[95] and is now being actively pursued by Quadra Logic of Vancouver for cancer treatment. Recently, this approach was approved for bladder cancer treatment.

For most applications, the basic technologies are already available. The major hurdles for wide use of such biomedical photonics equipment are:

(a) packaging which satisfies the rigorous safety standards for medical equipment;

(b) development of biochemical substances which efficiently and selectively translate photon energy to biochemical reactions; and

(c) empirical and time consuming optimization processes for the optical parameters and treatment conditions, e.g. wavelength, time duration, power level, etc.

3.4 Sensors

3.4.1 Smart Materials, Smart Structures

Initially the idea of smart structures was proposed in order to monitor the condition of composite materials within aircraft. By impregnating optical fibre in composite materials and interrogating the optical loss of the fibre, the condition of the composite material can be monitored at various stages starting from the manufacturing of the laminated material to the maintenance inspection of the aircraft. Furthermore, the idea of in-flight real-time monitoring and even control of the aircraft have been proposed based on this approach.

Recently, this concept has been expanded to more general civil engineering problems which require detection of micro strains. The possibility of impregnating an optical fibre in concrete is being explored in order to monitor microstrains in bridge structures.

The photonics approach is attractive because of its immunity to electromagnetic interference (EMI) and also the compatibility of optical fibre with composite materials as well as small size.

95 See, for example, Kenjiro Sakurai and Daisuke Kato, *"Laser and Cancer"*, Keisoku to Seigyo (in Japanese) Vol. 19 No. 6, 593 (1980) or Daisuke Kato, *"Argon Laser Photochemotherapy (PCT) of Cancer"*, Photomedicine and Photobiology Vol. 8 No. 2, 3, 1986.

These applications are still at the experimental stage especially for low cost applications. The key technical hurdles will be the interrogation scheme and its implementation in a practical environment. Potentially, OEIC can play a key role in order to overcome these hurdles. It will take several years before there are substantial implementations even for high cost applications such as military and space.

3.4.2 Remote Sensing

Satellites monitor reflections and emissions of light from the earth at several wavelengths in order to monitor agricultural and other human activities, environmental conditions, mineral deposit, oil spills, etc. on a global scale. Similarly, aircraft can monitor a smaller area. Pollutant detection can be performed by spectroscopic means in the atmosphere ranging from the stratosphere to the factory environment. Sensitive detector arrays, narrow line width lasers, optical signal processing technologies, and most importantly compact packaging of components and equipment are the crucial technologies for these applications.

In addition, optical fibre enables distributed sensing and remote spectroscopy in hazardous environments. Exemplary applications are leak detection in gas pipe lines, real time chemical analysis in explosive environments, and the monitoring of nuclear reactors. Signatures (absorption spectrum) to detect substances are scarce in the transparent wavelength region of the readily available silica based optical fibres. Fluoride glass fibre which is transparent in the IR region is most desirable for this type of applications. However, the technology associated with this fibre is not as mature as silica fibre, making actual field installations more difficult and costly.

3.4.3 Miscellaneous

For electric power systems, photonics-based current sensors will replace today's bulky, unreliable and insensitive transducers. For the same environment, numerous photonics sensors are being investigated primarily because of their immunity to electromagnetic interference.

A monitor for particle size based on light scattering provides a compact and real time sensor which can be used for biomedical and chemical reactors.

Sensors in general provide researchers an opportunity to demonstrate applications of physics. For this reason, extensive laboratory demonstrations have been reported by academic research organizations. However, for practical implementation of photonics sensors, the main hurdle is the unavailability of low cost reliable components and equipment, not because of the technical difficulty but because of the extremely diversified applications and approaches which provide only a small market for each component and equipment. In order to promote development work, it is crucial to identify some synergy among numerous applications and technologies and to identify key common components or subsystems which secure a reasonably large market size.

3.4.4 Gyroscopes

Size reduction, reliability and sensitivity enhancement, and cost reduction are achieved by replacing the mechanical spinning top with an optical ray which circulates within a coiled optical fibre. In addition to traditional gyroscope applications, numerous new opportunities are being proposed, e.g. navigational systems for automobiles (or land navigation), platform stabilization, arm guidance for robotics, well logging, etc. Commercial units are already available. However, further improvements in reliability, long-term drift and cost will be the engineering challenges for the future.

3.5 Metrology

A laser beam can be used to perform measurements based on triangulation. Photonics technology makes such measurements faster and more accurate utilizing high resolution CCD array detectors and data processing software. Applications include the alignment and measurements during automobile assembly and tree height measurements. Combined with more sophisticated beam scanning and data processing schemes, triangulation-based test equipment can utilize a machine vision which generates and stores the three dimensional image of an object.

A high resolution CCD camera alone can monitor an assembly process in a factory and the image can be compared with a computer generated reference image. Such measurement equipment is suited for an assembly which involves complex and cumbersome alignment procedures such as airframe manufacturing.

The resolution and accuracy of radar can be enhanced by using a laser. The "laser ranging system" can be used to map a terrain profile. This is also the key technology for the "automatic obstacle avoidance system" which is being developed for aircraft.

The coherence property of the laser is also used for interferometers. Motion control with sub-micron accuracy can be realized by real time monitoring and feed-back control with a position sensor based on a laser interferometer.

The laser Doppler velocimeter is a device which measures the velocity of an object by beating (heterodyne detection) the light reflected from the moving object (therefore, Doppler shifted) with the incident light. The applications of the device for blood velocity measurements and robotics have been discussed in other sections. It is also used as a vibration monitor for large objects, such as a space station.

3.6 Display, Imaging and Vision

This category of applications, including displays and image and vision systems, covers a wide variety of technologies and markets including bar code scanners (16%), cameras (11%), displays (16%), machine vision (16%), night vision (18%), and other applications.[96]

Vision systems often use infrared detectors in order to pick up a "thermal image" from an object of interest. This has obvious applications in night vision systems widely used in the military, and less obvious applications in detecting faults in coatings or surfaces (applicable in the automotive and aerospace industries, among others).

Miniaturization of photonics components into "micro devices" can also open up new applications; for example, infrared detectors incorporated into onboard systems for automobiles to help drivers "see" when driving in the dark.

Scanners based on photonics technology are widely used in commercial applications, the best known of which is the point of sale terminal at most grocery stores. Scanners work when the bar code scatters incident laser light. The scattered light is picked up by a photodetector which converts the scatter pattern into an electrical representation of the bar code.

Scanners take advantage of the "purity" of the laser light in being able to direct and shape the light, scatter it and subsequently detect the scanned pattern. The technique is also used for optical character recognition systems, used by laser scanners in computing and by the post office for sorting mail.

Traditional video displays use large tubes to direct electron beams onto a phosphor screen; the "cathode ray tube" or CRT. The pattern "etched" out continually on the screen becomes the displayed image or moving picture. Photonics screens can be large or small arrays of lenses (passive screen) or light sources (active display).

[96] Photonics Spectra, January 1993, p. 64

Small flat displays can be combined with night vision systems to create a helmet-mounted display for a fighter pilot, for example. Multiple flat displays can also be used, in combination with lenses, to create stereoscopic displays.

The development of active liquid crystal displays was a key enabler of laptop computer technology. One limitation, however, in flat screen displays has been the lack of components which support the full colour range which would be required for high fidelity television pictures. The development of blue LEDs is one of the enablers for display technology.

3.7 Memory, Information Processing and Interconnect

3.7.1 Memory

Optical devices can be employed to act as memories, in much the same way as the RAMs and ROMs of the electronics world do. Optics has the advantage of high capacity and of immunity to electromagnetic interference, making it a very durable and easy to use memory technology.

The best known memory device is the compact disk (CD). CD technology is now becoming commonplace for storage of images or combinations of image with text and sound. This has created a whole new category of "multimedia" products such as the encyclopedia on a disk. CDs work by reflecting laser light onto a detector which by "reading" the reflected pattern reproduces the information stored on the disk.

Holographic memories work in a similar way, except that the information stored is three-dimensional. Holograms are created by creating an interference pattern between the light reflected from an object of interest and an "incident" light beam. If the incident beam is pure laser light, the interference pattern is essentially an image of the object of interest superimposed on the single frequency laser light. Thus the hologram stores a three-dimensional image of the object. Holograms can be designed for visual light viewing, and are often used for security purposes. Being harder to counterfeit than other coding schemes, holograms are now often found as integral parts of credit cards and paper currency.

Traditionally, looking at a hologram, one sees a three-dimensional image which appears to be behind (or inside) the flat surface. Holograms can also be designed to project the image above the surface. This has many applications in imaging, particularly in prototyping and biomedicine.

Holographic techniques applied to CDs increase the memory capacity substantially since each storage element contains three-dimensional information represented by an interference pattern. Holograms will likely be a key element in an optical computer due to their high potential storage capacity and their robustness.

3.7.2 Information Processing

This sub-category encompasses the attempts to modulate the cross section of optical beams. The SLM (spatial light modulator) is a generic name for a device with such a function. The device consists of many pixels which intercept the light beam. By addressing pixels individually, the SLM becomes a passive modulator which functions as an image generator, a mask (or filter) of the optical signal, or a logic or memory element.

SLMs have potential in the areas of communications, display and information processing, leading to applications using neural network techniques, optical computing and artificial intelligence. To date the concept has been demonstrated using either ferro-electric liquid crystals or semiconductor quantum well devices.

Massive connectivity and parallelism, the two basic attributes of optics, combined with the large storage capacity and the parallel access of optical memories make optical technologies an ideal means to realize artificial neural networks. Today, the majority of research activities are concentrating on experimental demonstration of systems and devices rather than applications. This is still remarkable progress considering that the research activities about five years ago were mostly on architecture and algorithms.

Recently, SEED (self-electro-optic-effect-device) is one of the most frequently quoted devices. This semiconductor based array of "smart-pixels" was developed by AT&T. The quantum well device not only modulates amplitude or phase by changing the electric current but also performs as an optical logic device by using another light to modulate the light signal.

3.7.3 Interconnect

The impetus for development work on photonic interconnection comes from the problems associated with the electronic approach: clock skew, ground loop isolation, cross talk, loss, impedance matching and pin-out problems. The photonics approach is expected to overcome all of these problems. A more fundamental answer to the question of "why photonics for interconnection" was given by D. Miller of AT&T: "Optical interconnections provide an impedance transformation, allowing the coupling of high impedance electrical circuits through a low impedance propagation medium providing optics with its potential advantage in terms of communication energy per bit".[97]

Depending on the applications, i.e. chip-to-chip, module-to-module, or board-to-board, various approaches have been proposed and some demonstrations have been reported. Fibre or planar waveguides may simply replace the current backplane, or free space optical communications may take place between chip and board or between adjacent boards. Free space communications can be modulated or switched using the two-dimensional spatial light modulator which was discussed previously.

For some of the proposed approaches, the basic components to realize the concepts are available in today's technology. In the near future, more demonstrations and experimental applications may result in an industry standard which may further promote wider use of the technology in a commercial environment.

From a technical viewpoint, the key component will be a small board mountable transmitter and receiver at low cost and/or two-dimensional arrays with modulators. If waveguides are utilized, this application demands communication distances in the range of 10 cm to 1 m, which fall between optical fibre for long distances and planar waveguides for the cm region. Polymer-based planar waveguides may fulfil this particular need and find an application for the optical backplane.

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97 Miller, D.A.B., "Optics for low-energy communication inside digital processors: quantum detectors sources and modulators as efficient impedance converters", Optical Letters, 14, 1989, pp. 146-148

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