Devices and Components for Optical Signal Delivery and Processing in an Optically Controlled Phased Array Antenna

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ABSTRACT

This report examines issues of performance, cost, size, etc. related to the use of optical/optoelectronic devices and components in an optically controlled phased array antenna and more specifically, the use of fibre optic networks for microwave signal distribution to and from the central processor to the antenna's distributed T/R modules. The prototype "optical" phased array antenna architecture that is to be used as the basis for the analysis is described. A detailed review of the current commercial state-of-the-art is presented for the various optical and optoelectronic components used: laser sources, optical fibres, electro-optic modulators, optical amplifiers, optical couplers/splitters and high speed photodetectors. The relative merits of various competing device technologies are reviewed in terms of reliability and packaging issues, price and power consumption. A number of different schemes are presented illustrating how a practical RF-on-fibre distribution network can be implemented using present day optical/optoelectronic device and component technologies. Critical system parameters such as optical power delivered to the T/R module, device count, complexity, power consumption, weight, overall system cost are evaluated and future trends in optical/optoelectronic fabrication technologies are examined.

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1 Introduction

The use of optical techniques can provide substantial gains in terms of improved performance, reduced weight, lower cost, improved flexibility and ruggedness, etc., for the design and construction of large phased array antennas intended for both terrestrial and spaced-based applications such as radar and wireless communications. For example, the distribution of microwave signals to and from the thousands of individual antenna T/R elements can be accomplished using low loss RF-on-optical fibre techniques, which can be relatively low cost, are lightweight, are relatively immune to electromagnetic interference and can be more easily assembled and deployed than conventional networks of metal waveguide; a considerable advantage, particularly for a large satellite-based antenna. In addition to simple optical signal distribution, advanced optical and optoelectronic devices and components can be used to implement a wide variety of "electronic" functions within a phased array antenna system. These include microwave signal generation using optical heterodyning or optical signal mixing, optical injection locking of microwave oscillators for precise frequency and phase control, and antenna phase control using optical phase modulators or optical true-time delay.

The purpose of this report is to examine issues of performance, cost, size, etc. related to the use of optical/optoelectronic devices and components in an optically controlled phased array antenna. While, as mentionned previously, there are many functions that can be implemented using optoelectronics, this report will be limited to the use of fibre optic networks for microwave signal distribution to and from the central processor to the antenna's distributed T/R modules. In Section 2, the design and operation of the prototype "optical" phased array antenna architecture, that is to be used as the basis for our analysis, will be described. Since the performance of the antenna depends critically on the performance of the various optical and optoelectronic components used, a detailed review of the current commercial state-of-the-art will be presented in Section 3. This will include laser sources, optical fibres, electro-optic modulators, optical amplifiers, optical couplers/splitters and high speed photodetectors. It is not the intention of this report to go into extensive detail regarding the theory and design of each of these components, since in most cases their operating principles will be reasonably well known to the reader, however in many cases a brief review of device operation will be given as this may impact on the way it may be ultimately used in the system. Section 3 will also deal with the relative merits of various competing device technologies, reliability and packaging issues, price and power consumption. It is hoped that the information contained in this chapter will give the reader a better appreciation of the wide variety of high performance optical and optoelectronic devices and components currently available.

In Section 4 a number of different schemes will be presented illustrating how a practical RF-on-fibre distribution network can be implemented using present day optical/optoelectronic device and component technologies. The goal of this Section, is to investigate the performance of competing device technologies and determine critical system parameters such as optical power delivered to the T/R module, device count, complexity, power consumption, weight, overall system cost, etc. Since there are a large number of different devices and/or combination of devices that can be used to implement an RF-on-fibre distribution network, each with its own advantages and disadvantages, the information provided in Section 4 is primarily aimed at allowing the designer to investigate the performance of various technologies and then decide which is the best for a particular application based on a set of desired system specifications.

In the concluding sections, future trends in optical/optoelectronic fabrication technologies will be examined and the impact of improvements in device design and integration on overall system performance will be discussed.

2 System Description

The system configuration to be examined in this report is based on that first proposed by Belisle et al[1] describing a dual frequency antenna operating in both C-band (at 5.3 GHz) and L-band (at 1.3 GHz). In this design, the antenna consists of a rectangular planar array of 96 rows of 40 C-band Transmit/Receive (T/R) modules, 3840 in total, interlaced with 24 rows of 10 L-band T/R modules, 240 in total. The inter-row separation of the C-band modules is 4 cm and the separation of the L-band rows is 16 cm. The overall size of the antenna array is 3.84 metres by 16 metres. Beam forming and beam steering is accomplished by adjusting the amplitude weights and phase of the microwave signal at the individual T/R elements.

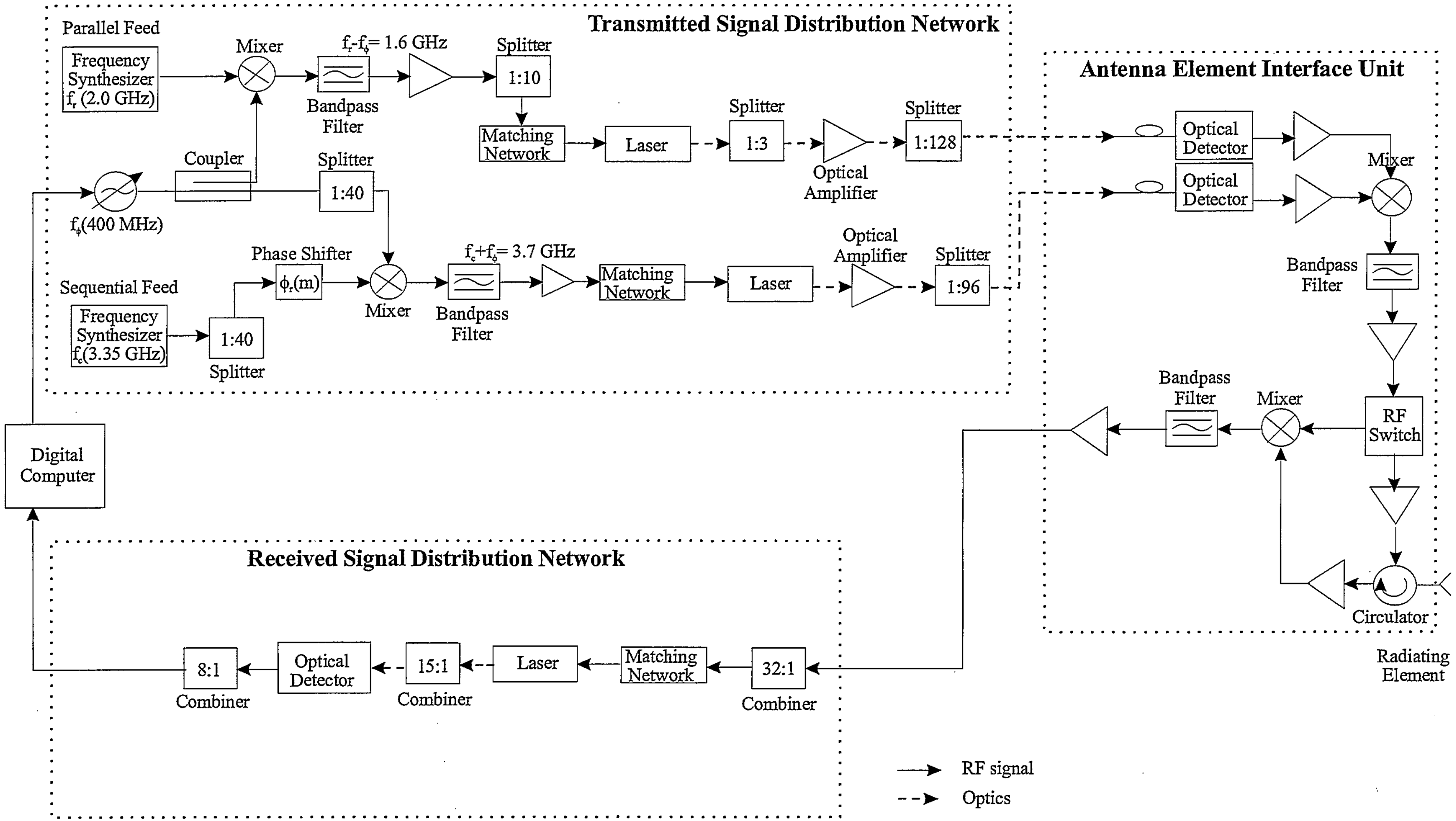
Using the approach described by Belisle et al[1], in the transmit signal distribution network, the phase weighting along-track (ie: from column to column across the 40 C-band columns of the phased array) is accomplished using a conventional microwave approach with a dedicated phase shifter for each of the columns. Phase weighting across-track, ie: along the 96 elements in each of the columns is achieved using a differential delay network. Using this configuration, implementation of the C-band antenna requires only 40 RF phase shifters. Using a similar argument, the L-band system can be achieved using only 10 phase shifters, ie: 1 per C-band column. With the use of the linear progression technique to provide phase weighting along each column, it is possible to replace a large number of additional microwave phase shifters by a frequency synthesizer.

A block diagram showing the key components of the C-band portion of such a phased array is given in Figure 1. The distribution of the transmit signal, with proper frequency and phase, is divided into 2 sections, a parallel feed, which provides a signal, with constant phase and amplitude, to all 3840 of the antenna elements and a sequential feed, which provides the appropriate phasing at each antenna element.

The parallel feed section is made up of a frequency synthesizer operating at a fixed frequency, f_r, that is mixed with the output of a second frequency synthesizer operating at a frequency, $f_{\emptyset}$, determined by the system controller according to the desired beam position. The mixer output is then passed through a bandpass filter and amplified to a level sufficient to drive an optical source of some kind. The RF modulated optical signal is then distributed to the individual antenna elements via optical fibres and associated optical hardware. Considerable care must be taken during the optical distribution to ensure that the effective path length to all elements is exactly the same to ensure that the phase uniformity across the array meets the required specification.

The sequential feed section uses a third frequency synthesizer, operating at a frequency, f_c. A series of microwave splitters then split this signal equally into 40 outputs, each with the same amplitude and phase, one for each column in the array. A series of 40 phase shifters is then used to provide the antenna array with 40 signals (1 for each column) with the appropriate along-track phase settings. The across-track phase settings are accomplished by mixing each of the 40 column signals with the signal from the frequency synthesizer operating at $f_{\emptyset}$. The resultant signals for each column are then passed through a bandpass filter and amplified to a level sufficient to drive an optical source and distributed to the appropriate column of the antenna array. When the optical signal reaches the column, it is then split and distributed sequentially to the 96 elements of the column. Once again it is important to ensure that the optical distribution network does not add any additional phase errors that could degrade the performance of the overall antenna.

Figure 1: Block Diagram Of C-Band Portion Of Optically Controlled Phase Array



The system controller is responsible for setting the frequency $f_{\varnothing}$, setting the along-track phase shifters and adjusting the frequency $f_{\varnothing}$ to provide the necessary active beam steering and data processing.

In transmit mode, the final output signal, to be broadcast from each antenna element, is obtained by using 2 high frequency photodetectors within each Antenna Element Interface Unit to detect the individual parallel and sequential optical signals, one at a frequency $f_c+f_{\varnothing}$ and one at a frequency $f_r-f_{\varnothing}$. The resultant RF signals are then mixed to provide the final output frequency f_r+f_c and with the appropriate along track and across track phase setting. Finally a microwave power amplifier is used to boost this signal to the required output level, and it then passes through a circulator to the radiating element itself.

Receive mode is accomplished in a slightly different manner. The microwave signal received at each element is first amplified, filtered and then combined together with the signals from 32 similar antenna elements along a row. This combined signal is then converted to optics and fed back via fibre to the payload. 15 of these optical signals are then combined onto a single photodetector and finally the outputs from the Receive Network's 8 photodetectors are combined and processed by the system controller for analysis. While the Receive Network's microwave signal handling is somewhat different than in the Transmit case, the functionality of the optical distribution is quite similar, consisting of optical sources capable of being modulated at RF frequencies, optical fibres, splitters, couplers and combiners and finally high speed photodetectors to reconvert the signals from optics to RF.

While it is possible to directly accomplish many of the microwave signal processing functions, such as frequency synthesis, mixing, optical phase shifting, etc., using optics/optoelectronics, this report will focus on the devices and components required for the optical distribution network. Since the technical issues facing the implementation of both the C-band and L-band antennae will be similar, only the higher frequency C-band system will be considered, since it requires a much larger optical distribution network, and as a result will largely determine the cost of the overall 2-band antenna. Similarly, since the Receive Signal Distribution Network will require much the same optics/optoelectronics as on the Transmit side, the detailed analysis will be limited to various devices and components and configurations that can be used to construct the Transmit Signal Distribution Network. Finally, for the purposes of this analysis, the values for the various frequencies will be f_r=2.0 GHz and f_c=3.35 GHz and $f_{\varnothing}$ =400 MHz ± 80 MHz. As a result, the optical sources used in the Parallel Feed Network will have to be modulated at 1.6 GHz, while the optical sources on the Sequential Feed Network will have to be modulated at 3.7 GHz.

The performance of any RF-on-fibre distribution system will depend critically on the performance of the various optical and optoelectronic devices used within it. In the following section, the availability of components such as advanced optical sources, photodetectors, optical modulators, optical splitters and combiners will be examined and device parameters such as output power, bandwidth, efficiency, noise figure, excess loss, etc. will be discussed.

3 Optical/Optoelectronic Components

With the ever-increasing demand for high capacity, long haul fibre-optic telecommunications systems, optoelectronics and optical component technology has matured rapidly. Low-loss optical fibres, splitters, couplers, etc. with excellent uniformity can be obtained routinely, and optical sources and detectors capable of supporting data rates in excess of 10 Gb/s have become commercially available. The use of optical/optoelectronic systems in very long haul transoceanic cables has also demanded that these components meet very demanding specifications in terms of environmental stability and long term reliability, which in many cases may meet or even exceed the requirements for military or space-based applications. As use of optical/optoelectronic networks has become more wide spread, there have been great strides in device development, particularly in packaging for cost reduction and improved reliability. As a result, in recent years there has been the design and fabrication of high performance lasers with lower threshold currents, higher output powers and improved performance at frequencies in the gigahertz range, detectors with improved efficiency and lower noise figures, very low loss couplers and splitters, and optical amplifiers that can be used to amplify optical signals without the need to first convert them back to the electronic domain.

In this section, optical and optoelectronic components that can be used for RF-on-fibre signal distribution such as lasers, fibres, modulators, detectors and optical amplifiers, will be discussed and the current commercial state-of-the-art will be reviewed. This discussion will include a brief technical description of each of the various components as well as an examination of critical issues that might affect the use or performance of these devices in a practical optical network for RF signal distribution.

3.1 *Optical Media*

While optical signals can be distributed in free-space, and in fact free-space optical signal distribution is currently being used in applications such as inter-satellite optical links and highly parallel computer backplane interconnects, the phased array antenna network envisaged here does not easily lend itself to such a distribution network. First the optics required to deliver the various optical signals to 7680 different photodetectors would be extremely complex, if not impossible and would be extremely difficult to assemble, costly and could lead to severe signal degradation resulting from optical crosstalk, spurious reflections and/or misalignment due to microscopic flexing of the array itself. For an optically controlled phased array to work properly, optical losses must be low and constant with time and the optical transit time to each element must be extremely well controlled to ensure good phase control and uniformity over the entire array. This transit time can be controlled best using optical fibres of equal lengths.

3.1.1 Fabrication

The first very-low loss fibres were step-index silica fibres. The index of refraction decreases abruptly from the core region to the cladding region thereby producing complete internal reflection. The core diameter is many tens of microns and can sustain many optical modes (MMF or multi-mode fibre). These various modes experience different group velocity giving rise to modal dispersion. This problem was reduced by the introduction of the graded index fibre. The refractive index decreases progressively from the high index core region to the low index cladding region. In that structure, the higher order modes spend more time in the lower refractive index region than the low order modes. With a suitable index profile, the greater instantaneous velocity compensates for the longer path of these modes so that the modal dispersion effects are greatly reduced (dispersion 120 ps/(nm*km) at 0.8 μm and 6 ps/(nm*km) at 1.3 μm). Subsequently, optical fibres with much smaller core diameters were introduced. The core diameter is such that only the fundamental transverse mode can be supported (SMF or single-mode fibre). This eliminates the modal dispersion completely. At 0.8 μm, there is still chromatic dispersion due to the fact that the index of refraction varies over the wavelength range of the transmitted optical signal. In conjunction with the development of the SMF, lasers emitting at 1.3 μm became available. At this wavelength, there is almost zero chromatic dispersion. Combined with the low loss (0.5 dB/km), these improvements led to the introduction of high-bandwidth long distance optical links.

3.1.2 Propagation loss

There exists another transparent window at 1.5 μm with an even lower absorption coefficient, 0.2 dB/km. However, the chromatic dispersion is not zero. Dispersion-shifted fibres (DSF) achieve a dispersion of zero at 1.55 μm by suitable modification of the index profile in the single-mode fibre. This fibre allows transmission over many hundreds of kilometres at rates of many gigabits per second. The dispersion is less than 3.5 ps/(nm-km). Further modifications to the index profile led to the dispersion-flattened single-mode fibre (DFSM). This structure allows a range of wavelengths to benefit from the zero-dispersion condition.

To increase the information carrying capacity of these fibres, wavelength division multiplexing (WDM) was introduced. Many tens of different wavelengths are combined together in one fiber, each carrying its own signal. Unfortunately, the appearance of intermodulation products between the various wavelengths is aggravated by the fact that the refractive index has a minimum there. Non-zero dispersion shifted fibres (NZDSF) were introduced to minimize this problem in WDM optical links and now, dense wavelength division multiplexing systems carrying 32 channels with only 100 GHz spacing on a single fibre are now available.

Silica is the most common material used in the fabrication of optical fibres but plastics are also used. There is the plastic-clad optical fibre (PCOF) and the plastic optical fibre (POF). The PCOF, which retains a vitreous silica core, exhibits a lower attenuation (typically 5 to 8 dB/km at 0.85 μm) than the POF. The Crofon fibre developed by DuPont has been described as a POF suitable for links over a distance of up to 150 metres with a data rate of 10 Mb/s. AMP offers a POF qualified for 20 Mbps operation over 50 m. The attenuation is 0.16 dB/m at 650 nm. A more recent development is DuPont's Polyguide. This material technology has been used by AMP to develop ribbon optical cables for electronic system interconnects. They reported a 144-channel ribbon cable with connectors[2] that operates at 3 Gbps over a length of 2.8 m.

The size of the fibre core affects the ease with which the light from an optical source can be injected and how easily the optical fibres can be joined together. MMF fibers are favored in that respect because not only do they have a larger cross-section but also they have a larger acceptance angle.

3.1.3 Radiation damage

Radiation damage can lead to an increase in transmission losses. This is due to the formation of colour centres[3]. The material is sensitive to radiation energetic enough to cause ionization damage in the fibre or fibre components. Included in this group are gamma radiation, beta radiation, neutrons and x-rays. The space environment would lead to exposure to most of these types of radiation. A pure silica fibre will see its loss at 1.3 μm increase to 10 dB/km under continuous irradiation at a rate of 10^5 rad/hr. Some materials are more susceptible than others. In particular, fibres doped with more than 1 % P_2O_5 are highly sensitive to radiation. Pure silica core fibres have most resistance to radiation and recover faster after the exposure is stopped. The incorporation of H_2 in the glass matrix can help "extinguish" the defects caused by the radiation. A hermetic carbon coating is required to seal the H_2 inside the fibre[4]. It can result in a reduction by a factor of 2 of the radiation-induced loss. Doping with multivalent elements such as cerium also has a beneficial effect.

3.1.4 Non-linear effects

The operation of optical fibres is generally analyzed in terms of linear optics. At higher light intensity, non-linear phenomena are observed such as stimulated light scattering of the Raman or Brillouin type, and the Kerr effect, in which the refractive index acquires an intensity dependent contribution. There may also be second harmonic generation. The first two scattering phenomena are generated by light coupling to vibration modes, "optical" phonons for the Raman effect and "acoustic" phonons for the Brillouin effect. Due to momentum conservation, the stimulated Brillouin scattering is forced to be backward while the stimulated Raman scattering is backward-forward symmetrical. In long fibres, the effect of Raman scattering may become relevant at a power level of 100 mW while Brillouin scattering may be felt at power levels as low as a few mW. These effects become important over long fibre length and the latter effect requires that the source linewidth be very sharp (20 MHz). In one experiment[3] with a length of fibre measuring 13.6 km, the reflection coefficient reached 65% at an input power of 10 mW and the output power saturated at 2 mW. In this application where the fibre lengths are of the order of 10 m, these effects should be considerably smaller. For the Kerr effect, signal degradation should be negligible below 1 W.

3.2 *Laser Sources*

A laser is a source of coherent light. Depending on the laser material, laser structure, etc., a laser can produce optical energy with powers ranging from mW to MW and with wavelengths from the UV to the far-infrared. There are several types of lasers available, but all function according to the same basic principle. First, excitation energy in the form of an electrical or an optical stimulus is applied to the laser material. This excitation causes electrons to be raised to a higher energy level, from which they decay spontaneously to lower energy levels either dissipating heat or radiating incoherent light. If the excitation of the material is performed at a sufficiently high rate and the electron lifetime in the excited state is relatively long, more electrons will be present in the excited energy level than in the ground state. A photon resulting from the spontaneous decay of an excited electron can stimulate the emission of photons from other excited electrons resulting in coherent radiation. Furthermore, by placing reflecting surfaces at the ends of the lasing material an optical cavity is created, providing feedback for sustained laser oscillation. One of the reflecting surfaces is made partially transmitting. In this manner, light is reflected back and forth, amplified, and only those optical modes that have sufficient energy to overcome cavity losses will be transmitted. Presently, the laser sources commercially available are gas lasers, semiconductor lasers, solid state lasers and fibre lasers. Gas lasers can be used for a wide number of different wavelengths and can have steady state output powers in excess of tens of watts or pulsed output in the kW range. However, they will not be considered here since they are physically very large, very inefficient, and generate low power levels at the wavelengths of interest, namely 1.3 and 1.55 μm.

3.2.1 Semiconductor Lasers

Semiconductor lasers use a planar semiconductor p-n junction or diode structure whose substrates are etched or cleaved perpendicular to the planar layers to form an optical cavity. Semiconductor lasers can be fabricated as Fabry-Perot (FP) resonators or as distributed feedback lasers (DFB) where the substrate layers are corrugated, thereby allowing for better frequency mode selectivity leading to narrower beams and more stable operation. Multi-quantum well DFB lasers also exist which use very thin active layers. These make use of quantum confinement states leading to narrower beams as well as lower threshold current, lower temperature sensitivity and improved modulation characteristics, such as better linearity. Finally, vertical cavity surface emitting lasers (VCSELs) which operate on multiple transverse modes and a single longitudinal mode have become available recently. These structures ensure stable coupling of power, low noise operation, and can be easily pigtailed to single or multi-mode fibres.

Table 1 provides a list of major manufacturers for devices operating at wavelengths of 1.3 μm and 1.55 μm. The most common devices used today are the distributed feedback diodes. As can be seen from Table 1, laser diodes can range in price from $1,140 US to $14,500 US depending on output power, frequency response, etc.. The devices provided by Ortel are much more expensive than those from other manufacturers, however their frequency of operation is significantly higher. At present they are the only source of laser diodes that can be directly modulated at frequencies over 5 GHz. Fujitsu, Alcatel, and Newport offer lasers diodes with much higher output powers than Ortel. Unfortunately, all except Fujitsu have very limited bandwidths. The VCSEL devices are also very limited in bandwidth. Nortel devices have

Table 1: SEMICONDUCTOR LASERS

Manufacturer And Model #	Type	Wavelength µm	Power Out (min / typ / max) mW	Operating Voltage (min / typ /max) V	Threshold Current (min / typ / max) mA	Efficiency mW / mA	Frequency Specification	Package Type	Cost $ US
ORTEL									
1540A	DFB	1.3	4.0 / 7.0 / -			0.16	+/- 2.0 dB up to 5 GHz	comb. D-sub	9500
1541A	DFB	1.3	2.4 / 5.0 / -			0.12	+/- 2.5 dB up to 10 GHz	comb. D-sub	12500
1541B	DFB	1.3	3.0 / 6.0 / -			0.1	+/- 3.0 dB up to 13 GHz	comb. D-sub	
1541C	DFB	1.3	3.0 / 6.0 / -			0.1	+/- 3.0 dB up to 15 GHz	comb. D-sub	14500
1740A	DFB	1.55	3 / - / -			0.05	+/- 2.5 dB up to 4 GHz	comb. D-sub	
1741A	DFB	1.55	3 / - / -			0.05	+/- 2.5 dB up to 10 GHz	comb. D-sub	
NORTEL									
LC131GC-20A	DFB	1.3	- / - / 2	- / 1.3 / 1.8	- / 15 / 35	0.04	-1.3 dB @ 2.5 GHz	Butterfly	1486
LC155GC-20A	DFB	1.55	- / - / 2	- / 1.3 / 1.8	- / 18 / 35	0.04	-1.3 dB @ 2.5 GHz	Butterfly	1486
FUJITSU									
FLD3F7CX	DFB	1.3	8.0 / - / 20.0	- / - / 1.5	- / - / 20.0	0.2	-3 dB @ 4.0 GHz	Butterfly	2000
FLD3F8CZ	DFB	1.3	2.0 / - / 4.0	- / - / 1.5	- / - / 20.0	0.08	-1 dB @ 1.5 GHz	Butterfly	1200
FLD3F6CX	DFB	1.3	2.0 / - / 5.0	- / - / 1.84	4.0 / - / 20.0	0.05	-3 dB @ 4.0 GHz	Butterfly	1140
FLD5F6CX	DFB	1.3	2.0 / - / 5.0	- / - / 1.75	7.0 / - / 25.0	0.04	-3 dB @ 4.0 GHz	Butterfly	1440
ALCATEL									
1905 LMI	DFB	1.55	20 / - / -	- / - / 2.5	- / - / 40.0	> 0.135		Butterfly	3630
1915 LMI	DFB	1.55	15 / - / -		- / - / 40.0	> 0.135		Butterfly	
1905 LMP	DFB	1.55	50 / - / -	- / - / 2.3	3.0 / - / 60.0	0.015 - 0.15	-3 dB @ 2.0 GHz	Butterfly	6500
NEWPORT									
LD-1310-11B	FP	1.3	- / 22 / -		- / 40 / -		-3 dB @ 2.5 GHz		5844
LD-1550-11B	FP	1.55	- / 15 / -		- / 55 / -		-3 dB @ 2.5 GHz		3732
LUCENT									
D2500P	DFB	1.55	- / 7 / -		- / 15 / -			Butterfly	
D2500	DFB	1.55	- / 2 / -		- / 15 / -			Butterfly	
D2500-26GXX	DFB	1.55	- / 7 / -		- / 15 / -			Butterfly	2000
A2300	DFB	1.3	4.0 / - / 13.0		- / 15 / -			Butterfly	
MITEL									
1A440	VCSEL	0.84	0.9 / 1.7 / 3.0	- / 1.9 / 2.2	- / 3.5 / 6.0	0.2	- 3 dB @ 2 GHz	TO- 46	
1A458	VCSEL	0.84	- / 10 / -	- / 2.2 / -	- / 30 / 40	0.25	- 3 dB @ 1 GHz		

acceptable bandwidths, but their output powers are very low. Most manufacturers offer their diodes in 14 pin butterfly packages. These packages typically include built-in thermoelectric coolers, precision thermistors, rear facet monitor photodiodes, optical isolators, and polarization maintaining fibre pigtails for stable operating performance under external temperatures ranging from –40 to +65 °C.

Examining Table 1 in detail, it is apparent that the laser diode FLD3F7CX as manufactured by Fujitsu stands apart from all the others. It can provide up to 20 mW of output power over a 3 dB bandwidth of 4.0 GHz at a cost of only $2000 US. These features make it highly recommended for use in the current project. A suggested improvement would be to obtain either chip-mounted lasers or wafer-mounted lasers. In this manner, only a single control circuitry (temperature, light intensity, etc.) would be required for the many lasers required to drive the entire antenna array, rather than having independent control circuitry for each laser diode. Some manufacturers do provide laser diodes in this custom format, however these are for select clients who regularly purchase many thousands of lasers per year.

3.2.2 Fibre Lasers

Fibre lasers are fabricated from either silica or fluoride fibres doped with small quantities of optically active atoms, usually erbium or praseodymium. The dopant atoms are excited by optically pumping the fibre with a light from a high power laser diode or a high intensity lamp. They are capable of very stable and very narrow wavelength operation as well as high power output. These lasers also provide very high optical conversion efficiency and exceptional mode quality that does not degrade with time or temperature change. As well, since the lasing medium is the fibre itself, it is very easy to directly couple its output into subsequent optical fibres. Production costs are also much lower than that of solid state lasers. While there are currently a number of manufacturers selling fibre lasers, MPB Technologies in Pointe Claire PQ, was the only one investigated in this work. They manufacture Er-doped fibre lasers that operate at a wavelength of 1.5 μm. They also have models that can be tuned over the range 1.53 to 1.562 μm. Output powers are typically 20-35 mW with a power consumption of 30 W. They typically cost from $29900 to $42960 $US, depending on whether a fixed wavelength or tunable model is desired. Unfortunately, these devices require power supplies and head assemblies that are bulky and heavy (13 Kg), making them unattractive for most applications outside the research lab.

3.2.3 Solid State Lasers

Solid state lasers are very well established devices that can provide high output powers over a multitude of wavelengths. They consist of a semi-transparent optical material such as ruby or yttrium garnet glass that is optically pumped using a high power flash lamp or a laser diode array. The most widely used solid state lasers are based on ruby (λ = 650 nm) and neodymium doped yttrium aluminum garnet (Nd-YAG) glass (λ = 1.06 μm or 1.32 μm). In this report, all of the models investigated were of the Nd-YAG variety. Suppliers and models of Nd-YAG lasers can be found in Table 2 for wavelengths of 1.064 μm and 1.319 μm. Unit costs vary from $5220 US to $42960 US, depending on power output, efficiency, etc. Power Technologies manufactures solid state lasers for roughly $5000 US that provide output powers of 100 to 250 mW, with a power consumption of 25 W. Lee Laser offers very high output powers ranging from 8 to 12 W, however their power consumption is very high, in the neighborhood of 4000 to 5000 W. Their models only accommodate flash lamp pumping which is much less efficient than diode pumping. Laser Systems provides models that have a fairly high output power (2 W), modest power consumption (20 W), and are reasonably priced $27900 US. However, like the fibre lasers, solid state lasers require heavy and bulky power supplies and head assemblies (15-30 Kg).

As indicated in Table 2, solid state (Nd-YAG) lasers are available that offer very high power levels in excess of 5 W. Unfortunately, at a cost of tens of thousands of dollars, they are

Table 2: FIBRE LASERS AND OTHER SOLID-STATE LASERS

Manufacturer and Model #	Laser Type	Wavelength um	Power Out W	Mode	Beam Diameter mm	Beam Divergence mrad	Polarization %	Pump Type	Power Consumption W	Weight (Head /Supply) Kg	Cost $US
MPB											
EFL-fixed	Er-doped fiber	1.525-1.528	0.02	single				diode	30	13	29900
EFL-R98-TS *	Er-doped fiber	1.525-1.528	0.02	single				diode	30	13	39400
EFL-R98-TS *	Er-doped fiber	1.525-1.528	0.035	single				diode	30	13	42960
LEE LASER											
812T	Nd-YAG	1.064	12					lamp	5000		18900
808T	Nd-YAG	1.064	8					lamp	4000		16500
LASER SYSTEMS DEVICES INC.											
DPLV-5000	Nd-YAG	1.064	5	single	1	3		lamp	150		15500
		1.064	2					diode	20		27900
UNIPHASE											
S106B-1000	Nd-YAG	1.064	1	single	1	2.5	100	diode	300	8 / 9.5	
S106B-3000	Nd-YAG	1.064	3		1	2.5	100	diode	<300	8 / 9.5	27650
MICRO-IR	Nd-YAG	1.064	0.25					diode			
POWER TECHNOLOGIES											
LCS-DTL-222	Nd-YAG	1.064	0.25	single	1.8	1.2	100	diode	25	1.0 / 25.0	5220
LCS-DTL-232	Nd-YAG	1.319	0.1		1.8	1.5	100	diode	25	1.0 / 25.0	5300
COHERENT											
Compas	Nd-YAG	1.064	4								40000
LIGHTWAVE ELECTRONICS											
125-1064-25	Nd-YAG	1.064	0.025	SM-FC				diode			29850
126-1064-700	Nd-YAG	1.064	0.7	free-space				diode	50		33750
126-1064-500	Nd-YAG	1.064	0.5					diode			26050
126-1064-200	Nd-YAG	1.064	0.2					diode			22350
126-1064-100	Nd-YAG	1.064	0.1					diode			17400
220-1064-7000	Nd-YAG	1.064	7					diode			32000
Series 2005	Heterodyne Controller	1.064									15000
125-1319-350	Nd-YAG	1.319	0.2	SM-FC				diode			34200

* tunable devices

very expensive. Complex optics is needed to focus relatively large output beams into 9 μm core single mode fibres. Solid state lasers cannot be directly modulated, making external modulators necessary for applications using RF signal input. These two requirements further increase the cost and complexity of systems based on solid state lasers. Also, high-powered solid state lasers consume over 100 W of power. This requires large power supplies and head assemblies which tend to be heavy and bulky (10's of Kilograms). For on-board space applications, real estate in terms of space, weight and available power is limited and very expensive, thus making Nd-YAG solid state lasers very unattractive devices. Finally, their lifetimes are very short, typically only a year before servicing is required, whereas satellites can stay in orbit for up to ten years or more. On-board components should last at least as long since no means to service them on satellites is possible. For all these reasons, current solid state laser technology is probably not feasible for onboard space applications such as the beam-steering phase-array project currently under study. For terrestrial applications, however, where size, weight and power consumption are not as big an issue, solid state lasers, such as the Nd-YAG, with their very high ouput powers, may offer considerable simplification of the optical distribution network.

The fibre lasers investigated (table 2) provide relatively low power (20-35 mW) and are presently priced as high as Nd-YAG solid state lasers. They too require external modulation, consume high power, and require heavy and bulky power supplies. As a result, fibre lasers are also unattractive for airborne space application. On the other hand, some of the semiconductor lasers surveyed can provide tens of milliwatts of power and are inexpensive (thousands of dollars) compared to the other types of lasers available. They are also very compact, with packages typically a few cubic centimeters in size. Most models come in butterfly packages that have built in temperature and light intensity control circuitry. Power requirements are typically less than 1 W and some models can be directly modulated into the GHz range. These higher-powered laser diodes have rated lifetimes of 15 years, which is a longer life span than most satellite missions. With their relatively low cost, low power consumption, high reliability and ability to be directly modulated, the semiconductor lasers would appear to offer the best option for use in a large optically controlled phased array antenna system. Of the laser diodes currently available, Fujitsu's FLD3F7CX offers the best combination of power, cost and bandwidth.

3.3 *Modulation Techniques*

3.3.1 Direct modulation

The optical fibre carries typically the information in the form of a modulated light intensity. As suggested in the preceding section, one way of achieving this modulation is by directly modulating the driving current to the semiconductor laser. There are some drawbacks to this approach. The change in current leads to variations in optical properties such as the refractive index. This may lead to a shift in the wavelength of the lasing mode(s), a phenomenon known as chirping. This change in wavelength leads to a change in transmission delay, which results in phase modulation for long fibre links. This is less of a problem if appropriate dispersion-shifted fibre is used. Moreover, DFB and DBR (distributed Bragg reflector) lasers are better at maintaining a constant wavelength than Fabry-Perot lasers under changing pump conditions.

Direct modulation is often limited to a few gigahertz by intrinsic properties of the semiconductor laser. The inter-relationship between the carrier density and the photon density defines the relaxation oscillation frequency. It is typically around 3 to 5 GHz. The noise and distortion worsen as this frequency is approached. For NTSC CATV transmission, it has been shown that for the CSO (composite second-order products) requirements to be met, a 7 GHz resonance frequency laser diode would be required, even though the CATV bandwidth did not extend beyond 550 MHz [5]. The requirements for the phased-array antenna may not be as stringent but noise and distortion should be evaluated carefully if the laser is to be modulated near its relaxation oscillation frequency.

3.3.2 External modulation

One way to circumvent the laser dynamic limitations is to perform external modulation. There are two main types of external modulators, one that uses interferometric principles and a second that modulates the absorption. In the interferometric category, there are two main types, the single output Mach-Zehnder modulator (MZM) and the dual output Y-fed balanced bridge modulator (YBBM). The input light is fed into an optical waveguide, which splits into two branches. The RF signal is applied to electrodes alongside the two branches. The effect of the electrical field on the refractive index causes the light transit time to change. The two branches then recombine and the light beams add or cancel depending on their phase relationship. Both modulators can operate at frequencies exceeding 10 GHz. In the ON condition, their operation is very similar but in the OFF condition, the Mach-Zehnder dissipates the optical energy internally while the YBBM redirects the light signal to a second output. In this way, the dual output YBBM can almost double the throughput of a CATV distribution system. However, the modulation of the second output is 180 degrees out-of-phase with respect to the first output. This phase change would not be tolerable in the phased-array distribution system.

The transfer function of these interferometric modulators has the form of a raised cosine. At the half-power (halfway between the ON and OFF conditions), the second-order linearities are minimized but third order nonlinearities worsen as the modulation amplitude is increased. Some schemes have been devised to "linearize" the MZM transfer function based on optical techniques or electronic techniques. The third order non-linearities may give rise to objectionable intermodulation products in a multifrequency system. This limits the modulation depth. The characteristics of various MZMs available commercially are shown in Table 3. The switching voltage is the voltage difference between the fully ON and fully OFF condition. As can be seen in the table, it is typically 6 V but can vary between 3 and 12 V. It gives an indication of the efficiency with which the RF signal can modulate the optical beam. The table also displays the On/Off extinction ratio, i.e. the transmission ratio between the ON and OFF condition. All products exhibit a value better than 20 dB.

Another parameter characterizing the MZM is the maximum input power. It depends strongly on the wavelength. The maximum power is 20 mW for operation at 830 nm, 50 mW at 1060 nm and 200 mW at 1310 and 1550 nm for the MZM fabricated by UTP. For that reason, in a system using a high power YAG laser, there would be an advantage in operating at 1319 instead of 1060 nm. The proton-exchange process developed by UTP to fabricate their MZM allows operation at higher optical power than the Lucent modulators which are limited to 100 mW, hence reducing the number of modulators required within the signal distribution network. Although the price of a single UTP MZM is $6500, it comes down to $4000 for quantities larger than 40.

The second type of external modulator is the electro-absorber. The optical transmission properties of a semiconductor vary rapidly with wavelength near the band gap. This band gap energy can be shifted by passing a current through the active region thereby controlling the optical transmission. The effect is accentuated in multi-quantum well (MQW) epitaxial layers. As these can be fabricated using a structure very similar to that of semiconductor lasers, monolithic integration of laser and modulator is possible. As shown in Table 3, Lucent and Fujitsu both offer optical sources integrating a diode laser and an electro-absorption modulator. Their bandwidth is in the range of 3.5 to 5 GHz. Like the MZM, their transfer function is not linear either. They are mainly used in digital transmission applications. The cost is comparable to that of a Mach-Zehnder modulator. The output power is between 1 and 10 mW, comparable to what would be achieved by combining the Fujitsu laser with a Mach-Zehnder modulator. The UTP Mach-Zehnder is capable of accepting up to 200 mW but it has a typical insertion loss of 3 dB so that a maximumf 100 mW can be delivered at the output.

Table 3: EXTERNAL OPTICAL MODULATORS

Manufacturer & Model #	Material	Wavelength	Optical Power	Bandwidth	On/Off extinction ratio	Optical insertion loss	Switching Volt	Operating Temperature min/max	Remark	Price qty > 40
		µm	mW	GHz	dB	dB	V	°C		$ US
MACH-ZEHNDER MODULATOR										
INTEGRATED OPTICAL COMPONENTS										
10 Gbps series		1.525-1.575		8	>20	<5	<4	0/70		
LUCENT										
m1613C	LiNbO3	1.3		>8	>20	<4	<4.5			
m2614C	LiNbO3	1.3		>16	>20	<4	<9			
m2623C	LiNbO3	1.55		>8	>20	<4	<6			
m2624C	LiNbO3	1.55		>16	>20	<4	<12			
m2420C	LiNbO3	1.3		.04-1.6	>20	<4	<3			
m2410C	LiNbO3	1.55		.04-1.6	>20	<4	<4.2			
UTP										
APEMZM-1.5-12	LiNbO3	1.52-1.57	<200	12	>20	<4	<6.5	-25/75		4000
APEMZM-1.3-12	LiNbO3	1.3-1.34	<200	12	>20	<4	<5.5	-25/75		
ELECTRO-ABSORPTION MODULATOR with integrated laser source										
FUJITSU										
FLD150F5CN	InGaAsP	1.55	2-6	5	>10		-5 to 1			
LUCENT										
E2500L	InGaAsP	1.55	1.3-10	3.5	>10		2.5		360 km version	4200
E2500U	InGaAsP	1.55	1.3-10	3.5	>10		2.5		600 km version	5200

3.3.3 Selection

The selection of the modulation scheme is a critical decision in the elaboration of the distribution network. In Section 4, "Microwave Signal Distribution using Fibre-Optic Networks", some aspects such as cost and weight will be discussed for various architectures. A priori, the direct modulation is appealing because of its simplicity, efficiency, low cost, compactness, lightweight and single power supply requirement. The "chirping" should not be a major issue because the DBR lasers minimize this effect and the optical links are short. It might be an issue if Fabry-Perot cavity diode lasers were to be used with multimode fibres at 0.8 μm because of the greater modal and chromatic dispersion at this wavelength but it should not be a problem at 1.3 or 1.5 μm. The major question is whether the distortion and noise constraints can be satisfied. This will require careful evaluation of the antenna requirements, circuit simulation and experimental measurements. Only then can we choose between direct and external modulation. This will be the subject of a subsequent report.

3.4 *Optical Amplifier*

The distribution of the optical signal to all the 3840 T/R modules requires the repeated division of the microwave transmit signal. If one single light source is used, this involves 12 levels of 1x2 splitters. At 3.5 dB loss per level, this means a 42 dB optical loss. Even the best APD receiver surveyed here requires a minimum input power of –38 dBm. This means that a modulated laser power of at least 4 dBm is required. This is close to the maximum laser power available for a fast diode laser. In all likelihood, either more than one laser source will be needed or the optical signal will require amplification or both. Optical amplifiers fall into two categories, the optical fibre amplifier and the semiconductor optical amplifier (SOA).

3.4.1 Optical fibre amplifier

Suitably doped optical fibres can be used as amplifiers. In a way similar to the gain process present in any laser, the electrons of the dopant atom can be raised to an excited state by illuminating it with a pump light source with a wavelength corresponding to the energy difference between the ground state and the upper level. From this upper energy level, the electrons decay to a lower excited level that has a relatively long lifetime. In a process called stimulated emission, a photon from the signal stream can induce an excited electron to return to the ground level and emit a photon of the same energy as the signal photon if the incident photon energy matches the energy difference between that excited state and the ground state.

The most common dopant is erbium in a standard silica fibre. It is designated EDFA for erbium-doped fibre amplifier. Its gain extends roughly from 1530 to 1560 nm. Note that zirconia-based optical amplifiers have been demonstrated, e.g. by Galileo. They offer gain over a wider wavelength range. However, this is not an issue in this system which is most likely to use a single wavelength. The EDFA can be excited using a laser source at either 980 or 1480 nm. Optical fibre amplifiers are easily integrated in an optical network since it is just another section of optical fibre. The critical parameters are gain, saturated output power, noise figure. In a WDM system, one might also add gain flatness. As seen in Table 4, the small signal gain is of the order of 30 to 36 dB. The maximum output power depends on the pump power. A single pump laser feeding 100 mW will allow an amplified output power saturating around 16 dBm. To increase the saturation power, a second pump laser is used to pump the EDFA from the opposite direction. Such a scheme can lead to a saturated output power of the order of 22 dBm. As shown in Table 4, the power consumption ranges from 6 to 35 W and the weight ranges from 0.5 to 5 kg depending on whether it is packaged as a component or an instrument.

Table 4: OPTICAL FIBRE AMPLIFIERS

Manufacturer & Model #	Wavelength µm	Saturated output power dBm	Small signal gain dB	Spont noise figure dB	Pump Wavelength µm	Weight kg	Power consumption W	Price $ US
ALCATEL 1901 OFA Power amplifier								
001AA	1530-1565	10		7				
139AA	1545-1560	19		8				
ALCATEL 1902 OFA with integrated electronics								
075AA	1530-1565	10		7				
179AA	1530-1565	15		7				
ALCATEL 1903 OFA preamp								
141AA	1530-1565		30	5				
ALCATEL 1911 OFA for analog application								
175AA	1549-1559	16		4.5				
174AA	1549-1559	19		4.5				
GALILEO Fluoride-based OFA module								
	1534-1562	13	30	4.5	1480			
JDS-Fitel								
OA915	1.53-1.565	>12	8	4.5	0.98	0.5	6	17900
LUCENT								
12CBC	1.53-1.56	16	>35	5	0.98		9.5	
13CBC	1.535-1.565	16	>30	8.5	1.48		10	24400
18CBC	1.53-1.56	16			0.98		10	25100
20CBC	1.53-1.56	16					10	25800
24FBC	1.53-1.56	21	21?	5.5			15.5	
24GBC	1.53-1.56	22	22?	5.5			19	35800
MPB								
P15	1.53-1.56	>15.5	>30		0.98	4	17	18700
P20	1.53-1.56	>20	>36		0.98	5	35	32000

The main source of noise is the amplified spontaneous emission. The quantum limit for the noise figure is 3 dB and a preamplifier like the MPB R35 comes close to that limit with noise figures of 3.2 to 3.3 dB in the wavelength range from 1541 to 1560 nm. The noise figure worsens on the short wavelength side. The optical amplifier is particularly useful in the long haul fibre optic links if it is located before the optical signal has become so weak that the SNR would be affected by the EDFA noise figure. It can boost the signal shining on the detector to prevent the photodetector noise from affecting the SNR. However, it is an expensive component, $25000 for an EDFA with a saturated output power of 16 dBm. It is unthinkable to place such an EDFA in front of each of the 7600 or so detectors. An APD with its intrinsic gain would be more cost effective. One could also think of using the EDFA closer to the distribution-tree trunk to reduce the number of lasers required. It would be acting as a power amplifier instead of a pre-amplifier. In that case, the same increase in optical power could be obtained by adding a number of lasers instead. An EDFA producing an optical power level of 20 dBm costs $32000. For that price, one could buy 16 Fujitsu lasers producing a total of 160 mW or 22 dBm. The cost benefit will be analyzed for specific distribution schemes in Section 4.

The gain is not uniform with wavelength and various techniques are used to flatten the gain region. For instance, filtering can be used to eliminate the peak at 1530 μm. This should not be an issue in the phased-array application because only one or two wavelengths might be used. The EDFAs are packaged in various ways. MPB and Galileo supply laboratory type EDFAs as instruments with integral power supply and controls. Other EDFAs are packaged specifically for telecommunication applications such as those supplied by Alcatel, JDS and Lucent. The package includes monitoring photodiodes at the input and output to detect failures or even to control the gain in order to maintain a constant output power level. An electronic output port will signal alarm conditions. They are designed as components for optical telecommunication systems and do not include a power supply, so this must be supplied externally. Note that radiation exposure will affect these EDFA just as it will affect optical fibres.

3.4.2 Semiconductor optical amplifier

An alternative to the EDFA is the semiconductor optical amplifier (SOA). Its structure is very similar to that of the semiconductor diode laser described above in Section 3.2. As in the diode laser, an electrical current generates the carrier population inversion giving rise to optical gain but elaborate means are taken to avoid optical feedback and prevent lasing such as deposition of antireflection coating on the facets, angling of the facets etc. It should be more efficient than the EDFA because it is directly powered by an electrical current instead of indirectly via an optical pumping system. Table 5 shows the characteristics of three SOAs, the gain wavelength range, the saturated output power, the small signal gain, the spontaneous noise figure and the price. Some SOAs are available commercially from AFC that operate at 1.3 μm and those manufactured by Alcatel operate at 1.5 μm. The small signal gain ranges between 13 and 30 dB and saturates at an output power between 9 and 13 dBm. They have a noise figure of 8 dB, larger than the low values of 3.5 dB seen in EDFAs. The drive current is approximately 200 mA into a load of a few ohms for a power consumption below one watt. To that must be added the power consumption of the internal Peltier cooler, a maximum of 6 W. Alcatel has indicated that their SOAs are produced in the research lab. They cost as much as the EDFA but the gain is lower and so is the saturation power. Alcatel mentioned that the price should come down to about twice that of a diode laser when the technology is transferred to the production line. That would be roughly $7000. At that point, the SOA would probably look more attractive than the EDFA because it is more compact and efficient despite the fact that it is noisier and has a lower saturation power.

Table 5: SEMICONDUCTOR OPTICAL AMPLIFIERS

Manufacturer & Model #	Wavelength µm	Saturated output power dBm	Small signal gain dB	Spont noise figure dB	Pump Wavelength µm	Weight kg	Power consumption W	Price $ US
AFC								
SA1310	1.29-1.33	13	30	8	not applicable			22500
ALCATEL								
1901/SOA	1.525-1.555	9	25	7	not applicable			20000
1921/SOA	1.525-1.555	10	13	8	not applicable			20000

3.5 *Photodetectors*

The function of the photodetector is to convert the optical signal to the maximum electrical signal with the minimum of added noise. The most standard detector is the pin photodiode. This is a semiconductor device with a structure that consists of three layers. The substrate is typically n-doped. In the middle is an intrinsic (undoped) layer that acts as the light absorption region. On top is the p-doped layer. This structure forms a diode that is operated under a reverse bias condition. The photogenerated electrons are collected at the substrate and the photogenerated holes are collected at the p-layer. As shown in Table 6, pin detectors are commercially available that have a 3-dB bandwidth well above 3.7 GHz, the upper frequency of the phased-array distribution system. Epitaxx offers the EPM743FJ-S with a bandwidth of 4 GHz and the EPM820FJ-S with a bandwidth of 8 GHz. The former is mounted in a TO style package while the latter is mounted on a SMA connector. The same chip mounted on a ceramic carrier (designated model ETX25B) exhibits a bandwidth of 18 GHz but is not hermetically sealed. Lucent also offers fast detectors that are hermetically sealed. The photodiodes offered by EG&G are one-fifth the cost of the previously mentioned suppliers but the bandwidth of 3.5 GHz barely meets our requirement. As indicated in Table 5, the photodiode cost varies over a wide range between $22 and $370. This is one hundredth to one sixth the cost of the Fujitsu diode laser at $2000.

The sensitivity of the pin photodiode is usually limited by the shot noise, which includes components due to the dark current and the background average photocurrent. In actual photoreceivers though, the limit to sensitivity is usually set by the noise of the load and preamplifier rather than by quantum effects[5]. The avalanche photodiode (APD) can improve the SNR by applying gain before the subsequent noise is added. The APD structure is similar to that of a pin diode but it is operated under much larger bias, typically 22 to 63 V. As the bias approaches the diode breakdown voltage, the carriers experience greater acceleration and can acquire enough energy to create a new electron-hole pair in an ionizing collision. Under sufficient high fields, this process is repeated many times giving rise to the avalanche phenomenon. In this way a single photogenerated carrier can give rise to a current involving many charged particles. However there is noise associated with the multiplication itself due to random fluctuations of the avalanche process and noise associated with multiplication of the dark current. The APD characteristics are presented in Table 7; these include the material, the wavelength of operation, the bandwidth, the photo-sensitive area diameter, the responsivity at 1.3 and 1.55 μm, the breakdown voltage V_b, the dark current and the capacitance, both at 90% of the breakdown voltage, the maximum gain and finally the price.

In ref. 5, the application of the APD is reviewed as follows: "*For digital intensity-modulated direct-detection systems, APDs are often used in order to improve receiver sensitivity. The gain of the APD is increased until the APD excess noise is the dominant noise process at the receiver. In subcarrier modulation (SCM) systems, however, the receivers are often narrow band with a consequent reduction in both thermal and amplifier noise. Signals from out of band subcarriers cause additional shot noise and the result is that narrow band SCM receivers can be operating in the shot-noise limited regime. This means that the use of an APD will not improve the noise performance of these receivers. In the case where broadband receivers are used, for example when receiver front ends capable of detecting all the transmitted subcarriers are needed, then the use of APDs may be advantageous.*" Therefore, since the phased-array distribution system operates within a narrow band, it would be advantageous to use the pin detector because of its greater speed and lower cost.

Some manufacturers integrate a photodetector with a preamplifier as those listed in Table 8. Their characteristics include wavelength of operation, bandwidth, sensitive area diameter, responsivity, power level, operating range, current consumption and price. These are mainly for digital applications and their bandwidth is barely sufficient to operate at the lower frequency

Table 6: PHOTODETECTOR PIN-TYPE

Manufacturer & Model #	Wavelength µm	Bandwidth GHz	Detector Diam. µm	Responsivity @ 1.3 µm A/W	Responsivity @ 1.5 µm A/W	Idark @ 5V nA	Capacitance @ 5V pF	Package	Price qty > 100 $ US
ALCATEL									
119AA	1.3-1.6	1							
EG&G									
16ECER	1.3-1.6	>3.5	50	0.86	0.9	0.5	0.35	ceramic carrier	22.4
37ECER	1.3-1.6	3.5	75	0.86	0.9	0.8	0.4	ceramic carrier	22.4
17ECER	1.3-1.6	3.5	100	0.86	0.9	1	0.55	ceramic carrier	22.4
17B,E	1.3-1.6	3.5	100	0.86	0.9	1	0.8	TO18+ball lens	25.2
17BFC	1.3-1.6	3.5	100	0.75	0.75	1	0.8	FC receptacle	36.4
17BQC	1.3-1.6	3.5	100	0.75	0.75	1	0.8	fiber pigtail	56
EPITAXX									
EPM600	1.3-1.6	1.5	100	0.9		0.3	1	hermetic package + SMF	
EPM601	1.3-1.6	1.5	75	0.8		0.15	1.1	SMF or SC receptacle	
EPM743FJ-S	1.55	4			0.96	2	0.3	hermetic package + SMF	
EPM820FJ-S	1.3-1.6	8	25	0.55	0.63	0.1		SMF & RF-SMA	
ETX25B	1.3-1.6	18	25	0.8	0.86	0.5		bare chip	
ETX25B-CER	1.3-1.6	2.8	25	0.76	0.82	0.25	0.4	grooved carrier	
ETX40FJ-S	1.3-1.6	4	40	0.8		0.1	0.4	TO-46+SMF	150
FUJITSU									
FID3S1HX	1.3	2	80	0.85		0.1	0.9	hermetic package + SMF	
FID3S1KX	1.3	2	80	0.85		0.1	0.9	hermetic package + SMF	
LUCENT									
type-128C	1.1-1.6	5		0.85		5	0.45	hermetic ceramic + SMF	140
type-170A	1.1-1.6	12		0.85		5	0.2	hermetic package + SMF	370

SMF: Single mode fiber

Table 7: PHOTODETECTORS APD-TYPE

Manufacturer & Model #	Material	Wavelength µm	Bandwidth GHz	Diam µm	Resp. @ 1.3 A/W	Resp. @ 1.55 A/W	Vb V	Id @ 0.9Vb nA	Cap. @ 0.9Vb pF	Max gain	Package	Price qty >100 $ US
ALCATEL 1900 DMC												
276AA	InGaAs	1.3-1.6	1								TO+window	
258AA	InGaAs	1.3-1.6	1								pigtail	
EG&G												
C30644ECER	InGaAs	1.3-1.6	2.4	50	0.89	0.94	70	6	0.3		carrier	280
C30644E	InGaAs	1.3-1.6	2.4	50	0.89	0.94	70	6	0.6		TO-18	330
C30644EQC	InGaAs	1.3-1.6	2.4	50	0.85	0.9	70	6	0.6		pigtail	390
J16A-18A-R10(	Ge		1.5	100	0.73		25	300	1.5		TO-18	
FUJITSU												
FPD3R2LX	Ge	1.3	2.5	50	0.78	0.7	30	150	1	40	can+MMF	
FPD3R2KX	Ge	1.3	2.5	50	0.78	0.7	30	150	1	40	can+MMF	
FPD5W1KS	InGaAs	1.55	2.5	30	0.8	0.95	55	50	0.5	30	can+MMF	
LUCENT												
126C	InGaAs	1-1.6	2.5	30	10.7			150	0.3	30	hermetic carrier	525
127	InGaAs	1-1.6	2.5	30	9.6			150	0.5	30	pigtail	

MMF: multimode fiber

Table 8: PHOTORECEIVERS

Manufacturer & Model #	Type	Wavelength µm	Bandwidth GHz	Detector Diam µm	Responsivity A/W	Power level min/max dBm	Supply Current mA	Package	Price $ US
ALCATEL 1911 SDH type 3CN00... integrated modules with APD+preamp+amp+clock&data recovery									
015AA	RxS1.1	1.3	0.155 Gbps			-29/-8		FC/PC receptacle	
085AA	RxL1.x	1.3-1.5	0.155 Gbps			-35/-8		FC/PC receptacle	
086AA	RxS1.1	1.3	0.155 Gbps			-29/-8		FC/PC receptacle	
087AA	RxL1.x	1.3-1.6	0.155 Gbps			-35/-8		FC/PC receptacle	
ALCATEL 1916 SDH type 3CN00... integrated modules with APD+preamp+amp+clock&data recovery									
004Z#	RxS16.1	1.3	2.5 Gbps			-18/0		FC/PC receptacle	
213Z#	RxL16.1	1.3	2.5 Gbps			-27/-8		FC/PC receptacle	
215Z#	RxL16.2	1.5	2.5 Gbps			-29/-8		FC/PC receptacle	
217Z#	RxU16.2	1.5	2.5 Gbps			-29/-8		FC/PC receptacle	
FUJITSU FRM... series APD or PIN with transimpedance amp, may work as analog									
13S621CU	APD+amp	1.3	0.6		0.7	-36/-3		DIP14+SMF	
15S621CU	APD+amp	1.5	0.6		0.7	-38/-3		DIP14+SMF	
13S621PR	pin-preamp	1.3	0.6		0.7	-25/-7	<40	FC receptacle	
FUJITSU FRM5.. Optimized as digital receiver, may work in analog									
FRM5W231D:	APD+amp	1.3	1.8	30	0.75	-31/-8	<50	BF-8 with MMF	
FRM5W231D:	APD+amp	1.55	1.8	30	0.9	-31/-8	<50	BF-8 with MMF	
LUCENT									
type-1318	pin+amp	1.1-1.6	1.5 Gbps			-27/-2		DIP20+SMF	
type-1319B	APD+amp	1.3-1.6	2.5 Gbps			-34/-10		BF14+SMF	820
UTP SIRU	pin+amp	1.3-1.6	.01-3		0.85	/+3	250	16x83x57mm	1000

BF: butterfly package
DIP: dual in-line package
MMF: multi-mode fibre
SMF: single-mode fibre

(1.6 GHz) of the phased-array distribution system. Since additional components will be included in the T/R module such as mixers, some kind of MIC (microwave integrated circuit) will have to be assembled anyway so there is little to gain in purchasing an integrated detector-amplifier. However, their specifications give and idea of what can be achieved in terms of sensitivities. The APD-amplifier circuits have sensitivities typically between –38 and –27 dBm while the pin-amplifier circuits have sensitivities of approximately –25 dBm. Both types of photoreceivers tend to saturate for optical signals between –10 and 0 dBm and it is likely that the signal levels of 1.55 and 6.55 dBm proposed in Fig 12 of reference 1 would saturate these photoreceivers.

The metal-semiconductor-metal (MSM) photodetector should also be considered. It consists of two interdigitated metal contact patterns deposited on the surface of a high resistivity semiconductor material such as undoped GaAs or InGaAs. The metal contacts form back-to-back Schottky diodes. They exhibit a fast response, good responsivity and low dark current. The fabrication technology has been developed at CRC and the MSMs fabricated on undoped epitaxial GaAs have demonstrated bandwidths exceeding 15 GHz. They exhibit a responsivity of 0.14 A/W at 800 nm. The process has also been used to fabricate two-dimensional arrays of photodetectors. MSMs were also fabricated on InGaAsP for the Telecommunication Research Laboratory in Edmonton. Their main advantage is ease of integration with other MSMs or other active components such as MESFETs. As part of the activities of the Canadian MSM Consortium, circuits integrating monolithically a 3x3 MSM array with transimpedance amplifiers were designed at CRC and fabricated at Nortel[6]. There are no large arrays of photodetectors required in the link to deliver the microwave signal to the individual T/R modules but the monolithic integration of the photodetector with the transimpedance amplifier would provide a photoreceiver unit at the T/R module with a larger bandwidth than if it were assembled of discrete components. On the receive side, there may be an opportunity to use an array of MSMs since the design in ref. 1 p.19 specifies that eight photodetectors are used.

3.6 Optical Splitters

The components required to deliver one optical input to many optical output ports are called optical fibre splitters. They have become a commodity and are available at significant discount in large quantities. Various techniques are used to fabricate them. The first popular method was developed at CRC and is known as the "fused biconical taper" technique. The procedure consists of twisting two or more fibres around each other as they are heated near the softening temperature of glass and are slightly stretched to form a region where the core of the various fibres are narrowed by the stretching, brought closer together and fused together upon cooling. This allows the mixing of the light from the various fibres. This technique is still used to fabricate 1x2 and 1x3 splitters but for larger splitting ratios the concatenation of 1x2 fibre splitters becomes onerous. The trend is toward the use of planar lightwave circuits (PLC). The PLC consists of a flat supporting surface on which are defined optical waveguides. The substrate can be glass or the surface of a semiconductor. The material for the optical waveguide can be glass, polymer or another semiconductor material. A 1x2 optical splitter consists in a waveguide pattern that has the shape of the letter "Y". Larger splitting ratios are obtained by fabricating a succession of "Y" branches. For large splitting ratios, an alternative to the "Y" branches is the use of a large multimode rectangular section with the input fibre at the centre of one side and with the opposite side bordered by an array of closely packed fibres. In this case, the spitting ratio is very sensitive to the device geometry. The performance of the splitters fabricated by the "fused biconical taper" technique and those fabricated using PLCs are comparable. The characteristics of splitters offered by a number of suppliers are shown in Table 9. One can expect an excess loss of roughly 0.6 dB per splitting level. The uniformity worsens by 0.5 dB for each additional splitting level. The uniformity is defined as the difference between the strongest and the weakest outputs. The prices in quantities of 100 vary by 40%. The cost of each FC/PC connector is between $20 and $45 and an extra $5 to $8 may be required for FC/APC connectors. The angled facet of the FC/APC connector reduces the amount of light reflected at the interface. For the larger splitting

Table 9: OPTICAL SPLITTERS

Manufacturer & Model #	Wavelength µm	Port Config	Insertion Loss dB	Return Loss dB	Uniformity dB	Polarization Stability dB	Connector	Size (note 1) mm	Fibre coat	Price qty > 100 $ US
JDS-Fitel										
ACF	1.5-1.58	1x2	<3.8	>55		<0.1	no			160
AC	1.5-1.58	1x2	<3.8	>55		<0.1	no	38x6x6	bare	
ACW1400	1.31 or 1.55	1x4	<7.5	>50	<0.8		no	60x6	ribbon	760
ACW1x16	1.31 or 1.55	1x16	<14.5	>50	<1.5		no	80x8	ribbon	1330
FC/PC										40
MP Fiberoptics										
02AB0NE	1.55	1x2	3.5	>55	0.4	<0.1	no	54x3	bare	26
03BB0NE	1.55	1x3	<5.8	>55		<0.2	no	60x3	bare	75
04BB0NE	1.55	1x4	<7.2	>55	<1.2		no	60x3	bare	120
08DR0NE	1.55	1x8	<10.8	>55	<1.8		no	142x102x11	bare	320
16FR0NE	1.55	1x16	<14.5	>55	<2.4		no	173x125x14	bare	605
32GR0NE	1.55	1x32	<18	>55	<3.0		no	218x162x14	bare	1120
FC/PC										20
FC/APC										25
PIRI Single mode 1xn splitter model SM-1x...										
2-M-250	1.26.-1.6	1x2	<4.6	>55	<.6	<0.3	no	70x10x6	bare	200
4-M-4R	1.26.-1.6	1x4	<7.9	>55	<.8	<0.3	no	70x10x6	bare	270
8-M-8R	1.26.-1.6	1x8	<11.3	>55	<1	<0.3	no	70x10x6	bare	430
16-M-8R	1.26.-1.6	1x16	<15	>55	<1.5	<0.3	no	90x10x6	bare	770
32-M-8R	1.26.-1.6	1x32	<18.5	>55	<2.5	<0.3	no	100x15x6	bare	1400
FC/PC & APC for 1x2										30
FC/PC & APC for 1x4 & 8										20
FC/PC & APC for 1x16 & 32										44
CANSTAR										
CFL	1550	1x2	3.8				FC/PC	51x2.5	TFE	125
JDS	1550	1x3	6		1		FC/PC		bare	195
GGL	1550	1x4	7.5		1.5		FC/PC		TFE	305
GGL	1550	1x8	11.5		2		FC/PC		TFE	630
GGL	1550	1x16	15		2.5		FC/PC		TFE	1150
GGL	1550	1x32					FC/PC		TFE	2475
FC/APC connectors: add $8 per connector										

note 1: mm refers to the dimension along each direction. The form "axbxc" refers to the dimensions of a parallelopiped while the form "axb" refers to the height and diameter of a cylinder.

ratios, the output can be in the form of ribbon fibres or the assembly might be packaged inside a rectangular box with rows of FC/PC receptacles on the side. Since the specifications are very similar, one would recommend purchasing from the supplier with the lowest price, MP fiberoptics in this case. A technology to define waveguides using polymers has been developed at CRC. Polymers are very inexpensive, so it is indeed possible that price can still be reduced. It can be easily integrated with semiconductor devices. A 4x4 optoelectronics crossbar switch has been fabricated at CRC. Four polymer waveguides defined on the surface of the semiconductor wafer deliver optical signals to separate rows of a 4x4 MSM array[7]. The propagation loss is typically 1 to 2 dB per cm.

Table 10 shows how various splitting ratios could be implemented and the calculated characteristics. The *ideal splitting loss* is simply the decrease in power due to the fact that the input power is being divided between many outputs. The *total loss* is the sum of the insertion losses specified by the manufacturer MP Fiberoptics in Table 8. The difference between the *ideal splitting loss* and the *total loss* is found under the heading *Additional/Excess Optical Loss per Channel*. The total cost is shown in the last column. Note that the *Excess loss* increases with the splitting ratio and the number of splitting levels. One can see that a rough approximation of the *excess loss* per splitting level is 0.6 dB.

3.7 *Connectors/Splices*

The optical signal distribution system will be assembled from various elements: fibres, fibre splitters, lasers, detectors and possibly external modulators and fibre amplifiers. The connections can be made either using splices (fusion or mechanical) or connectors. Mechanical splices involve the use of external alignment planes such as fine ceramic tube, square glass tube or precision V-groove. Most mechanical splices used with multimode fibres provide splice losses of the order of 0.1 dB [ref. 3, p. 721]. To achieve the same low loss with SMF, the alignment tolerance is 0.8 μm [ref. 3, p.717]. These splices are permanent if epoxy is used to hold the fibres in place. Fusion splices achieve even lower losses. They are made by applying a brief electrical discharge between the two ends of the fibres to be joined.

The fibre connectors offer flexibility and ease of assembly. In a developmental system, this is a great advantage. It makes it much easier to experiment with various components to determine how the performance of the system is affected. The three main types of fibre connectors are FC/PC, SC and ST. Their optical characteristics are similar. The former has a metal housing while the later two have a plastic housing. An FC/PC connector adds $20 to $30 per fiber to the cost of a fibre splitter. A loss of 0.3 dB can be achieved if the mechanical tolerance is 5 μm for a MMF and 1 μm for a SMF. This assumes that the end faces are in contact, thereby eliminating the 0.36 dB reflection loss. Connectors are also available for fibre ribbon cables (8 and 16 fibres). Their coupling losses tend to be higher, in the neighborhood of 0.5 dB.

Reflections can affect the operation of diode lasers. When connectors are used, the reflection at the interface can be reduced either by making sure that the two fibre tips are in contact or by the use of beveled faces. Direct contact can reduce the reflection to values below –30 dB while angled facets such as those used in the FC/APC connector can achieve reflection losses of –40 dB [ref. 3, p. 737].

In summary, fusion splices offer the best performance with excess loss near 0 dB and excellent reliability. However, ribbon connectors have significant advantages for construction of a large system. These include relatively low assembly cost and ease of repair.

Table 10: Interconnection Losses Using Commercial Splitters

(Assumes all interconnections between splitters use fusion splices with near zero additional loss)

Split Ratio	Ideal Splitting Level (assume no loss) (dB)	Commercial Splitters Required	Total "Loss" per Output Channel (dB)	Additional/Excess Optical Loss per Channel (dB)	Cost per Splitter Chain ($US)
1:480	-26.8	1:16+16x1:32	14.5+18	5.7	19800
1:192	-22.8	1:3+3x1:2+6x1:32	5.8+3.8+18	4.8	7370
1:96	-19.8	1:3+3x1:32	5.8+18	4	3680
1:48	-16.8	1:3+3x1:16	5.8+14.5	3.5	2030
1:40	-16	1:5+5x1:8	8.2+10.8	3	1900
1:32	-15.1	1:32	18	2.9	1200
1:24	-13.8	1:3+3x1:8	16.6	2.8	1130
1:16	-12	1:16	14.5	2.5	650
1:8	-9	1:8	10.8	1.8	350
1:4	-6	1:4	7.2	1.2	125
1:3	-4.8	1:3	5.8	1	80

Note: Must add an additional 0.25 dB loss per connector per channel if connectorised components are used

4 Microwave Signal Distribution using Fibre-Optic Networks

4.1 *Possible Architectures*

In the previous section, a wide variety of different optoelectronic and optical devices and components were identified that can be used to optically distribute an RF signal. The choice of the particular components used within any phased array antenna architecture will depend, to a great extent, on the other components that are to be used within the network. For example, the use of a high power CW Nd-YAG laser as the optical source requires the use of some form of intensity modulator to launch the RF signal. If laser diodes are used, they can be directly modulated, so that external modulators may not be necessary. Similarly, if a laser diode based system is used, it is possible to use large multimode fibers, provided the transmission distance is not too large. However, if electro-optic modulators are required, coupling to the laser source will require single mode, polarisation maintaining fibre. In the following section a number of possible architectures that can be used for optical signal distribution will be discussed and preliminary systems issues such as cost, performance and reliability will be examined.

4.1.1 Parallel Feed Network

In general, the distribution of the Parallel Feed signal is reasonably straightforward. A signal at 1.6 GHz is distributed, in parallel, to all 3840 of the antenna's T/R modules, where it is detected and then mixed with the 3.7 GHz Sequential Feed signal to produce the 5.3 GHz signal, with appropriate phase, that will be broadcast from the module's radiating element. While this may appear relatively simple, the challenge is to ensure that the parallel signal delivered at each of the 3840 T/R modules will have exactly the same phase, and that there is sufficient received optical power to meet the antenna's signal-to-noise specifications. In Appendix 1, ten possible architectures that can be used to implement a Parallel Feed network are illustrated. The cost, power consumption, received power, device count, etc. for these designs is then listed in Table 11.

The first seven designs, use the Fujitsu FLD3F7CX, a laser diode with a 20 mW output at 1.3 μm, as the optical source. The choice of a semiconductor laser has a number of advantages. First, it can be directly modulated, eliminating the need for an additional external modulator and thereby reducing device count, system complexity, etc. and with a 3 dB bandwidth of 4 GHz, it is suitable for operation at both the 1.6 GHz of the Parallel Feed Network and the 3.7 GHz of the Sequential Feed Network. The Fujitsu device is also the highest power laser diode currently available at either 1.3 μm or 1.55 μm.

In design P-1, a total of 8 Fujitsu lasers are used to distribute the Parallel Feed signal to the T/R modules, with each laser feeding 480 elements. In this situation, a 1:8 microwave splitter must first be used to distribute the microwave Parallel Feed signal to the 8 lasers with their associated matching circuitry. The output from each laser is then divided equally among 480 elements using a 1:480 optical splitter chain, such as the one listed in Table 8. Assuming a maximum optical signal of 20 mW DC from each laser with 100 % modulation at 1.6 GHz, the maximum received signal at each T/R module is only 8.9 μW or -20.3 dBm. The cost of the optical/optoelectronic components used in this design is $174,000 US, based on a cost of $2000 US per laser diode and $19,800 US per 1:480 splitter chain. In the loss estimates, it is also assumed that fusion splices with no excess loss are used throughout. In this design, the magnitude of the signal delivered to each detector is relatively low, corresponding to detector output of only -66 dBm electrical (assuming a detector responsivity of 0.7 A/W). As a result, considerable electrical amplification could be required to bring it up to a level sufficient to drive subsequent mixer and output stages.

Table 11: Part Count and Costs of Selected Laser Based Transmitter Configurations

Parallel Feed @ 1.6 GHz

Design No.	No. of 20 mW Laser Diodes	No. of EDFAs/SOAs	No. of Splitters	Maximum Received Optical Power at Detector (dBm)	Cost ($K US)	Power Consumption (W)
P-1	8	-	8(1:480)	-20.3	174	1
P-2	40	-	40(1:96)	-11.3	227	4
P-3	96	-	96(1:40)	-6.8	374	11
P-4	192	-	192(1:20)	-3	436	21
P-5	384	-	384(1:10)	-1.5	837	42
P-6	2	96	2(1:48) 96(1:40)	-4.9	1630	480
P-7	3	120	3(1:40) 120(1:32)	-2.5	1956	600

Design No.	No. of YAG Lasers	No. of E-O Modulators	No. of Splitters	Maximum Received Optical Power at Detector (dBm)	Cost ($K US)	Power Consumption (W)
P-8	1 @1.06μm 250 mW	8	8(1:480)	-23.3	226	35
P-9	1 @1.06μm 5 W @1.06μm	96	1(1:96) 96(1:40)	-11.1	646	200
P-10	20 @1.3μm 200mW	20	20(1:192)	-9	837	500

Notes:

Cost of 20 mW Fujitsu Laser: $2K US
Cost of UTP E-O Modulator: $4-7K US
Cost of MPB Low Power EDFA: $19K US Max. Input Power of EDFA: -4 dBm
Cost of MPB High Power EDFA: $32K US Max. Input Power of EDFA: -4 dBm
Cost of High Power YAG Laser @1.3μm: $28K US
Cost of High Power YAG Laser @1.06μm: $28 Power Consumption: 20W

In designs P-2 through P-5, the number of laser diodes sources are increased so that the splitting of the 20 mW output from each diode can be reduced and hence the power to the detectors at each antenna element can be increased. For example, in design P-2, 40 lasers are used corresponding to one feed laser per array column. In this case the modulated 20 mW is only split to 96 detectors, and the maximum received power at each detector is only -11.3 dBm optical, corresponding to an rms photodetector output of -48 dBm electrical. Using 96 lasers, one per row, as in design P-3 the rms photodetector output increases to -39 dBm and if 384 are used, 4 per row or 1 laser per 10 T/R modules, the rms photodetector output is -28 dBm requiring a single 25 dB gain block to bring it up to levels sufficient to drive a mixer. These results are listed in Table 11. As the number of lasers is increased both the cost and power consumption of the Parallel Feed Network increases from $174K and 1 Watt for the 8 laser case to nearly $840K and 42 Watts for the design that uses 384 lasers.

If smaller numbers of lasers are used, optical amplifiers can be used to boost the received signal at the final photodetectors. Two examples using a combination of 20 mW laser diodes and optical amplifiers are shown in designs P-6 and P-7 and the corresponding system parameters are listed in Table 11. In both cases, the maximum input power allowed to the EDFAs or SOAs is -4 dBm optical and the maximum output is +15 dBm optical. Using design P-6 with only 2 lasers and 96 EDFAs, the output of each must be split to 40 photodetectors, the maximum DC received optical power -4.9 dBm, corresponding to a detector output power of -35 dBm electrical. Using 3 lasers and 120 amplifiers, the photodetector output can be increased to -30 dBm and again would only require a single 25 dB gain block to bring the signal up to levels necessary for the mixer stage. Unfortunately, at present optical amplifiers are expensive, typically $15 - $20K US each, considerably more than a laser diode. As a result, the cost of design P-7, which gives a similar detector output as an all-laser diode design costing $840K US, is nearly $2000K US. Fibre amplifiers are also power hungry, requiring nearly 5W per amplifier. As a result design P-7 would consume approximately 600 W of power. It must be noted that while the cost and power consumption of the optical amplifier design are considerably higher, this type of design is probably easier to implement from an RF point-of-view. The all-laser design with 384 laser diodes would require splitting and distribution of the RF drive signal to 384 lasers using microstrip or waveguide. This could be quite a complex process in itself. With the optical amplifier design, the RF drive needs only be distributed to three different lasers, considerably reducing the need for microwave splitters and laser matching circuitry.

Designs P-8 through P-10, illustrate the use of solid state lasers such as the Nd-YAG laser. P-8 uses a single "medium-power" laser producing about 250 mW at 1.06 μm. Since solid-state lasers can not be directly modulated, high frequency electro-optic modulators such as the one sold by UTP must be used. In this design, the laser output is first split into 8. Each of these 8 beams then feeds an E-O modulator (with about 4 dB of insertion loss). The output of each modulator is then split to 480 of the antennas T/R modules. In this situation the maximum DC optical power at each detector is 4.7 μW or -23.3 dBm optical. This would then produce a photodetector output signal of only -72 dBm electrical. Design P-9 makes use of a high power industrial laser, with an output of 5 Watts at 1.06 μm. Since, at this wavelength, the maximum input power that can be handled by the E-O modulator is 50 mW, the laser output must be split into 96 beams, corresponding to 1 modulator per row. The output of each modulator is then divided equally among 40 T/R modules. The maximum received power at each module is -11 dBm optical in this case, corresponding to an rms detector output of -47 dBm electrical. The photodetector output in this case is 25 dB larger than the previous design, eliminating the need for at least 1 gain block of post amplification in each T/R module, however the cost of the network also rises from $226K US to $646K US and the power consumption from 35 Watts to 200 Watts. Design P-10 makes use of the fact that at longer wavelengths, E-O modulators can tolerate significantly higher input powers. For example, while the maximum optical input power at 1.06 μm is 50 mW at 1.3 μm, the modulator can handle 200 mW. In Design P-10, 20 "medium-power" Nd-YAG lasers with 200 mW of output power operating at 1.3 μm, are used as the optical sources. Each laser is directly coupled to an E-O modulator, the output of which is then split to 192 T/R modules. In this case, while 20 lasers are used, the RF drive circuitry is simplified from the previous case where 96 modulators were used. With this design, the maximum received optical power at each detector is increased to -9 dBm optical, corresponding to -43 dBm electrical. While the cost and power consumption are relatively high ($840K US and 500 Watts respectively) it is relatively simple to implement requiring a relatively small number of optical and RF splitters and RF drive circuitry.

The 10 designs described above are only a few of the possible ways of optically implementing a Parallel Feed Network. They do however, give an insight into some of the issues, such as cost, signal-to-noise and power consumption that will have to be considered when any such network is to be constructed. In actual fact, the choice of a final design will be a trade-off between cost, complexity, and performance of both the optical and RF components used in both the payload and the T/R modules. For example, it may be considerably cheaper to build in a number of stages of post-detection amplification into the T/R modules, than to use larger numbers of laser diodes or optical amplifiers as a means of boosting the signal strength at each module. On the other hand if the signal-to-noise has been seriously degraded at the end of the optical distribution network, optical amplifiers may be the only means of maintaining signal integrity. All of these factors will have to be studied in detail prior to choosing which design will provide the best performance at the lowest cost.

4.1.2 Sequential Feed Network

While the distribution of the Parallel Feed is relatively straightforward (ie: basically distributing the same signal to all of the T/R modules), the distribution of the Sequential Feed is a bit more difficult. In this case, the 3.7 GHz signal must be fed to each of the 40 columns in the array, however the phase of each of these signals must be carefully controlled so as to obtain a beam with the required shape and orientation. The across-track phase setting (across the 96 rows) is then specified by a passive differential delay network. In Appendix 2, four possible architectures are shown that could be used for distribution of the 3.7 GHz Sequential Feed signal, and in Table 12, parameters such as optical loss, received optical signal, cost and power consumption of the various designs are given.

Design S-1 is probably the simplest means of implementing the Sequential Feed network. In this design, the RF drive is divided and used to directly modulate 40 semiconductor lasers, one for each column. The phase of the signal to each of these lasers is set by a separate phase shifter in the laser driver circuitry, which is controlled by the system's computer. The individual laser signals are then divided amongst the 96 T/R modules of that column via a differential optical delay network. The laser used is once again, the Fujitsu FLD3F7CX. However, since the 3-dB bandwidth of the device is only 4 GHz, the 20 mW output measured at 1-2 GHz, is reduced to only 10 mW. After splitting 1:96, the maximum DC optical power delivered to each T/R module is 42 μW or -13.8 dBm optical, corresponding to an rms photodetector output of -53 dBm electrical. Two 25 dB post-detector gain blocks could bring this up to -3 dBm, sufficient for a subsequent mixer stage. This design uses relatively little power (4 Watts) and would cost only $227K US, two-thirds of which represents the cost of the 1:96 splitters themselves. To increase the received power at each T/R module it would be necessary to increase the laser count. In Design S-2, each column is divided into 4 subgroups of 24 modules each with one laser feeding each subgroup. As in the previous case, the phase setting within each subgroup is set by a linear optical differential array, however now an additional 3 RF phase shifters must be added to control the relative phase of each subgroup. In total the network now contains 160 lasers and an additional 120 RF phase shifters. The maximum power received at each module is 220 μW or -6.6 dBm optical, producing an rms photodetector output of -38 dBm. The additional 15 dB of photodetector signal comes at the cost of an additional $273K US, with the final price of $500K US being more than twice the price of the original design. It also comes at significantly higher

Table 12: Part Count and Costs of Selected Laser Based Transmitter Configurations

Sequential Feed @ 3.7 GHz

Design No.	No. of 20 mW Laser Diodes	No. of EDFAs/SOAs	No. of Splitters	Maximum Received Optical Power at Detector (dBm)	Cost ($K US)	Power Consumption (W)
S-1	40	-	40(1:96)	-13.8	227	4
S-2	160		160(1:24)	-6.6	501	18

Design No.	No. of YAG Lasers	No. of E-O Modulators	No. of Splitters	Maximum Received Optical Power at Detector (dBm)	Cost ($K US)	Power Consumption (W)
S-3	20 @1.3μm 250 mW each	80	20(1:4) 80(1:48)	-7.5	1085	500
S-4	1 @1.06μm 2W o/p power	40	1(1:40) 40(1:96)	-13.8	357	25

Notes:

Cost of 20 mW Fujitsu Laser: $2K US
Cost of UTP E-O Modulator: $4-7K US
Cost of MPB Low Power EDFA: $19K US Max. Input Power of EDFA: -4 dBm
Cost of MPB High Power EDFA: $32K US Max. Input Power of EDFA: -4 dBm
Cost of High Power YAG Laser @1.3μm: $28K US
Cost of High Power YAG Laser @1.06μm: $28 Power Consumption: 20W

part count, with an additional 120 phase shifters, 120 lasers and 120 optical splitters required. Increasing the received power at the detectors by adding additional lasers further increases the complexity, cost and part count, with relatively small improvements in detector output. For example, using 320 lasers (8 per column), would also require active control of 320 phase shifters and would cost an additional $300K US, while only increasing the T/R module's photodetector output from -38 dBm to -30 dBm.

Design S-3 illustrates how the network could be implemented using twenty 1.3 μm Nd-YAG lasers. Once again, E-O modulators must be used to obtain the RF modulated optical signal. The 250 mW output of each laser feeds 4 modulators, 2 per column requiring a total of 80 RF phase shifters. Each of the modulator outputs then feeds 48 T/R modules. Using this arrangement, a maximum DC signal of 180 μW, -7.5 dBm optical, can be supplied to each T/R module, resulting in a detector output of -40 dBm electrical, which is roughly equivalent to that obtained using 160 laser diodes. The cost however is nearly $1.1M US, twice that of the semiconductor laser network. As well, the 20 medium-power YAG lasers consume approximately 500W of electrical power.

Design S-4 is quite similar to the first of the semiconductor laser designs, S-1. In this case a single high power (2W) Nd-YAG laser feeds 40 E-O modulators which in turn feed 96 T/R modules. The design requires only 40 RF phase shifters, 40 E-O modulators, 40 optical splitter chains and a single YAG laser. The maximum received optical power at the detector of the T/R module is -14 dB optical, corresponding to detector output of -53 dBm. The performance of the S-4 network is almost exactly the same as Design S-1 which uses 40 laser diodes, however the cost is $357K US or 57% higher.

There are many more designs possible and as discussed in the section on the Parallel Feed Network, optical amplifiers can be used to increase the signal delivered to the individual T/R modules. Unfortunately, with a maximum input power of only -4 dBm optical, it would be difficult to find a cost effective way of incorporating optical amplifiers into a Sequential Feed design.

4.2 *Phase uniformity – Length tolerance*

The shaping of the microwave beam by the phased-array antenna requires very good control of the phase at each of the T/R modules. In ref. 1, p. 4, the phase uniformity requirement for the pulse is quoted as ± 0.5 deg. This imposes strict constraints on the accuracy of the respective fibre length.

Let us evaluate the length variations allowed while still maintaining the proper phase. The number of amplitude modulated RF cycles over an optical length of fibre is given by

$$\phi = k\, n\, L \qquad (1)$$

Where
k: propagation constant in free space. For ν=3.7 GHz, then k=3.7 E9 s^{-1} / 3 E8 $m\text{-}s^{-1}$ = 12 m^{-1}
n: refractive index of the optical medium, in this case 1.4585 for vitreous silica
L: fibre length

The phase change in degrees with respect to a change in length is given by the derivative:

$$d\,\phi = 360\ k\, n\, dL \qquad = 360 * 12 * 1.4585\ dL$$

Hence, to maintain the phase within ±0.5 deg, the length must be determined with an accuracy of

$$dL = 0.5 / (360 * 12 /m * 1.4585) = \pm 80\ \mu m$$

Furthermore, the phase delay is affected by the fibre temperature. Taking the derivative of eqn 1 with respect to the temperature T gives

$$\frac{d\phi}{L\,dT} = k\,n\,\frac{dL}{L\,dT} + k\,\frac{dn}{dT} \qquad (2)$$

For vitreous silica, the refractive index dependence has been shown to be negligible[8]. The main temperature effect is due to the thermal expansion. For vitreous silica

$$\frac{dL}{LdT} = 5\ E\text{-}7/°C$$

Then, the phase change per unit length is

$$\frac{d\phi}{LdT} = 360 * 12 /m * 1.4585 * 5\ E\text{-}7 /°C = \frac{3.15\ E\text{-}3\ deg}{°C\text{-}m}$$

The distance from the antenna centre to one of the corners is approximately 9 m. Therefore

$$\frac{d\phi}{dT} = 9\ m * \frac{3.15\ E\text{-}3}{°C\text{-}m}\ deg = \frac{2.84\ E\text{-}2\ deg}{°C}$$

A phase error of ±0.5 deg is avoided if the temperature difference is kept

$$dT < 1\ deg / 2.84\ E\text{-}2\ deg/°C = 35\ °C$$

Therefore the temperature difference between fibres must be kept within 35 °C. This phase change adds to the phase inaccuracies due to length difference at a constant temperature so that the phase error specifications may be exceeded before this temperature difference is observed.

This may be an opportune point to discuss how one can approach the challenge of cutting 7680 fibres to an optical length of 9 m within ±80 μm, including the fibre lengths through the fibre splitters. The 80 μm corresponds to one fifth of the typical thickness of a semiconductor wafer. It may not be possible to do it with a ruler and cleaver. There are points in the circuit where additional errors are likely to be introduced such as when fusion joints are made or when the fibres are positioned in front of the photodetectors. One might consider some active measurement of the optical length using an OTDR. A good resolution commonly available from many suppliers is 25 cm. Only Opto-Electronics Inc specifies their OTDR as having a resolution as good as 0.2 mm. Note that this is not an absolute accuracy. It only means that if two features are present, they can be distinguished if they are 0.2 mm apart. Taking this into account, the optical fibre cutting could proceed as follows. First, the fibre would be cleaved approximately to a length exceeding the desired length by a few centimeters. Then, the phase delay would be measured actively using a network analyzer. The deviation from the desired phase delay would then be used to determine the length of fibre that needs to be cut back. We estimate that the new cleave can be positioned at best within ±0.5 mm of the desired position, using the existing techniques. This represents a phase accuracy of ±3.2°.

An alternative to fabricating the fibre network with very accurate lengths is to relax the constraints for absolute fibre lengths but to include hardware that would allow dynamic adjustment of the optical delay to the individual T/R modules. This could be done in a number of ways:

1- Mechanical adjustment of the fibre distance from the photodetector surface
2- Switchable optical delay loops such as could be implemented with surface waveguides and thermal optical switches (Akzo Beambox, for instance).
3- Adjustable optical delay provided by heating element such as a resistive wire running along each fibre.
4- Adjustable optical delay provided by a surface waveguide made of an electro-optic material such as $LiNbO_3$ and controlled by an electric field.
5- Adjustable electronic delay in the T/R module circuitry.

Maintaining a constant phase at the T/R module will be a challenge considering the strict phase constraints and the variations in ambient conditions.

4.3 *Long Term Reliability*

Optoelectronic/optical device technologies have matured rapidly and now long-haul fibre links criss-cross virtually all of the world's continents and oceans. Many of these applications require that the components used (ie: laser diodes, photodetectors, integrated electronics, etc.), must function under a wide range of environmental conditions and for long periods of time. These transcontinental and transoceanic links cost many hundreds of millions of dollars and carry hundreds of thousands of telephone calls, and billions of bits of data, every second between homes and businesses in towns, cities and countries around the world. While the repair costs associated with locating and repairing a fault in an undersea cable would be enormous, it is the loss of service and service revenues that would be most critical for the telecommunications providers. As a result, telecommunications companies require very strict performance testing and demanding reliability standards. In many cases, the reliability criteria will meet or exceed those used for military applications. For example, Fujitsu test requirements for their lightwave components (laser diodes, pin photodetectors, repeater modules, etc.) meet or exceed those used for MIL-STD-750 and MIL-STD-883 and include tests such as a 1000 hour burn-in at 50% of rated output power, vibration and shock testing and temperature cycling to ensure that their devices and components perform reliably for extended periods. To ensure such high reliability, exhaustive reliability testing studies have been carried out and new semiconductor materials and structures have been developed that enable the fabrication of devices with CW lifetimes of 10^5-10^6 hours and Alcatel specifies a 15 year lifetime for their high power, 50 mW laser diodes.

Fibre optic systems have clearly demonstrated that they can meet all of the strict reliability criteria demanded by advanced terrestrial telecommunications networks and while there has been relatively little testing carried out for specific space-based applications, it appears that these devices and components would meet or exceed most if not all of the requirements for a satellite mission. The one aspect of a space-based application that differs from the conditions that may be experienced on Earth is exposure to radiation. Some work has been carried out at CRC recently to investigate the effects of ionising radiation such as neutrons, protons, and high energy electrons on the lifetime of carriers in light emitting diodes and some effects have been observed, however the exact effects on device performance (laser threshold current, detector dark current, etc.) are unknown It appears that lattice damage is the major problem, however this requires energetic particles such as neutrons and protons. While observable, this effect appears to be relatively small, and it is likely that appropriate shielding would be effective as a means of reducing or eliminating negative effects on component performance.

5 Future Directions/Trends/Improvements

As the demand for communication and data services continues to grow, fibre-optic and optoelectronic device and components technologies will continue to evolve. This is illustrated by the rapid development of advanced wavelength division multiplexing systems that combine many different optical wavelengths onto a single fibre to enable higher data rates without having to increase the speed of the system's signal processing electronics. The stringent wavelength requirements of WDM have meant that new laser structures had to be developed so that the emission wavelength can be maintained extremely accurately. As well, very narrow band wavelength selective splitters and combiners, add/drop units, and wideband optical fibre amplifiers have had to be developed so that different wavelengths can be routed to their appropriate input/output ports. It can be expected that increased demand and new applications will lead to similar improvements, particularly in the area of short haul "photonic-wireless" with RF-on-fibre signal distribution. This will require the development of low cost, high power lasers that have output powers in excess of +10 dBm and that can be directly modulated at frequencies of 10 GHz or higher. As well, low cost, wideband receivers will be required that incorporate high speed, low noise photodetectors with both post-amplification and some level of signal grooming/processing. This integration of many optical and electronic functions onto a single chip will lead to considerable gains in functionality and performance, while also reducing components size, weight and cost and improving device ruggedness and long term reliability.

5.1 Improvements in Packaging

One of the key issues at present in virtually all applications of optoelectronic/optical devices and components is packaging. For practical applications, components such as lasers, photodetectors, phase modulators, etc. may require packages that are application specific. For example, current commercial laser diodes consist of a laser chip that is packaged with its own monitoring photodiode, a thermistor and Peltier coolers. While this allows excellent control and uniformity of device temperature, in an application where many laser diodes are being used, provision would have to be made in the system controller to monitor and control all of the individual devices, necessitating additional control lines and programming complexity. In a practical system, it would be advantageous to mount a number of laser diode chips on a single block. This would then require only one temperature monitor with associated temperature control hardware, reducing the size, cost and power consumption of the laser assembly.

The assembly and packaging of optical fibres and optical interconnects is always a challenge. The use of planar lightwave circuits and in particular polymer-based interconnects such as those being developed at CRC offers considerable promise, both for lower cost, improved performance and increased reliability and ruggedness. Other such work includes the "LIGA" process at the Institut fur Mikrotechnik Mainz[9]. It involves the definition of guide patterns in thick photoresist then electro-forming to define a positive image. The latter is then used as a mold in an injection molding process. They have demonstrated the fabrication of 2x2 single-mode guide splitters which include snap-fit slots for the fibres, making it extremely easy to attach the fibres to the splitters with the required alignment accuracy. These techniques have a great potential for reducing the fabrication cost of fibre optic components.

5.2 New Devices, Lower Cost

This complex optical distribution system offers great potential for integration. For the C-band antenna, a minimum of 41 modulated light sources are required, one for the parallel feed and 40 for the sequential feeds. Integrating these 41 lasers monolithically would have many benefits. This IC chip could be mounted on one plate with a single cooler/ heater and temperature controller. This would reduce the complexity of the electronics dedicated to maintaning a constant laser temperature. Further integration could include laser biasing and driving circuitry plus impedance-matching elements. The techology for the fabrication of SOA has improved. These optical amplifiers could be integrated on the same wafer as the laser since the semiconductor layer structures are very similar. Similarly, SOA-compatible photodetector structures could be developed such that a monolithically integrated detector/optical amplifier circuit could be used at each T/R module. This could greatly reduce the high cost presently associated with using optical amplifiers, and would significantly enhance the SNR at each of the 3840 T/R modules.

The research effort at CRC to develop polymer optical waveguides has been very successful. This technology could be used to fabricate on the same wafer the complex optical branching tree that will deliver one optical signal to up to 3840 photoreceivers at the T/R modules. This would offer great savings in space and would simplify the assembly greatly. This integration would give better performance at a lower cost.

There is also potential for further integration at the T/R module. Two photoreceivers and a mixer must be assembled at each T/R module plus a circulator and a power amplifier. The MSM is a photodetector which lends itself easily to integration with other semiconductor devices such as MESFETs because of its very simple structure. Such integration was demonstrated in a 3x3 OE switching array designed at CRC and fabricated at Nortel. This unit integrated on one chip nine MSMs with three transimpedance amplifiers[6]. There is no apparent reason why additional circuits elements such as a mixer and a phase controller could not be added to such an IC. Again, CRC's polymer waveguide technology could be included. This technology was used to demonstrate a 4x4 OE switch that integrated monolithically 16 MSMs and four waveguides[7]. The four waveguides deliver the optical input signal to four MSMs each. Even further integration could be envisioned. For example, since the return path for the radar signal will require the generation of an optical signal at each T/R module, the laser and driving circuitry could be integrated on the same wafer as the photoreceiver. The benefits would be reduced cost and improved reliability.

It would be tempting to use wavelength-division-multiplexing (WDM) in order to distribute both the parallel and sequential signals to the individual T/R modules via the same fibres. However, the phased-array antenna architecture proposed by Belisle et al[1] requires that the parallel distribution network provides equal delay to all the T/R modules while the sequential distribution network implements a controlled increase in delay for the elements along one column. A possible implementation of WDM would see one wavelength used in transmit mode and a second in receive mode. This would allow bi-directional signal distribution from the payload to the antenna without any problems related to crosstalk, optical reflections, etc. It might also be possible to use WDM to multiplex the optical control signals for the L-band and C-band antennae.

6 Conclusion and Recommendations

The use of advanced optical and optoelectronic devices and components in next generation phased array antenna systems offers considerable promise for improved functionality and performance, lower cost, reduced weight, and ease of construction and deployability, particularly for satellite-based systems. With the tremendous advances in device and component technology that have accompanied the rapid expansion of long-haul and local fibre-optic communications networks, there are now commercially available high power, broadband semiconductor lasers, high speed optical intensity and phase modulators, optical amplifiers, low loss, low cost optical combiners and splitters and high responsivity photodetectors that can be used to implement antenna functions such as microwave signal generation, signal mixing, phase modulation and microwave signal distribution, with performance comparable to or better than conventional microwave techniques. Further progress in device integration using technologies such as polymer planar waveguides, monolithically integrated optical pre-amplifiers, photodetectors and post-detection circuitry promises to further improve performance, lower device count, improve reliability, lower cost and lower power requirements and will enable the construction of optically controlled phased array antenna systems with significantly improved performance, for both terrestrial and space-based applications.

To further investigate issues related to the performance and fabrication of optically controlled antennae, it is recommended that a Phase II of this work be initiated. In this phase, a number of simple architectures would be investigated in detail. This investigation would make use of the information described in this report to choose specific device, component and sub-system strategies. For example, 2 possible strategies could be the following: the first would use high power, directly modulated semiconductor lasers operating at 1.55 μm. To keep costs at a minimum, optical amplifiers would not be used throughout the array, however, these could be used along one or more of the output lines to investigate the performance improvements that can be obtained if optical pre-amplification is used. The second design would incorporate semiconductor lasers operating at 1.55 μm in the CW mode, feeding a series of RF-modulated electro-optic modulators. The advantage of this configuration is that while it may have higher cost, it allows operation of the antenna to frequencies beyond 10-20 GHz, without the need for complex RF multiplier circuitry. Performance analysis of these 2 configurations would include in-depth end-to-end numerical modelling and simulation to study critical performance parameters such as signal-to-noise ratio (SNR), phase uniformity across the antenna, antenna bandwidth, the advantages of optical and/or electrical amplification, as well as critical packaging issues such as control of fibre length, optical coupling losses, optical/electrical integration within the T/R modules, etc.

If the results of the design and simulation phase are promising, a Phase III would be then be initiated. In this Phase III, work would include the construction of a 20-40 element prototype array that could be used to evaluate the performance of various aspects of the array. This prototype would also serve as a testbed which could be used to evaluate advanced optical and optoelectronic components being developed at CRC such as AlInAs/InGaAs/InP long wavelength MSMs and low cost polymer splitters and optical interconnects. By assembling this testbed, it should be possible to identify critical issues related to the design, fabrication and performance of an optically controlled phased array antenna and thus gain valuable insight into the technologies that will be required to build a practical, large antenna array for either terrestrial or satellite applications.

7 References

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Appendix 1:

Possible Designs

that Could be Used For

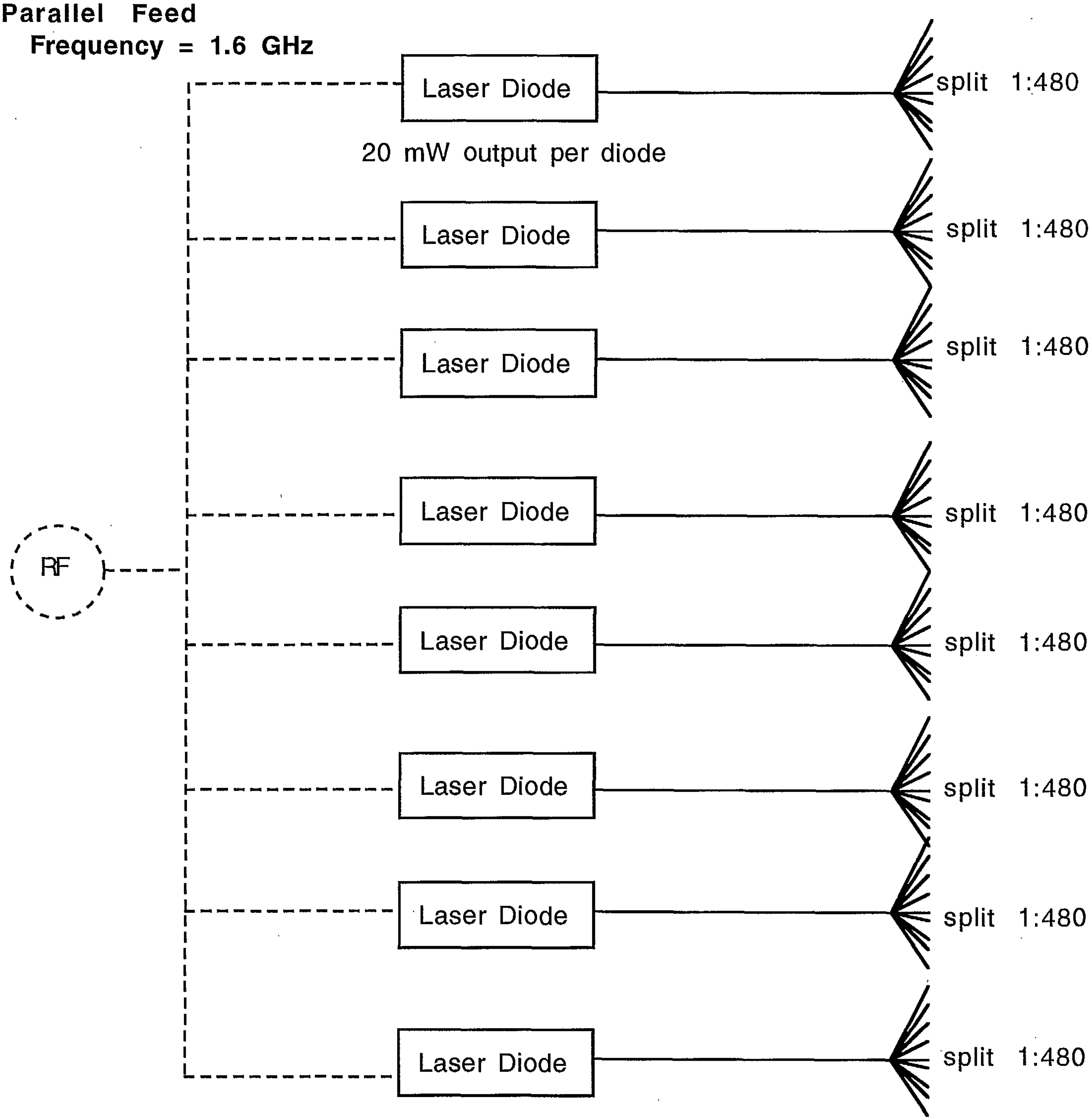
Parallel Feed on Transmit Side

at

f=1.6 GHz

Design P-1 Directly Modulated Laser Diodes

Parallel Feed
Frequency = 1.6 GHz



(Price =$2 K each)

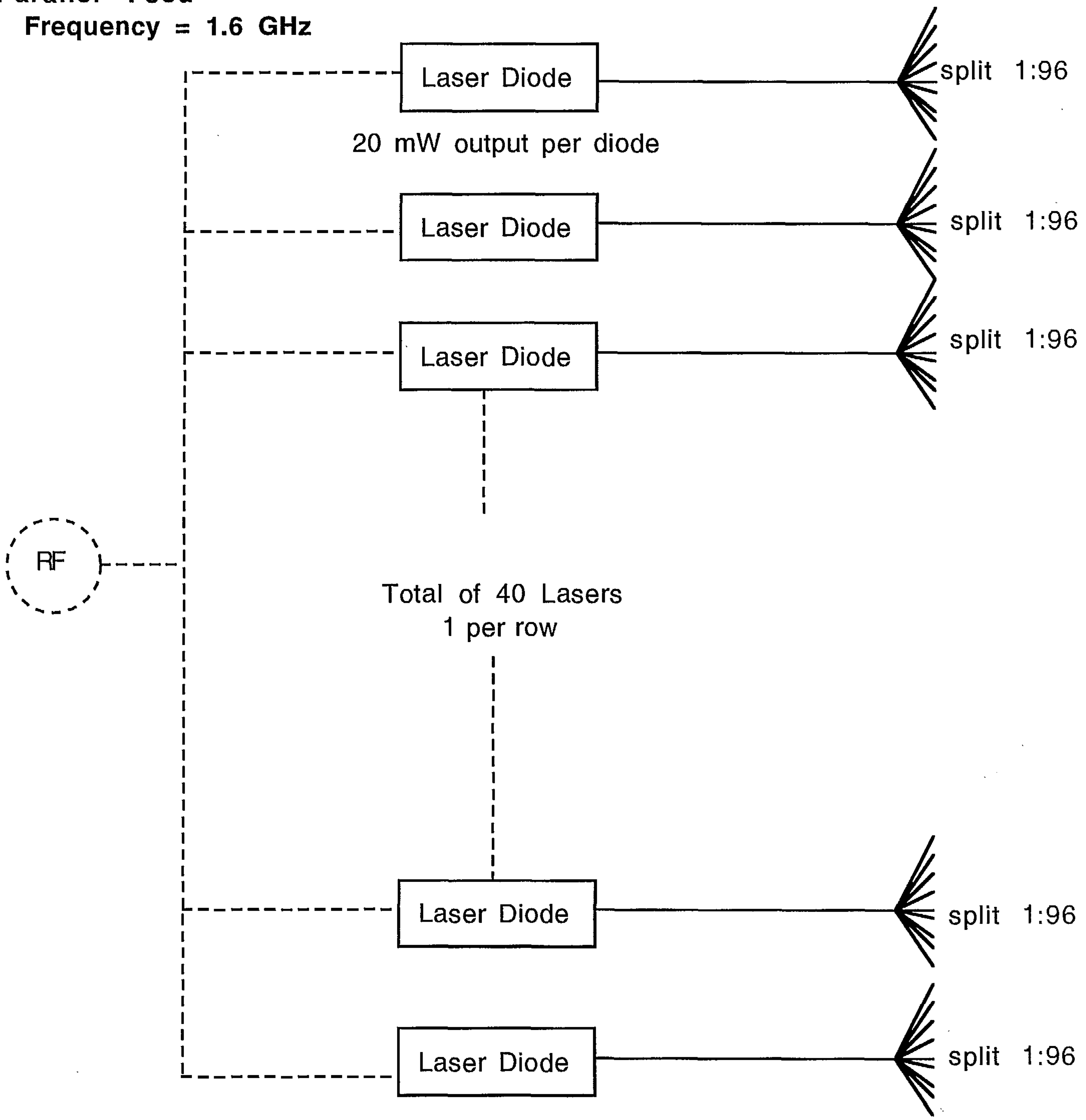
Total Price = $174 K

Power per detector
= - 20.3 dBm

Note: Lasers mounted in pigtailed butterfly packages with integrated thermoelectric coolers and power monitoring.

Design P-2 Directly Modulated Laser Diodes

Parallel Feed
Frequency = 1.6 GHz



(Price =$2 K each)

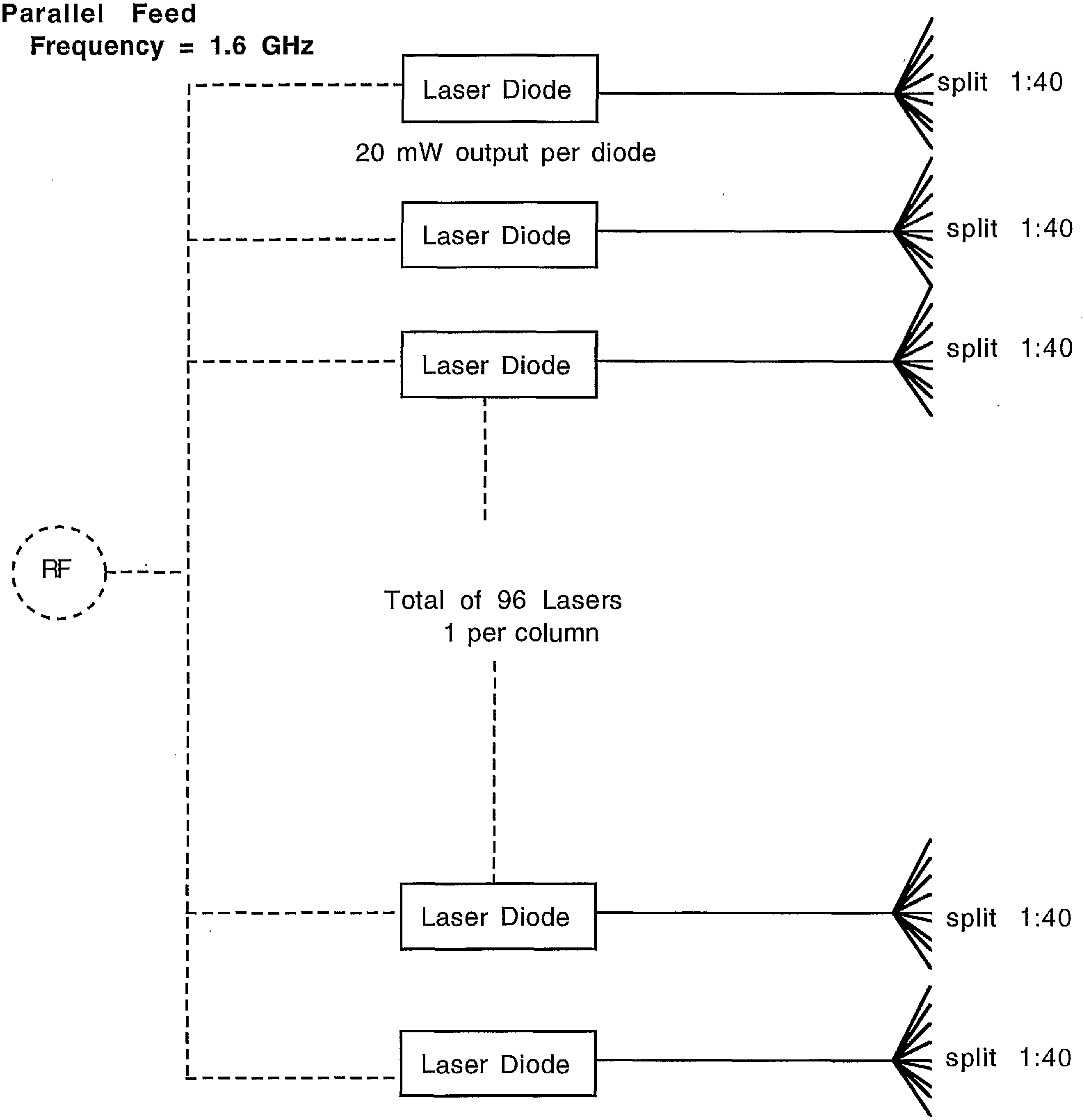
Total Price = $227 K

Power per detector
= - 11.3 dBm

Note: Lasers mounted in pigtailed butterfly packages with integrated thermoelectric coolers and power monitoring.

Design P-3 Directly Modulated Laser Diodes

Parallel Feed
Frequency = 1.6 GHz



(Price =$2 K each)

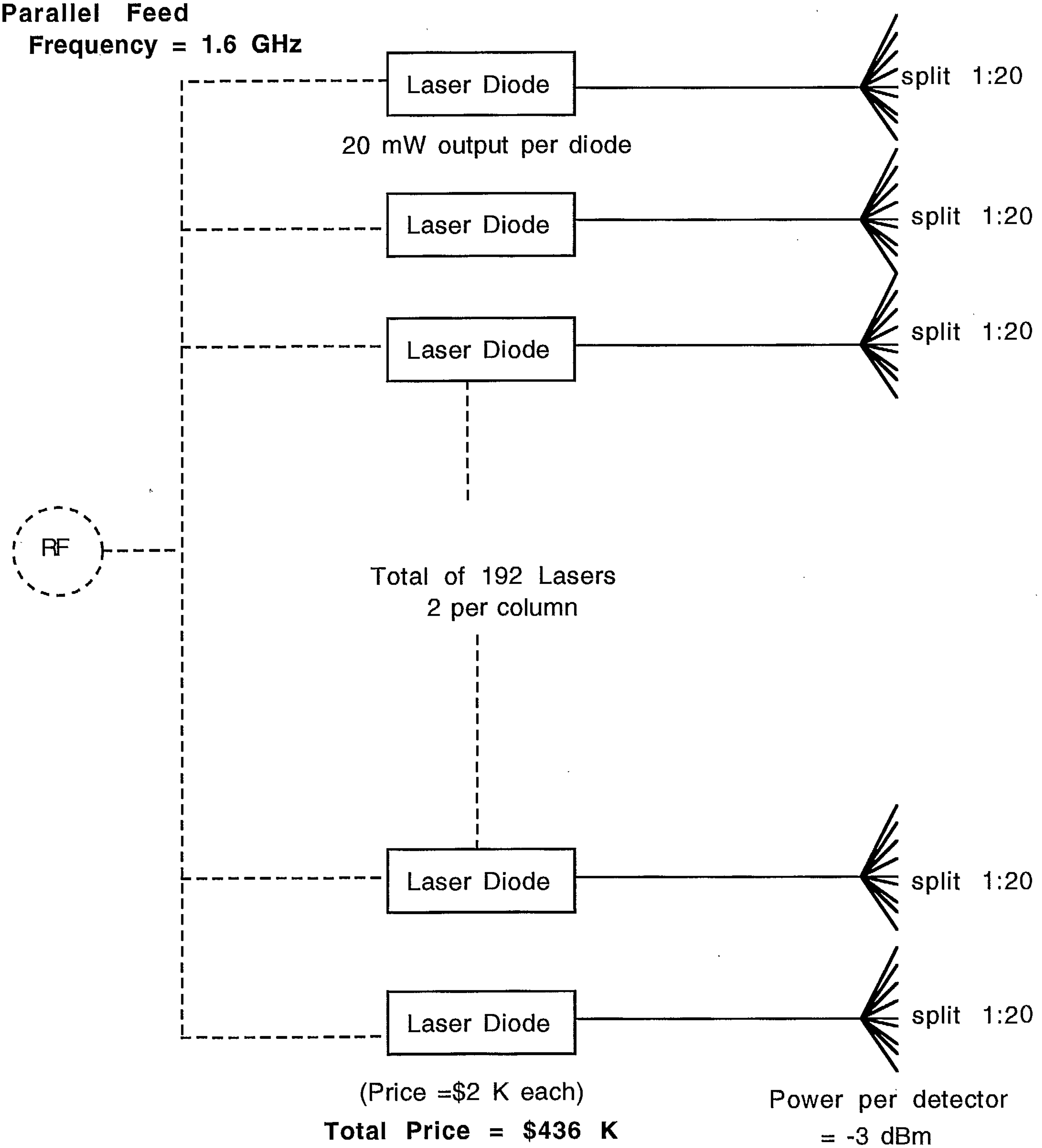
Total Price = $374 K

Power per detector = -6.8 dBm

Note: Lasers mounted in pigtailed butterfly packages with integrated thermoelectric coolers and power monitoring.

Design P-4 Directly Modulated Laser Diodes

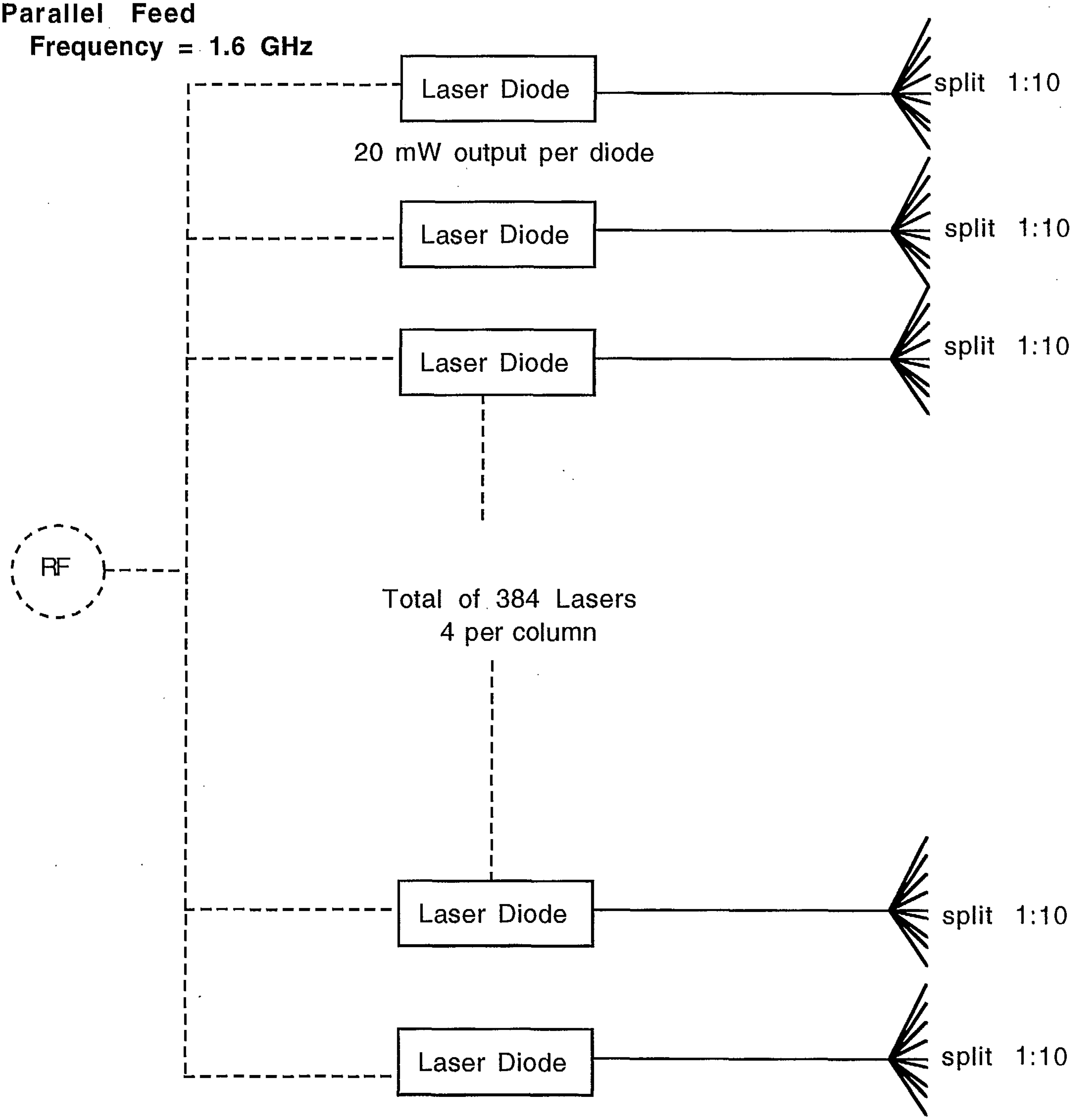
Parallel Feed
Frequency = 1.6 GHz



Note: Lasers mounted in pigtailed butterfly packages with integrated thermoelectric coolers and power monitoring.

Design P-5 Directly Modulated Laser Diodes

Parallel Feed
Frequency = 1.6 GHz



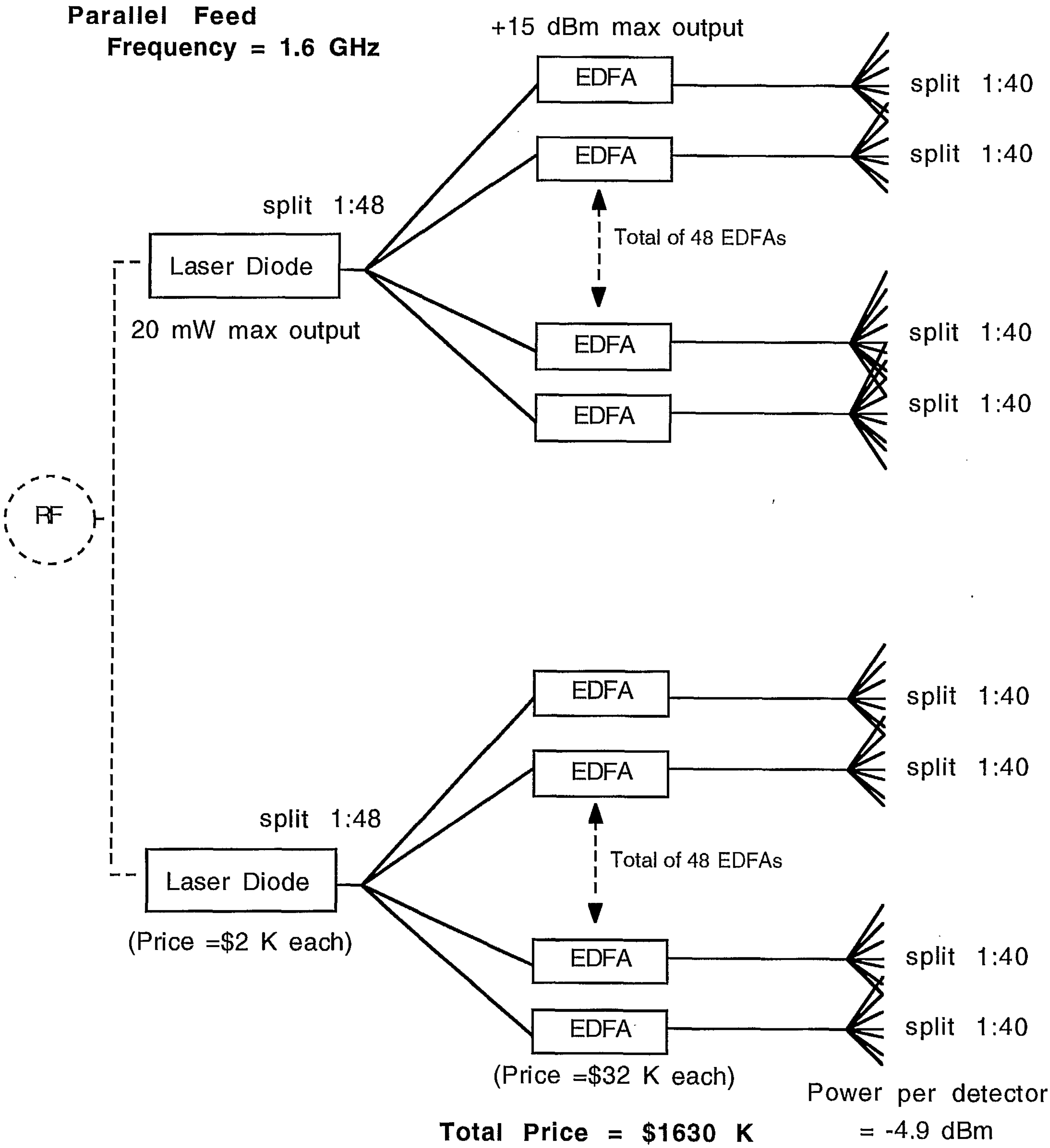
(Price =$2 K each)

Total Price = $837 K

Power per detector = -1.5 dBm

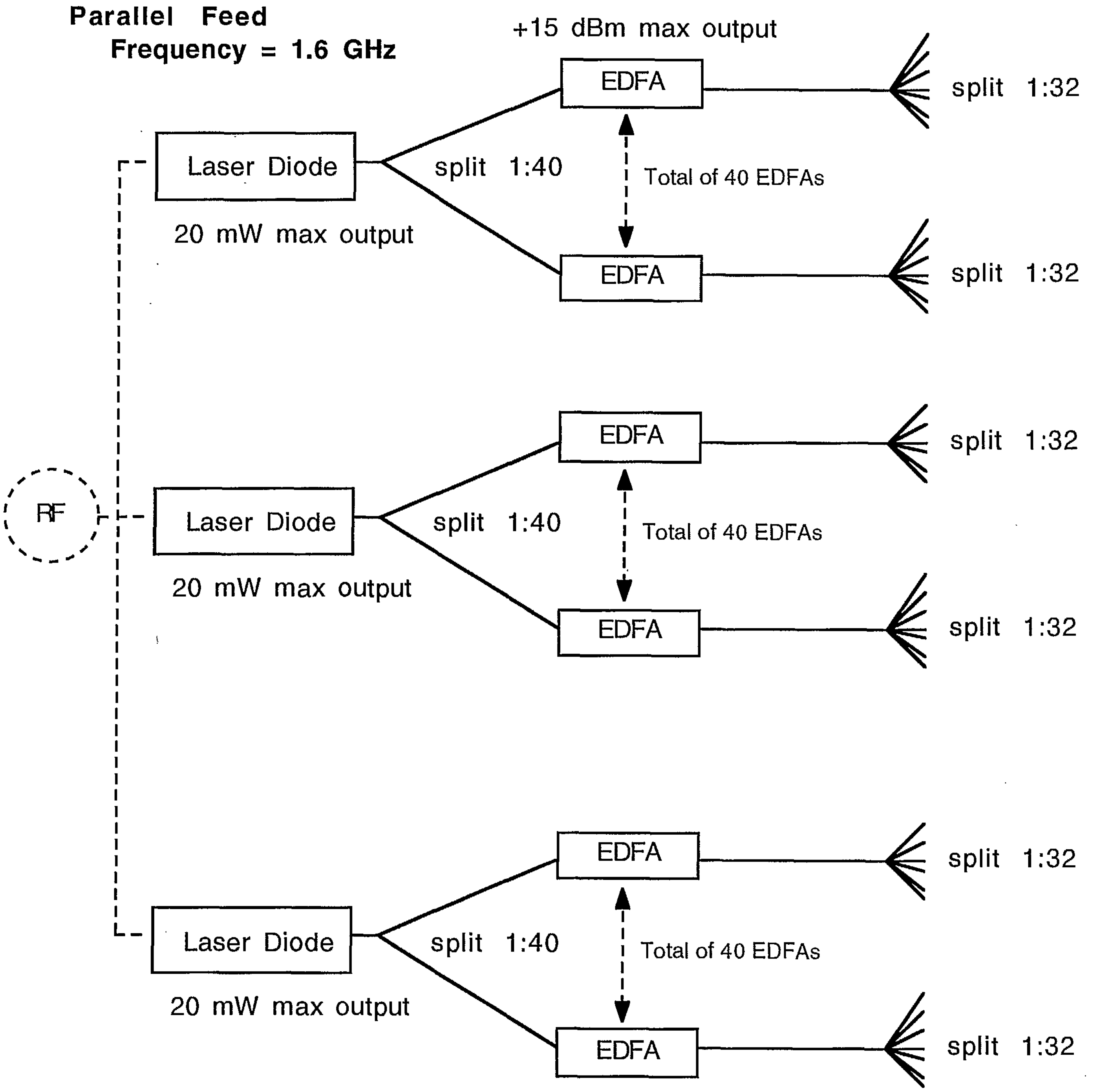
Note: Lasers mounted in pigtailed butterfly packages with integrated thermoelectric coolers and power monitoring.

Design P-6 Directly Modulated Laser Diodes with EDFAs



Note: EDFAs power consumption
is typically 17W per device

Design P-7 Directly Modulated Laser Diodes with EDFAs

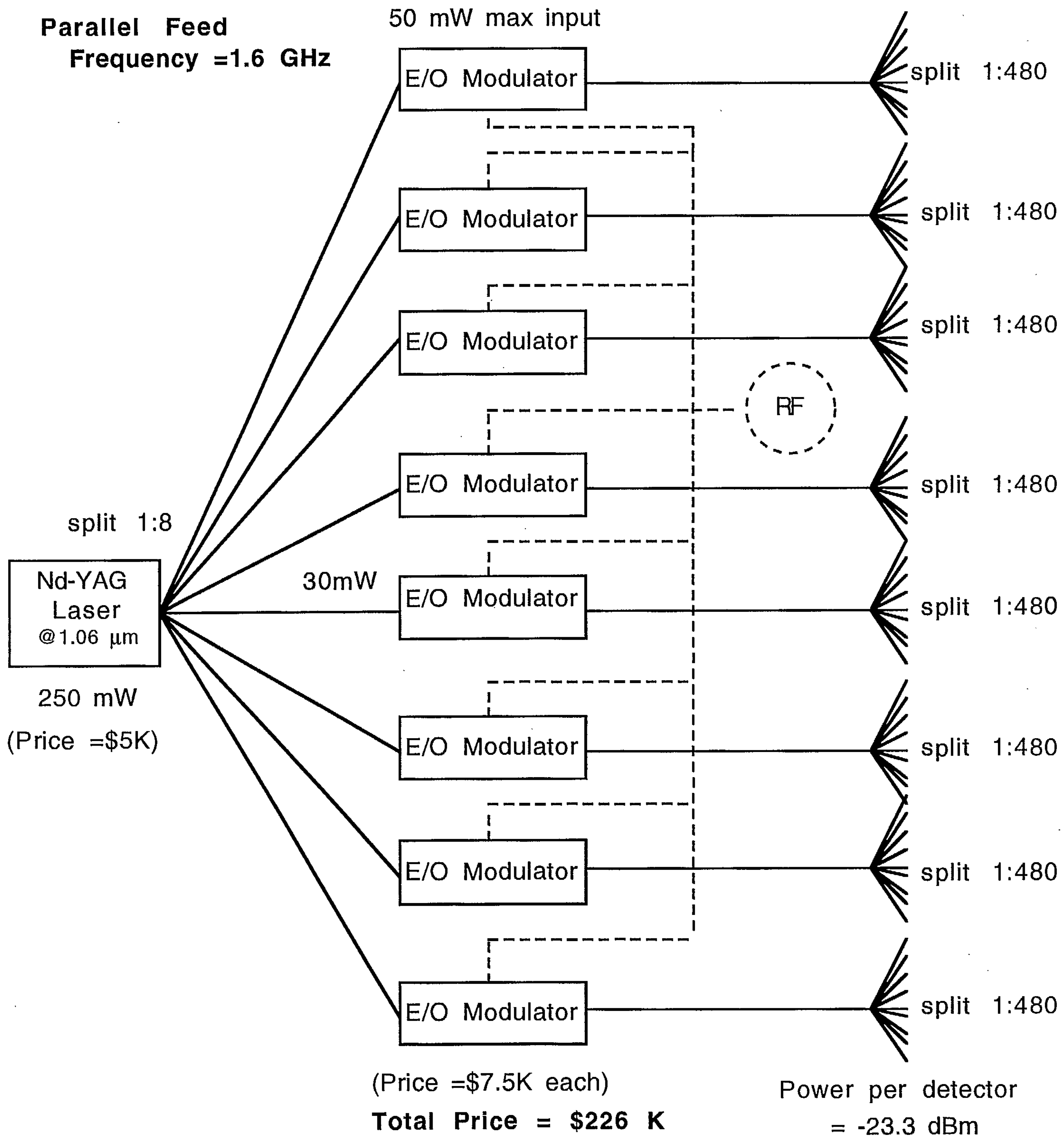


Note: EDFAs power consumption is typically 17W per device

Power per detector = -2.5 dBm

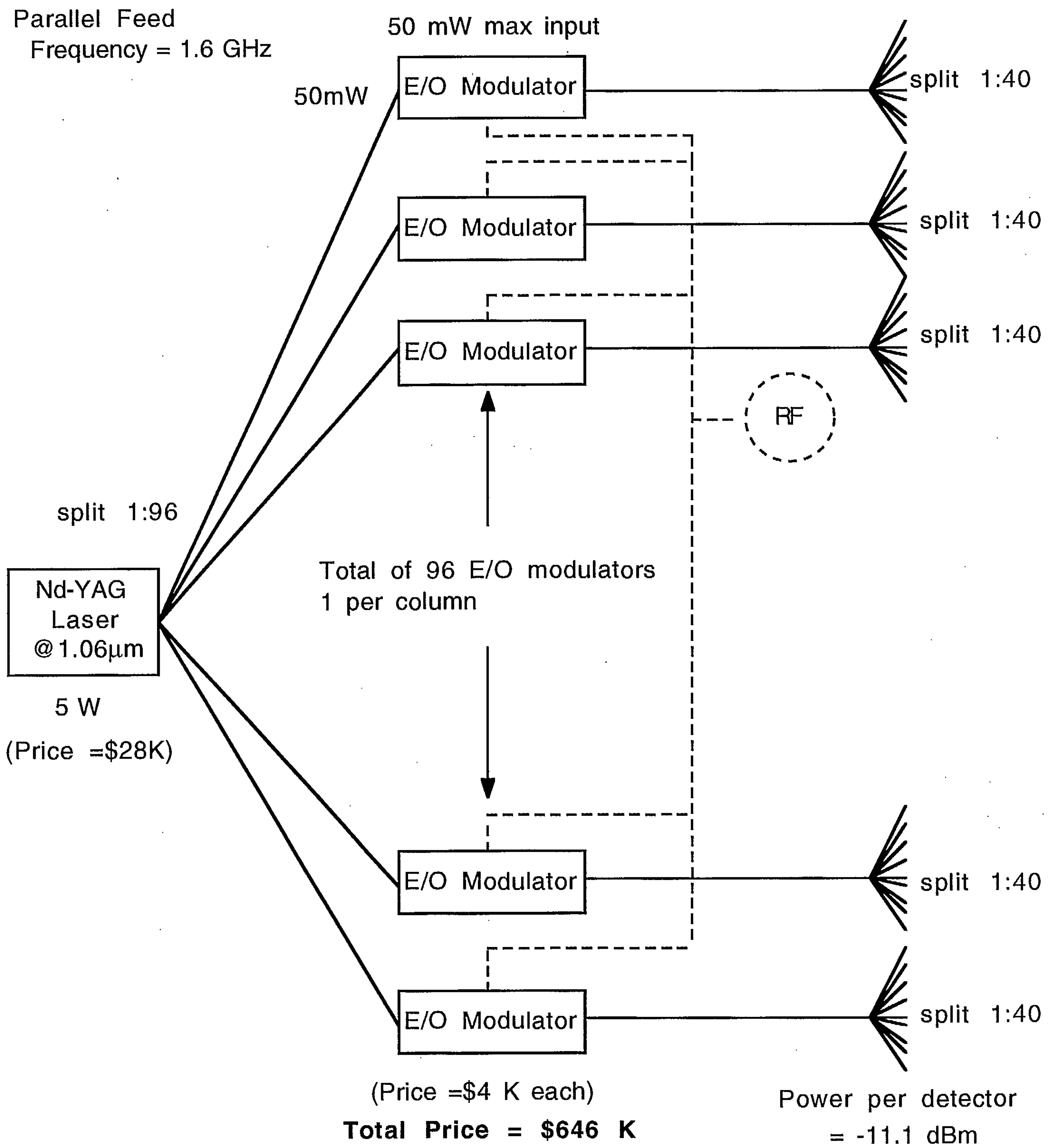
Total Price = $ 1956 K

Design P-8 YAG Laser with E/O Modulators



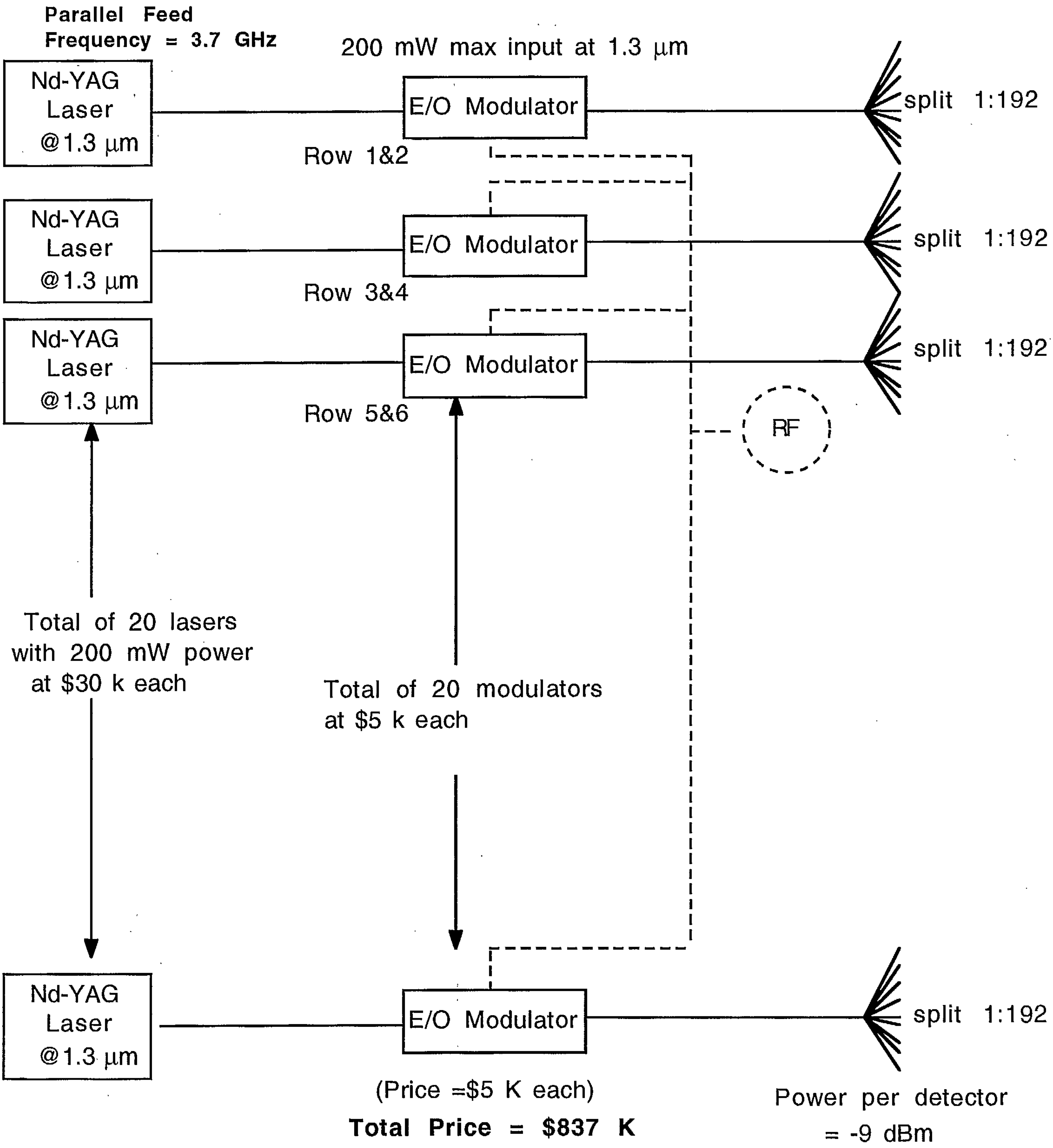
Note: E/O Modulators would require additional thermoelectric coolers and would require YAG laser to be pigtailed to PM fibre with possible high insertion losses

Design P-9 YAG Laser with E/O Modulators



Note: E/O Modulators would require additional thermoelectric coolers and would require YAG laser to be pigtailed to PM fibre with possible high insertion losses

Design P-10 YAG Lasers with E/O Modulators



Note: E/O Modulators would require additional thermoelectric coolers and would require YAG laser to be pigtailec to PM fibre with possible high insertion losses

Appendix 2:

Possible Designs

that Could be Used For

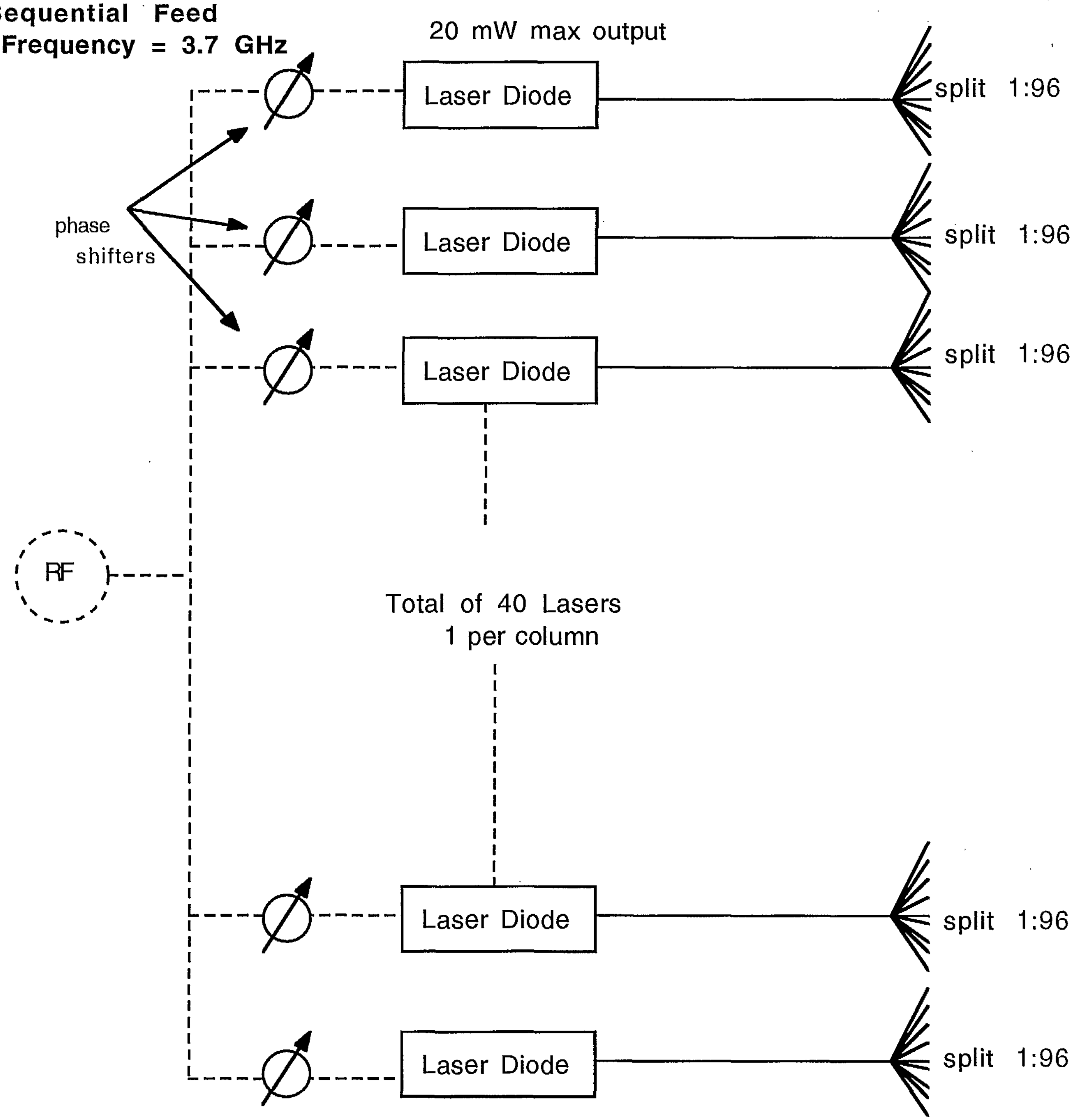
Sequential Feed on Transmit Side

at

f=3.7 GHz

Design S-1 Directly Modulated Laser Diodes

Sequential Feed
Frequency = 3.7 GHz



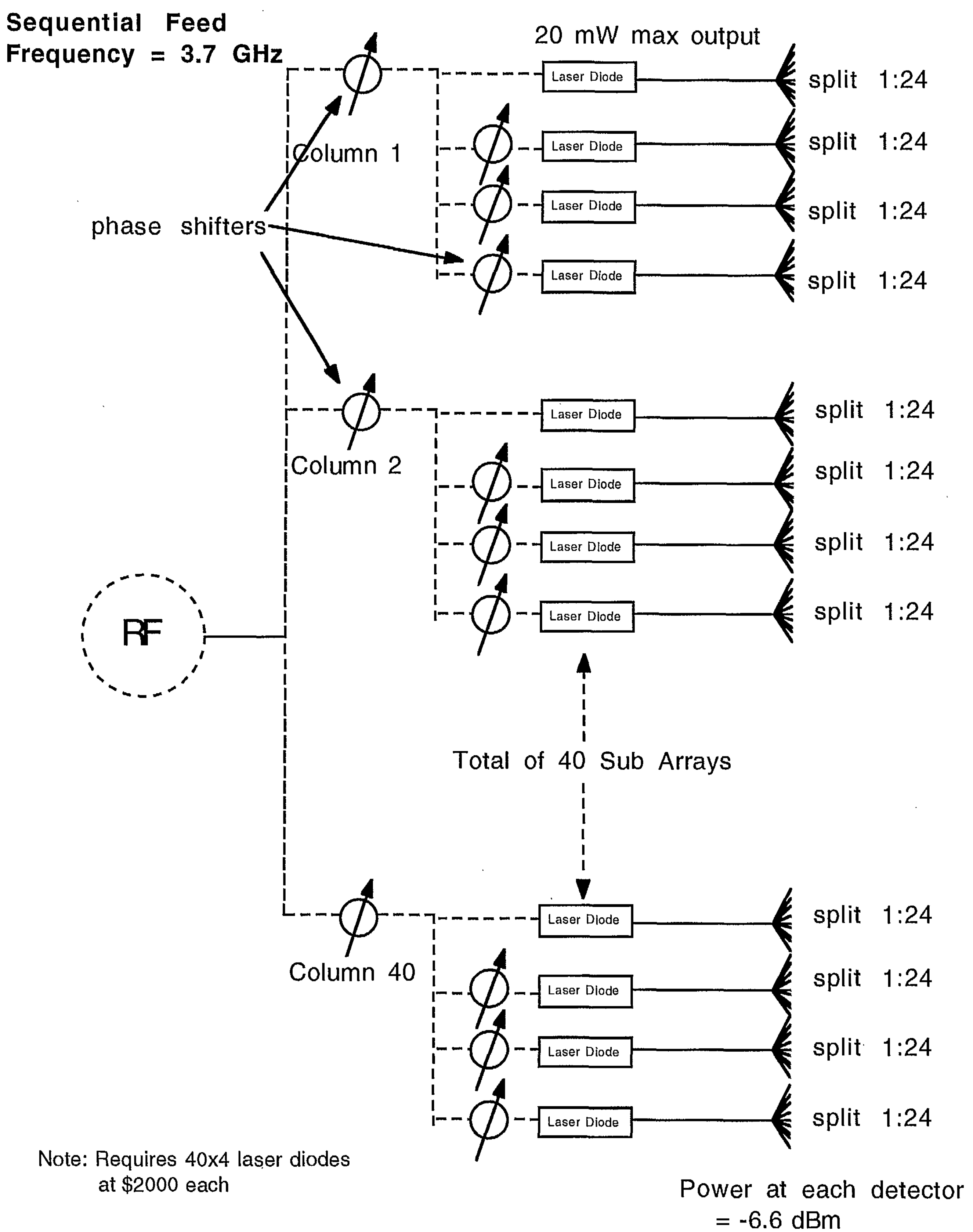
(Price =$2 K each)

Total Price = $227 K

Power per detector
= -13.8 dBm

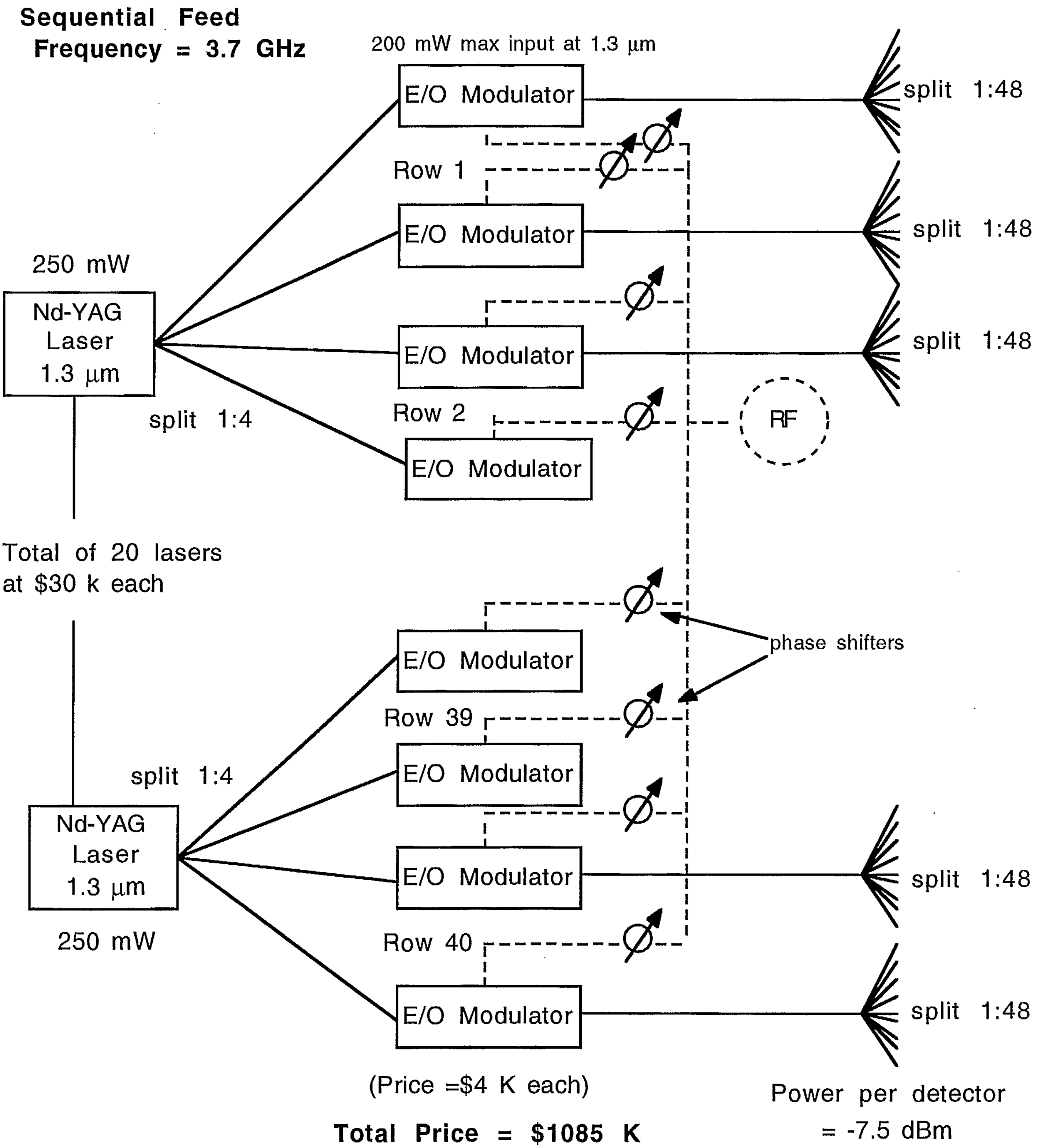
Note: Lasers mounted in pigtailed butterfly packages with integrated thermoelectric coolers and power monitoring.

Design S-2 Directly Modulated Laser Diodes



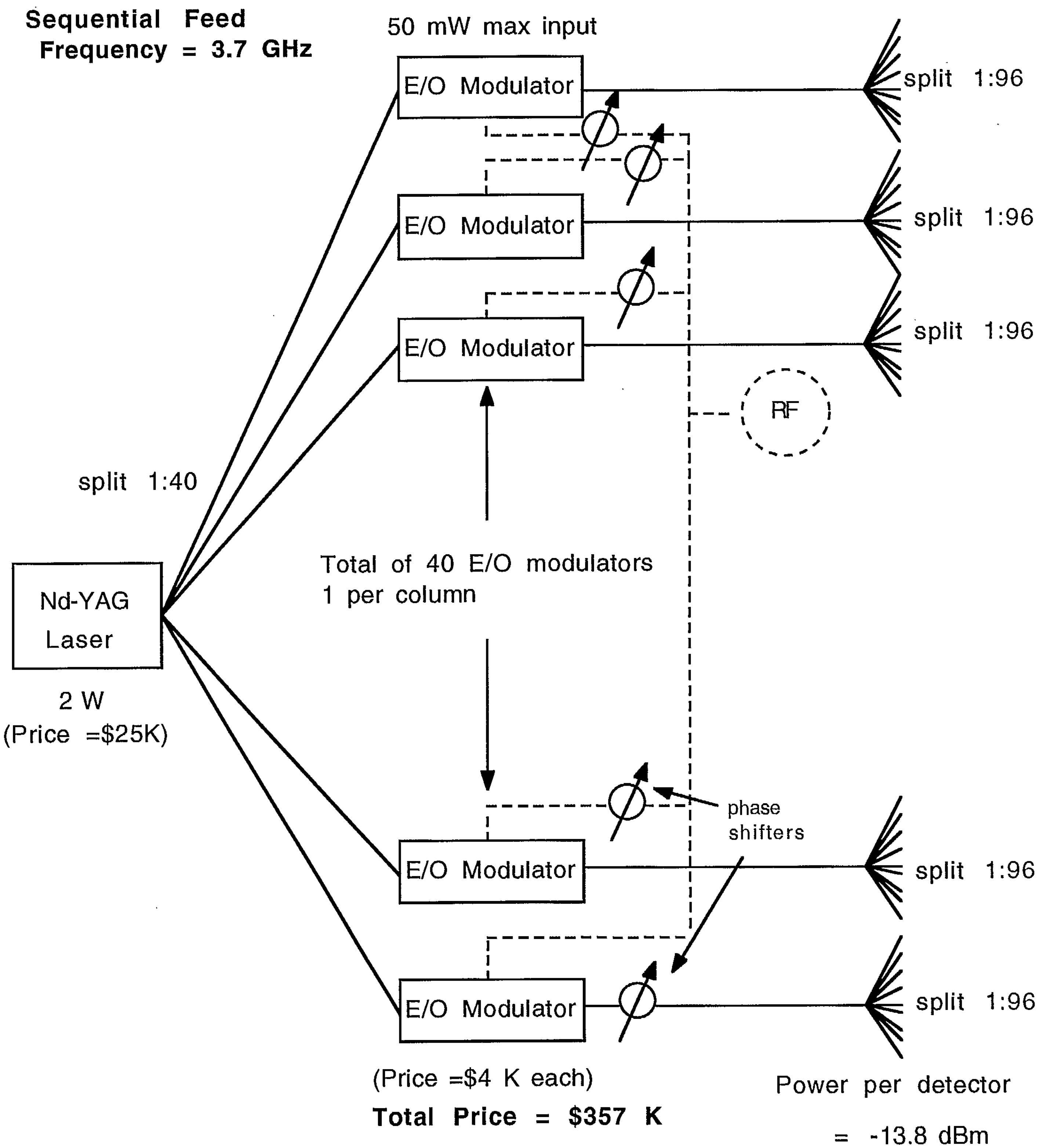
Total Price = $501 K

Design S-3 YAG Lasers with E/O Modulators



Note: E/O Modulators would require additional thermoelectric coolers and would require YAG laser to be pigtailed to PM fibre with possible high insertion losses

Design S-4 Single YAG Laser with E/O Modulators



Note: E/O Modulators would require additional thermoelectric coolers and would require YAG laser to be pigtailed to PM fibre with possible high insertion losses

DATE DUE

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