OPTICAL COMMUNICATIONS

and

THE FUTURE OF CABLE TELEVISION

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ABSTRACT

The technical problems facing the Canadian cable television industry are mentioned and the possibility of solving these problems through the application of optical communications technology is discussed. The characteristics of coaxial cables and optical fiber waveguides are compared and the advantages of the optical fiber waveguide are pointed out. Possible system configurations of an optical-cable television system are presented and the present state of optical communications technology is discussed. The research and development required to produce a practical optical-cable television system are pointed out. It is concluded that there are no obvious technical reasons that would prevent development of such a system in 10 ± 5 years. The problems that will affect the timing are pointed out and the question of cost is touched upon.

The views expressed in this paper are those of the author and do not necessarily represent the views of the Communications Research Centre or the Department of Communications.

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I INTRODUCTION

The year 1974 is the 100th anniversary of the invention of the telephone by Alexander Graham Bell. Among the many inventions made by him, it appears that the photophone shown in Fig. 1, was considered by Bell himself to be his greatest invention(1). Voice communication over a distance of 200 meters or so was achieved by this device. It could be said that the photophone was the first optical communication system to rise above the very low information rates of ancient optical communication devices such as smoke signals, blinking lights and the heliograph. The high expectations by Alexander Graham Bell of the photophone communicating without any conducting wire was never realized because of the practical problems of transmitting and guiding light beams through the atmosphere as well as the problem of providing a suitable light source.

However, by the emergence of the laser(2) and semiconductor light sources(3),(4) in recent years, together with the development of low loss optical fiber waveguides(5), Alexander Graham Bell's expectations are being realized today. Light beams can now be guided around corners and over long distances by optical fiber waveguides. Light emitting diodes and lasers have replaced the sun as a light source. Today we are about to see an explosive growth of the optical communications technology based on low-loss optical fiber waveguides and semiconductor light sources.

This new technology will have a significant impact on the future of the cable television industry and may provide solutions to a number of technical problems facing the industry today. For example, compliance with Broadcast Procedures 23 presents difficulties to many cable systems, particularly to those that have extended trunk lines that produce poor quality signals due to the cascading of many amplifiers. Congestion of broadcast channels and difficulties with channel allocation are being experienced by some cable television systems today. The midband service offered through the use of a converter has provided one solution but assurance of signal quality may be a problem in some systems that employ single-ended trunk amplifiers. For the long term outlook, implementation of two-way or bidirectional services on a large scale to provide so-called wired-city services such as pay TV, information retrieval, remote shopping and banking will be a technical challenge for present day coaxial cable technology. These problems facing the present and future coaxial cable television systems can be solved through developments in optical communications technology.

II COMPARISON OF COAXIAL CABLES AND OPTICAL FIBER WAVEGUIDES

The principles utilized in optical fiber waveguide technology are a natural extension of the principles applied in coaxial cable technology. In other words, Maxwell's equations apply to optical frequencies as well. Table 1 lists a comparison of frequencies and wavelengths of the frequency spectrum of electro-magnetic waves. The spectrum starts from below the audio region and extends into and beyond the visible light region. The very high frequencies of 10^{14} Hz for optical waves offers the possibility of transmitting extremely large bandwidths of information corresponding to several thousand TV channels. Initially, research workers were attracted to this potential. The interest in optical communications has increased further in the last few years because optical communication system components have shown promise to be competitive in cost with conventional radio-frequency system components such as the coaxial cable. Indeed waveguides for optical frequencies should have better characteristics than coaxial cables in many respects. The optical fiber waveguide is described below and its characteristics are compared with the coaxial cable.

A. The Optical Fiber Waveguide

The cutaway view in Fig. 2 shows the basic structure of an optical fiber waveguide. The material of the fiber is glass or

TABLE 1

THE ELECTRO-MAGNETIC SPECTRUM

	FREQUENCY (Hz)	WAVELENGTH (m)
OPTICAL WAVES	$3X10^{14}$	10^{-6}
mmWAVES	$3X10^{11}$	10^{-3}
TELEVISION	$3X10^{8}$	1
RADIO	$3X10^{6}$	10^{2}
TELEPHONE	$3X10^{3}$	10^{5}

fused quartz and the core has a higher index of refraction than the cladding. A light ray is propagated along the fiber by total internal reflection at the core-cladding boundary. Propagation characteristics of the fiber waveguide are determined by the physical dimensions, indices of refraction and material properties. A typical fiber waveguide has an outside diameter of approximately 130 μm and is as fine as a human hair. Individual fibers can be protected with a thicker plastic sheath which reinforces the mechanical strength of the fiber. The overall diameter of such protected fibers is about 1 mm and multiple "conductor" cables can be fabricated readily.

B. The Attenuation Factors

One of the major advantages of optical fiber waveguides when compared to conventional coaxial cables is shown in Fig. 3. The attenuation of coaxial cables varies with frequency. For example, in the case of RG-17/U, the attenuation changes approximately by a factor 10 for a frequency change from 1 MHz to 100 MHz. In comparison, the optical fiber waveguide can be designed to have a constant attenuation over such a bandwidth. This is possible because the 100 MHz the bandwidth corresponds to only 1 part in a million of the 10^{14} Hz optical frequency and as far as the fiber propagation characteristics are concerned, the optical frequency is unchanged by such a small bandwidth of modulation. In comparison, for the coaxial cable the 1 to 100 MHz bandwidth covers almost 5 octaves. Of course the optical fiber waveguide is not without an upper frequency limit but fibers capable of transmitting 1 G bits/sec over a 1 km distance are readily fabricated. In terms of system engineering, the constant frequency response of the fiber will eliminate the need for frequency compensation circuits, or so called "tilt controls" and simplify the circuitry of repeater amplifiers which will most likely be similar to conventional radio frequency (RF) amplifiers except for the optoelectronic circuitry that converts RF signals to optical signals or optical signals to RF signals. The attenuation of the optical fiber can be lower than most coaxial cables and a fiber with a 20 dB/km loss is available commercially† today and fibers with losses less than 4 dB/km have been produced in the laboratory(38). With a 4 dB/km loss, trunk amplifier spacings of more than 5 km (3 miles) is a possibility.

C. The Temperature Coefficients

The optical fiber waveguide has another significant advantage over coaxial cables in terms of temperature stability. The attenuation factor of a typical coaxial cable has a temperature dependence of approximately 0.2%/°C which also differs for different frequencies. This introduces troublesome temperature compensation requirements, particularly in Canada where the ambient temperature shows a large seasonal variation. The temperature sensitivity of the coaxial cable arises from the dimensional change as well as the change in the dielectric constant with temperature of the coaxial cable material. These changes are directly related to the linear coefficient of expansion of the materials. Table 2 lists the coefficients of typical materials

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† Corning Glassworks, Corning, N.Y.,U.S.A.

The lack of radio frequency leakage and pickup will assist in many ways towards compliance with radio regulation standards by eliminating radio frequency ingress and egress problems. The absence of cross-talk between optically shielded fibers will ease the implementation of spatial division multiplexing. Troublesome ground loop problems will also be eliminated because the fiber is an insulator. The low attenuation factor of the fiber will permit spacings larger than 1 km between trunk amplifiers which may mean lower system cost compared to coaxial cable systems in some cases. Fewer repeater amplifiers for a given distance will mean easier compliance with performance standards contained in Broadcast Procedure 23. The non-use of copper may become significant in future years because the known high grade copper ore is predicted by some to become depleted in about 15 years[6].

Of course , the coaxial cable has some significant advantages over optical fibers. The coaxial cable technology is well developed and many communication services can be provided satisfactorily through coaxial cables. Compared to optical fibers, splicing in the field is carried out readily and highly skilled linesmen are not required for such operations. The coaxial cable is also not susceptible to catastrophic mechanical failure when subjected to mechanical abuse such as overbending, kinking and stretching. An optical fiber will break if subjected to such abuse but the coaxial cable will often function, although marginally,

TABLE 2

TEMPERATURE COEFFICIENTS

	LINEAR EXPANSION $10^{-4}/°C$
FUSED QUARTZ	0.004
"VYCOR" GLASS	0.008
SODA GLASS	0.12
POLYETHELENE	1.5 to 3.0
ALUMINUM	0.24
COPPER	0.17

TABLE 3

COMPARISON OF OPTICAL FIBER WAVEGUIDES AND COAXIAL CABLES

ADVANTAGES OF OPTICAL FIBER WAVEGUIDES

1. Small cross-sectional area; large number of communication channels per unit conduit cross-sectional area
2. Constant frequency response
3. Negligible temperature coefficient
4. Absence of RF leakage & RF pickup
5. Complete absence of crosstalk between suitably sheathed fibers
6. Absence of ground loop problems
7. Low attenuation factor
8. Possible cost reduction because copper is not required

ADVANTAGES OF COAXIAL CABLES

1. Technology is well developed
2. Splicing in the field is carried out readily; no complex training of service personnel is required
3. Mechanical abuse does not generally lead to catastrophic failure

after mechanical abuse. Thus, in comparison to coaxial cables, the optical fiber requires great care in handling.

With further development of optical communications technology, the advantages to be gained from the application of optical fiber waveguides may soon outweigh the disadvantages. The development to date in optical communications has produced the basic components required to construct optical communication systems. System engineering of an optical-cable television system can be considered seriously.

III AN OPTICAL CABLE TELEVISION SYSTEM

A. The Basic System

Figure 4 shows basic block diagrams of optical communication systems. The simplest system, shown in Fig. 4-(a), uses a direct modulation technique where the light source itself is modulated by varying the RF excitation current of the light source. The source may be a light emitting diode (LED) or a semiconductor continuous wave double heterostructure laser (CW DH laser)[7]. The RF signal may be in analogue or digital form. Pulsed FM and various pulse code schemes may be employed. The system shown in Fig. 4-(a) has the advantage of a simple modulation scheme but coupling problems between the light source and the fiber may be present.

The system shown in Fig. 4-(b) uses an independent laser source and an external modulator which is driven by RF signals. The laser system may be a neodymium : yttrium aluminum garnet (Nd^{3+}: YAG) laser[8] or a He:Ne gas laser.

Since such lasers have well collimated beams, coupling into the fiber is accomplished much more readily than in the case of the semiconductor light sources. This ease in coupling will permit the useof fibers with very small cores of order of 1 μm diameter which can provide transmission bandwidths of the order of G bits/sec for the fiber. External modulators capable of dealing with such high bit rates have been tested in the laboratory[40]. Detectors with responses suited for G bits/sec rates are available today†.

B. The Optical Cable Television System

In an optical-cable television system,the characteristics of each component must be matched. Initially, the limitations in the modulation bandwidth of the light sources will force the use of spatial multiplexing where an optical fiber cable containing many independent fibers is used. The bidirectional system will be simplified by dedication of some fibers to exclusive transmission of signals back towards the headend. A multiple-fiber cable containing 20 or more fibers will be smaller than a conventional trunk-line coaxial cable and the installation cost should be comparable. Future expansion of services can be accommodated at minimum cost by installing an optical fiber cable containing extra fibers, or through an improvement in the modulation bandwidth of the light sources. The transmission

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capacity of a fiber can be utilized to the fullest by wavelength multiplexing through the use of light sources that emit at different wavelengths.

The modulation of the light can be in the form of amplitude (intensity) modulation, pulsed FM, or pulse-code modulation(PCM). Amplitude modulation requires only simple circuitry compared to pulse-code systems, but a good signal-to-noise ratio is difficult to maintain over long distances. Probably the pulse-code system is most suited for long trunk lines while the analogue system is suited for short lines such as droplines to the subscriber. The pulsed FM system appears to be a good compromise of the two methods of transmission. Systems engineering work is required to determine the optimum design for a given requirement.

An example of a distribution point in an optical cable television system is shown in Fig. 5. Independent fibers are used to provide bidirectional service. The optical signal from the headend is detected by a photodiode and converted to an RF signal which is amplified by the repeater and fed into a DH laser for further transmission. The RF signal is also fed into a driver which distributes the signal to subscribers through DH lasers. The optical fiber waveguide to a subscriber is used bidirectionally by using two different optical wavelengths Λ_{out} and Λ_{in}. The dichroic beam splitters perform the same function as the diplex filter in conventional coaxial bi-directional systems. The multiplexer combines the return signal from the subscribers for transmission back to the headend. The basic components to construct such an optical cable system are available today.

IV PRESENT STATE OF OPTICAL COMMUNICATIONS TECHNOLOGY

A. The Optical Fiber Waveguide

The cladded type optical fiber waveguide described in Fig. 2 has been investigated by many groups and several types are available commercially.† An attenuation factor as low as 20 dB/km is achieved readily and Table 4 lists the physical characteristics of one such fiber. Values less than 5 dB/km have been reported for experimental fibers of similar design(9). The attenuation is determined by absorption due to impurities in the materials as well as scattering due to thermal and concentration fluctuations. The concentration fluctuations include inhomogeneities introduced during the manufacturing process. Figure 6 shows a typical attenuation curve for a quartz fiber. The scattering loss decreases with an increase in wavelength at a rate of $1/\lambda^4$, where λ is the

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† Corning Glassworks, Corning, N.Y., U.S.A.; Galileo Electro-Optics Corp., Sturbridge, Massachusetts, U.S.A.; Pilkington Brothers Ltd., Lathorn, Ormskirk, Lancashire, England.

TABLE 4

SPECIFICATIONS OF A

CLADDED OPTICAL FIBER WAVEGUIDE

OUTSIDE DIAMETER (COATED)	135 μm
CORE DIAMETER	85 μm
NUMERICAL APERTURE (NA)†	0.14
CORE INDEX OF REFRACTION	1.5
MAXIMUM LENGTH	1 km (3280 ft)
MAXIMUM ATTENUATION @ 820 nm WAVELENGTH	20 dB/km

† $NA = n\sin\theta = (n_1^2 - n_2^2)^{\frac{1}{2}}$

n_1 = index of refraction of the core

n_2 = index of refraction of the cladding

n = index of refraction of air

θ = maximum allowed angle of incidence on the fiber face for a light ray to be propagated through the fiber wavelength, in accordance with Rayleigh scattering theory. The large absorption peak in the vicinity of $\lambda = 0.95$ μm is caused by the OH-bond vibrational absorption of the water molecule which is contained as an impurity. Light emitting diodes, semiconductor DH lasers and Nd^{3+}:YAG lasers have wavelengths in the region of low attenuation.

The maximum transmission bit rate (bandwidth) of a fiber is determined by material dispersion (variation of the index of refraction of the material with wavelength) which causes the different wavelengths to propagate at different velocities(10). This material dispersion when combined with the spectral width of an LED causes a pulse spreading of approximately 1 to 5 nsec over a length of 1 km. A DH laser which has a much narrower spectral width will cause a pulse spreading of approximately 1/10 that of an LED(10). The Nd^{3+}:YAG laser has still a narrower spectral width and a further 1/10 reduction in pulse spreading can be expected(10).

The maximum transmission bit rate is also limited by the choice of core diameter and indices of refraction of the core and cladding. Differences in the path length taken by a straight-through light ray and a ray propagating by multiple reflections produces differences in arrival times and broadens a pulse. This broadening can be kept small by making the difference in the indices of refraction of the core and cladding very small. A similar result can be obtained by reducing the core diameter to 1 μm or so. Then the fiber transmits only those rays that travel nearly parallel to the axis because of the electromagnetic properties of such a configuration. Such fibers with small core diameters or very small differences between the core and cladding indices are known as single-mode fibers and other fibers with larger core diameters or large differences in indices are known as multimode fibers. The example shown in Table 4 is a multimode fiber and the pulse dispersion due to the difference in the propagation lengths of the rays is 5 to 10 nanoseconds for a kilometer length[11].

This dispersion arising from the structure of the fiber can also be reduced by replacing the step index profile of a cladded fiber with an approximately parabolic index variation which decreases outwards from the centre of the fiber (graded index fiber) and reaches the constant index value of the cladding. An optical ray is propagated by continuous inward refraction in such a structure. The dispersion becomes lower because the velocity of light is higher in the low index region and compensation in terms of time is provided for the ray that travels a longer path. The pulse dispersion can be lowered to less than 1 nsec for a 1 km length in such a fiber[11].

There are other fiber designs that have been successfully manufactured in the laboratory in lengths exceeding 100 meters. Attenuation of 3 dB/km at a wavelength of 1.15 μm has been achieved for one configuration[12] and an attenuation of 10 dB/km together with a pulse dispersion of less than 0.73 nsec/km using a DH laser as a source, has been achieved in another[13]. A G bits/sec information rate is possible in the latter case and if a Nd^{3+}:YAG laser is used as the source, a 10 G bits/sec rate should be possible over a 1 km distance. A 10 G bits/sec rate corresponds approximately to 100 PCM colour television channels.

B. <u>The Light Source, Modulation, Bandwidth and Coupling to Fibers</u>

The most readily available light source is the light emitting diode (LED). A number of LEDs providing more than 1 mW output at approximately 900 nm wavelength with light risetimes less than 5 nsec are commercially available†.

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† General Electric SSL-4; Monsanto ME-4

Modulation of such LEDs with bit rates higher than 30 M bits/sec is readily achieved. Rates in excess of 100 M bits/sec have been reported for experimental LEDs[14].

The CW double heterostructure (DH) laser will most likely become commercially available early in 1975[15]. The short lifetime problem that plagued earlier developmental types has been solved and lifetimes well in excess of 10^4 hours are expected[16]. Lifetimes of 10^5 hours are projected. Lifetimes of LEDs are well in excess of 10^5 hours[17]. Similar results can be expected for the high radiance LED†. Using a DH laser with a graded index fiber (SELFOC®) a system transmitting 500 M bits/sec was successfully operated over a distance of 500 meters[18]. The coupling to the fiber was accomplished by a graded index fiber section specially designed to match the DH laser output to the fiber.

The CW Nd^{3+}:YAG laser excited by LEDs is perhaps the most promising light source for long distance optical transmission systems with G bits/sec rates because the output beam of the Nd^{3+}:YAG laser is well collimated and suited for coupling into single mode fibers. Such lasers have been operated successfully in the laboratory[19] and miniature versions using a single LED as a pump source have also shown the possibility of CW operation[20].

† The high radiance LED has a small emitting area for a given light output.

In addition to the collimated output, the Nd^{3+}:YAG laser has the advantage of a narrow spectral width which is required for a G bits/sec information rate, and an output wavelength of 1.06 μm which corresponds to the low loss region of the optical fiber.

The coupling of optical energy into the fiber is a problem when LEDs are used as the light source because the direction of light emission is not well collimated. Efficient coupling to a single fiber, even if it is a multimode fiber is extremely difficult. The most suitable approach for such sources is the use of closely packed fiber bundles that have cross-sectional areas approximately equal to that of the light emitting area of the LED. Such a bundle with 19 fibers in a hexagonal packing is available commercially†. The coupling even in this arrangement is inefficient and a loss of 20 dB or so can be expected[(21)].

High radiance LEDs with small emission areas having a diameter of 50 μm is available commercially†† and the coupling into a fiber with a 50 μm core size and numerical aperture of 0.44 ($\theta = 26°$) can reduce the coupling loss to less than 8 dB[(22)].

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† Corning Glassworks, Corning, N.Y., U.S.A.

†† Plessey, Optoelectronics Microwave Unit, Northamptonshire, England

In order to collect most of the LED energy, the core diameter and the maximum allowed incident angle θ must be as large as possible but these conditions designate a multimode fiber with a low information bandwidth which will be typically much smaller than 100 M bits/sec for a km length fiber(23). However, light sources with well collimated output beams will permit the use of high bandwidth single mode or graded index fibers.

In comparison to LEDs, the Nd^{3+}:YAG and gas lasers such as the He:Ne laser have a collimated output beam that is well suited for applications with single mode fibers. Theoretical calculations show that coupling losses less than 0.5 dB can be achieved for single mode fibers(24). External modulators must be used with these lasers. Digital modulation rates in excess of G bits/sec have been accomplished experimentally(25).

The bandwidth capabilities have been discussed mainly in terms of bit rates in this paper. This is partly because of the interest held by most research laboratories in digital systems and partly because of the difficulty in achieving broadband linear analogue modulation of the light sources. Systems carrying single TV channels through an intensity modulated signal can be constructed readily today. Figure 7 shows an example of a system transmitting a single television channel. However, more research and development is required before many more channels can be satisfactorily carried by a light beam through analogue modulation.

C. The Detectors

There is a large selection of PIN photodiodes† and avalanche photodiodes suited for demodulation of the optical signal. Response times less than 5 nsec are not uncommon††. The avalanche photodiode appears to be best suited for long distance links because of its higher sensitivity arising from the avalanche gain . However, their sensitivity to ambient temperature and requirement of voltages higher than 100 V may be a hinderance in some applications. The PIN photodiode requires only a low voltage (10 ∿ 20 V) and is simple to use. No serious problems are expected in the area of detectors.

D. The Integrated Optics Technology

Analogous to the integrated circuits in electronics, integrated optical circuits(26) can be fabricated for optical signals. Figure 8 shows a schematic of a distributed feedback semiconductor laser constructed by integrated optic techniques. The laser was operated successfully at a temperature below 80°K. The oscillation wavelength was 845.9 nm for one device and 842.0 nm for a second device. By changing the periodicity of

† The PIN diode structure has an intrinsic (I) semiconductor layer between the p (P) and n (N) regions to improve response time and sensitivity over that of conventional pn photodiodes.

†† Hewlett-Packard, No. 5082-4203; RCA, C30817

the rippled structure, the oscillation wavelength can be varied over a range of approximately 10 nanometers[27]. Such a variation will be useful for wavelength multiplexing. The spectral width of the output appears to be narrower than the normal semiconductor laser. Room temperature operation of such lasers should be accomplished in the near future.

Theoretical calculations have shown that the distributed feedback structure can be used to construct narrowband optical filters[28]. Such filters will also be useful for wavelength multiplexed systems. Many other optical circuits have been fabricated. Among them is a waveguide modulator capable of operating in the G bits/sec region[29].

V COST

In 1972 a graded index fiber (SELFOC®) with a loss figure less than 20 dB/km was available at \$23.00/m (\$7.00/foot). Recently, a cladded fiber with a similar loss figure has become available at \$3.00/m (91¢/ft) in 1 to 50 km quantities and at \$1.50/m (46¢/ft) in quantities over 100 km†. These costs are for single fibers that have a suitable sheathing for protection. Further costs will be incurred when these fibers are fabricated into cables suitable for practical application. High loss (2000 dB/km) fiber bundles containing more than 100 fibers per bundle have been on the market for some time at a cost of less than \$1.00/m (30¢/foot)†. In the

† Corning Glassworks, Corning, N.Y., U.S.A.

long term, the low loss fiber can be expected to reach below this cost figure. This means that the cost of an optical fiber cable will become comparable or lower than a coaxial cable that has an equivalent communication capacity. The timing of such a occurrence will be influenced by the cost of materials such as plastics, copper, aluminum and high purity materials used to produce the optical fibers. The optical fiber cable will certainly require less plastic than a coaxial cable because of the smaller physical dimension of the fiber. In the future, the cost of metals will certainly be higher than high purity materials for the glass and quartz fibers because such materials are more abundant and the unit cost of purification will decrease with an increase in production. Systems designers can be expected to face the problem of trade-off between optical fibers and coaxial cables as early as 1976, if the present rate of development in optical communications technology is maintained.

If we take into account the simplifications introduced by the absence of tilt control and temperature compensation circuits required of a coaxial cable, as well as the larger spacings between trunk amplifiers and assume that these simplifications will offset the added complication of up and down conversions to optical frequencies, the optical trunk line should cost no more than the conventional coaxial system. The advantage of the optical system will be in the potential to provide more services of higher quality for the same cost. A systems engineering study will be required to substantiate whether the assumptions made here are correct.

VI RESEARCH AND DEVELOPMENT REQUIREMENTS

At present, components are available commercially to construct systems capable of dealing with 30 M bits/sec over a 1 km length. The main limitation lies in the bandwidth capability of the optical fiber and the spectral width of the LED. The almost certain availability of the CW DH laser in early 1975 combined with graded index fibers or single mode fibers with pulse dispersions less than 1 nsec/km will raise the bit rate well above G bits/sec. However, further research and development is required to bring the optical cable television system to practical utilization.

Table 5 lists the areas that are receiving attention at a number of laboratories although no laboratory has yet indicated an extensive interest in the field of cable television. A systems engineering analysis is required to determine the optimum configuration. Most likely PCM will be used for long trunk lines while short distribution lines may rely on analogue or pulsed FM transmission. Both spatial and wavelength multiplexing could be combined to optimize bidirectional service. Distribution systems can also be redesigned to take advantage of the long spacings between repeater amplifiers .

The useful analogue modulation bandwidth can be improved through optical feedback circuits which should improve the linearity[30]. The performance of external modulators must be evaluated to determine whether they have the linearity demanded of a broadband system. Some commercial units claim to have frequency responses in excess of 50 MHz at present† . More work is required in this area of analogue modulation.

The single mode fiber combined with a Nd^{3+}:YAG or gas laser will most likely be used for long trunk lines. Transmission distances in terms of intercity connections can be considered if PCM is employed. The DH laser combined with a graded index fiber is also a possible candidate for such applications.

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† Isomet, TFM S13

TABLE 5

RESEARCH AREAS IN THE DEVELOPMENT OF OPTICAL CABLE TELEVISION SYSTEMS

1. SYSTEMS ENGINEERING
   - Analogue, Pulsed FM and Pulsed Code Modulation (PCM)
   - Spatial and Wavelength Multiplexing
   - Two-way Service
   - Network Design

2. ANALOGUE MODULATION
   - Optical Feedback
   - Modulation Devices

3. OPTICAL FIBER
   - Multimode and Single Mode
   - Cladded and Graded Index Fibers
   - Cabling

4. LIGHT SOURCE
   - LED and DH Laser
   - Nd^{3+}:YAG Pumped with LED
   - Gas Lasers

5. SPLICING OF FIBERS

6. COUPLERS, SPLITTERS

7. INTEGRATED OPTICS

For short distance transmission, multimode fibers combined with LED sources can be used. To be of practical use, the fibers must be arranged into a suitable cable configuration which may contain reinforcing steel wire and copper pair power lines.

Further work is required to perfect the CW DH laser and to assure the life time of high radiance LEDs. The LED pumped Nd^{3+}:YAG laser may become a practical device through the development of LEDs specially designed for exciting the Nd^{3+}:YAG laser crystal. Gas lasers, although generally neglected as a light source for practical applications, may prove to be useful in special forms, such as the capillary waveguide laser[31].

Splicing of fibers with losses less than 0.5 dB have been accomplished under laboratory conditions[32]. However, practical methods for use in the field must be developed. Devices using waveguide principles[33] and epoxies may prove to be useful. It will appear that highly skilled personnel will be required for the operation.

Some couplers similar to BNC connectors have been developed in the laboratory[34]. T-joints and splitters have also been constructed in the laboratory and operated satisfactorily[35].

The optical communications technology will undoubtedly follow the pattern of semiconductor technology and move from the discrete component system to integrated circuitry. This field of integrated optics is being explored extensively by many groups. The number of practical devices will undoubtedly grow rapidly in the future.

VII CONCLUSIONS

There are no obvious technical reasons to prevent the development of an optical-cable television system. It will probably take 5 to 15 years to develop a practical system. The end result of the development most likely will be the realization of the wired-city[(36),(37)] total communication system. Table 6† lists the possible services that might be offered by a fully bidirectional optical-cable television system. Narrowband and broadband switched services are also included because there undoubtedly will be a high speed optoelectronic switching system available in the future. Thus, aside from the one-way broadcasting activity, a full range of interactive services will become possible. Interactive educational TV may bring education to many people who cannot be reached under today's educational system. The wide scale use of transaction exchanges will result in the realization of the "cashless society". A number of social

† Source: EIA Response to FCC Docket 18397, Part V, Electronic Industries Association, U.S.A., Oct. 29, 1969

TABLE 6

WIRED CITY SERVICES

BROADCAST	REAL-TIME POINT-TO-POINT	STORE AND FORWARD
COMMERCIAL TV	TELEPHONE	LIBRARY ACCESS
INSTRUCTIONAL TV	VIDEOPHONE	NEWSPRINT AND MAGAZINES
COMMERCIAL RADIO	TELEGRAPH/TELETYPE	COMPUTER SERVICES
INSTRUCTIONAL RADIO		INTERACTIVE INSTRUCTION
		TIME-SHARED COMPUTATION
		AIDED DESIGN
		TRANSACTION EXCHANGE
		REMOTE VENDING
		AIRLINE AND THEATRE TICKETS
		POINT OF SALE VENDING
		BANKING AND CREDIT
		SECURITIES
		POLLING
		METER READING
		VOTING
		TV SHOPPING
		MAIL
		ALPHANUMERIC
		GRAPHIC

SOURCE : EIA RESPONSE TO FCC DOCKET 18397, PART V, ELECTRONIC INDUSTRIES ASSOCIATION, OCTOBER 29, 1969.

problems will arise from implementation of these services and studies of their impact during inception must be made so that undesirable effects might be prevented.

Whether the Canadian cable television industry will play a significant role in the development of the optical cable television system and eventually, the wired city system, depends very much on the decisions and actions taken in the coming years. By actively participating in the technical development, the industry may secure a firm position in the wired city scheme while fostering the growth of a Canadian industry that may dominate the world market. Otherwise, the cable television industry will be confined to the role of distributing broadcast signals. Challenging but interesting problems await the future of cable television.

REFERENCES

(1) Robert V. Bruce, Alexander Graham Bell and the Conquest of Solitude , Little Brown & Co., Boston, Mass., 1973, p. 337.

(2) Arthur L. Schawlow, "Advances in Optical Masers", Scientific American, Vol. 209, No. 1 , July 1963, p 34 - 45.

(3) Frederick F. Moorehead Jr., "Light-Emitting Semiconductors", Scientific American, Vol. 216, No. 5, May 1967 , p 108 - 122.

(4) Ralph W. Campbell and Forrest M. Mims III, Diode Lasers , Howard W. Sams Co. Inc. Indianapolis, Indiana, 1972.

(5) W. Bart Bielawski, "Low-Loss Optical Waveguides: Current Status", Electro-Optical System Design, Vol. 5, No. 4, April 1973, p. 23-28.

(6) Y. Kinoshita, Institute for Future Studies, Tokyo, Japan, private communication.

(7) Morton B. Panish, "Heterostructure Injection Laser", Bell Laboratories Record, Vol. 49, No. 11, November 1971, p. 299-304.

(8) Joseph E. Geusic, William B. Bridges and Jacques I. Pankove, "Coherent Optical Sources for Communications", Proceedings of the IEEE Vol. 58, No. 10, October 1970, p. 1431-1435.

(9) W.E. Martin and D.J. Albares, Fiber and Integrated-Optic Communication Technology , NELC/TR1891, Naval Electronics Laboratory Centre, San Diego, California, August 1973, p. 7.

(10) F.L. Thiel and W.B. Bielawski, "Optical Waveguides Look Brighter than Ever", Electronics, Vol. 47, No. 6, March 21, 1974, p. 91.

(11) Corning Glassworks Telecommunication Products Dept., Product Information Bulletin No. 1, 1974.

(12) P. Kaiser and H.W. Astle, "Low-Loss Single-Material Fibers Made from Pure Fused Silica", Bell System Technical Journal, Vol. 53, No. 6, July-August, 1974, p. 1021-1039.

(13) The Journal of the Institute of Electronics and Communication Engineers of Japan, Vol. 57, No. 6, June 1974, p. 763.

(14) C. A. Burrus, "Radiance of Small-Area High-Current-Density Electroluminescent Diodes", Proceedings of the IEEE, Vol. 60, No. 2, February 1972, p. 231-232.

(15) I. Hayashi, Nippon Electric Company, Japan, Private Communication.

(16) B.C. DeLoach Jr., "The Physics of Failure of GaAs Solid State Lasers" paper presented at the VIII International Quantum Electronics Conference, June 1974, Digest of Technical Papers, No. I.1.

(17) Hiroshi Kojima and Keigo Shimono "Reliability of GaP Light Emitting Diodes", Toshiba Review, Vol. 28, No. 4, 1973, p. 388.

(18) I. Hayashi, "Progress of Semiconductor Lasers in Japan", paper presented at the 1973 IEEE/OSA Conference on Laser Engineering and Applications; Digest of Technical Papers, No. 12.8, p. 69,70.

(19) F.W. Ostermayer Jr., R.B. Allen and E.G. Dierschke, "Room Temperature CW Operation of a $GaAs_{1-x}P_x$ Diode-Pumped Nd:YAG Laser" Applied Physics Letters, Vol. 19, No. 8, Oct. 15, 1971, p. 289-292.

(20) David A. Draeyent "Single-Diode End-Pumped Nd:YAG Laser", IEEE Journal of Quantum Electronics, Vol. QE-9, No. 12, Dec., 1973, p. 1146-1149.

(21) F.L. Thiel and W.B. Bielawski, "Optical Waveguides Look Brighter than Ever", Electronics, Vol. 47, No. 6, March 21, 1974, p. 93.

(22) D.C. Johnson and B.S. Kawasaki, The Coupling of Light from Light-Emitting Diodes into Optical Fibers: The Analysis of Close-Coupling Geometry, Communications Research Centre Report No. 1250, Dept. of Communications, Government of Canada, Jan. 1974.

(23) F.L. Thiel and W.B. Bielawski "Optical Waveguides Look Brighter than Ever", Electronics, Vol. 47, No. 6, March 21, 1974, p. 91.

(24) Masaaki Imai and Elmer H. Hara "Excitation of Fundamental and Low-Order Modes of Optical Fiber Waveguides by Gaussion Beams", I:T:Hed Beams", Applied Optics Vol. 13, No. 8, Aug. 1974, p. 1893-1899.

(25) Stewart E. Miller, Tingye Li, and Enrique A.J. Marcatili, "Research Toward Optical-Fiber Transmission Systems Part II: Devices and Systems Considerations" Proceedings of the IEEE, Vol. 61, No. 12, Dec. 1973, p. 1733-1736.

(26) M.K. Barnoski, Editor, Introduction to Integrated Optics, Plenum Press, New York, 1973.

(27) Electronics, Vol. 47, No. 15, July 25, 1974, p. 38-39.

(28) K.O. Hill, "Aperiodic Distributed-Parameter Waveguides for Integrated Optics", Applied Optics, Vol. 13, No. 8, August 1974, p. 1853-1856.

(29) Optical Spectra, Vol. 8, Issue 4, April 1974, p. 22.

(30) The Journal of the Institute of Electronics and Communication Engineers of Japan, Vol. 56, No. 1, January 1973, p. 148.

(31) Bell Laboratories Record, Vol. 50, No. 5, May 1972, p. 162.

(32) C.G. Someda, "Simple Low-Loss Joints Between Single-Mode Optical-Fibers", Bell System Technical Journal, Vol. 52, No. 4, April 1973, p. 583-596.

(33) D. Schicketanz, "Connectors for Multimode Fibers", Siemens Forsch.-u. Entwickl.-Ber.,Vol.2, No.2, 1973, p. 204-205.

(34) W. Bart Bielawski, "Low-Loss Optical Waveguides: Current Status", Electro-Optical Systems Design, Vol. 5, No. 4, April 1973, p. 28.

(35) Electronics, Vol. 46, No. 26, December 20, 1973, p. 30-31.

(36) Ronald K. Jurgen, "Two-Way Applications for Cable Television Systems in the 70's", IEEE Spectrum, Vol. 8, No. 11, November 1971, p. 39-54.

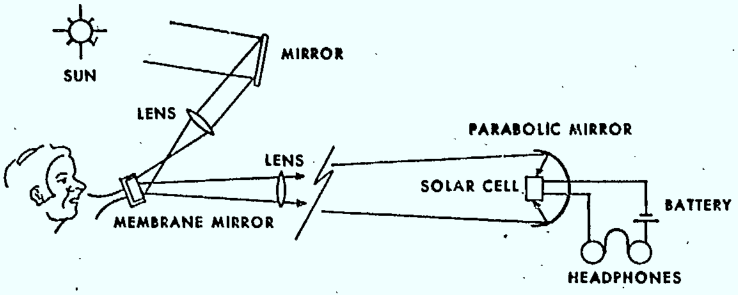
(37) Gerald M. Walker, "Stringing the Wired City : Two-Way TV Descends from Blue Sky to Real World", Electronics,Vol. 44, No. 2, September 27, 1971, p. 44-55.

(38) Laser Focus, Vol. 10, No. 8, August 1974, p. 67.

(39) R.W. Dawson, "Effect of Ambient Temperature on Infrared Transmission Through a Glass Fiber", Bell System Technical Journal, Vol. 51, No: 2, February 1972, p 569 - 571.

(40) Stewart E. Miller, Tigye Li and Enrique A.J. Marcatili, "Research Toward Optical-Fiber Transmission Systems Part II: Devices ans Systems Considerations" Proceedings of the IEEE, Vol. 61, No. 12, Dec.1973, p. 1734.

THE PHOTOPHONE—1880
Alexander Graham Bell



I have heard a ray of sun laugh and cough and sing!

We may talk by light to any visible distance without any conducting wire

'Alexander Graham Bell and the Conquest of Solitude'
Robert V. Bruce
Little, Brown & Company p337

Fig. 1

The Photophone

The sunlight is projected onto a membrane mirror which vibrates according to the acoustic waves that are received. The vibrations intensity modulate the sunbeam which is transmitted over a distance through the atmosphere. The receiver focusses the modulated light onto a selenium cell which converts the intensity modulated light onto a modulated electric current which is passed through a set of headphones. The headphones convert the electric current modulation back to acoustic waves.

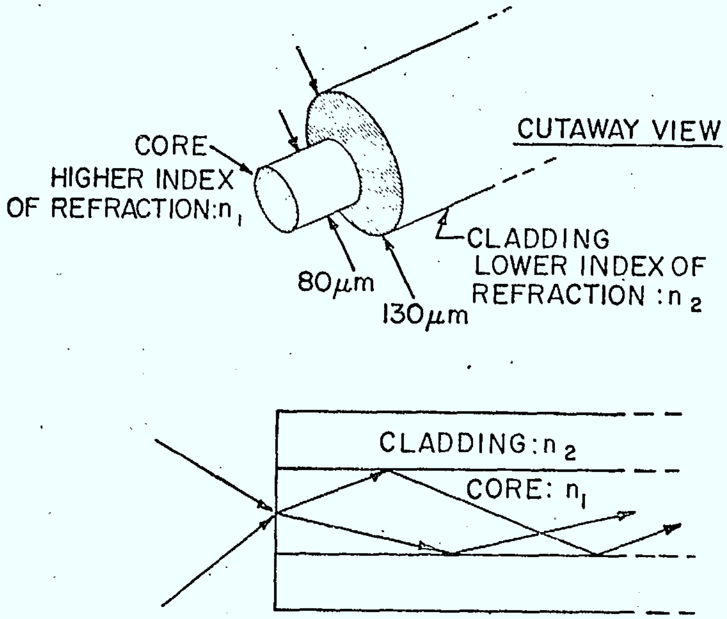


Fig. 2

The Optical Fiber Waveguide

The material is glass or fused quartz. Plastics may also be used in limited cases. Propagation of light through the fiber is by total internal reflection.

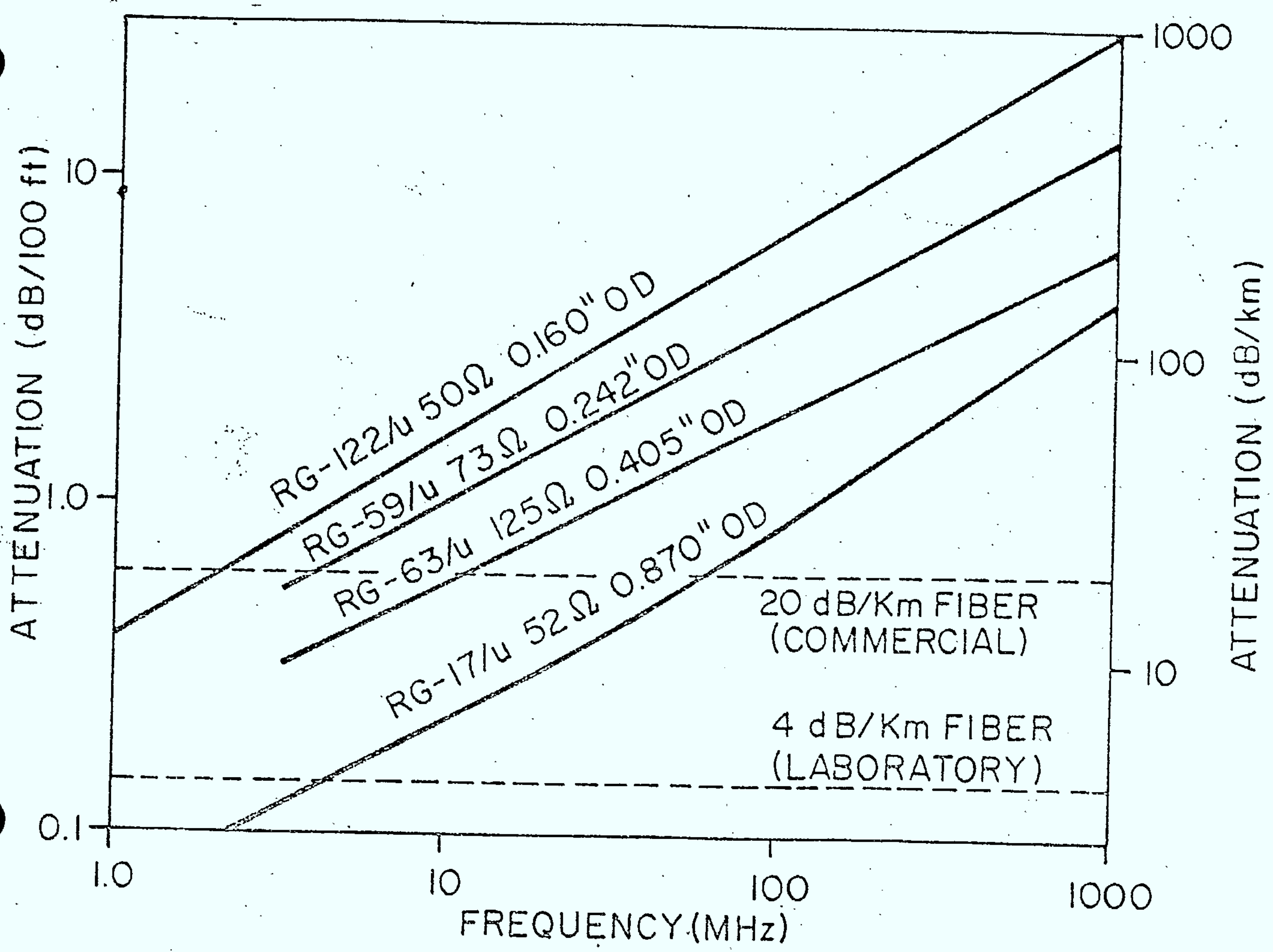
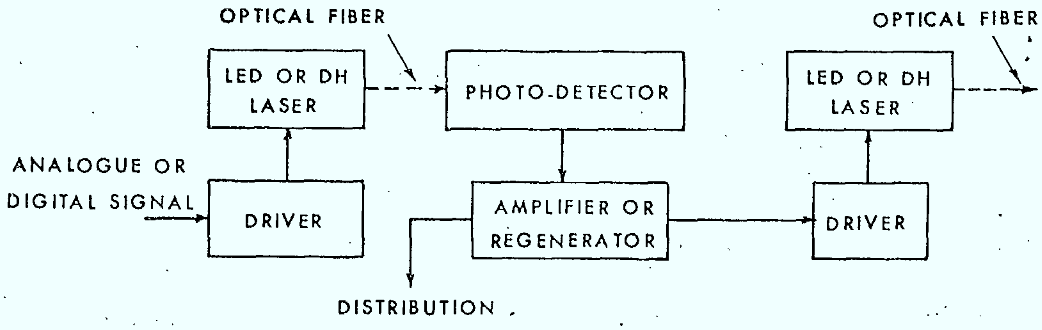


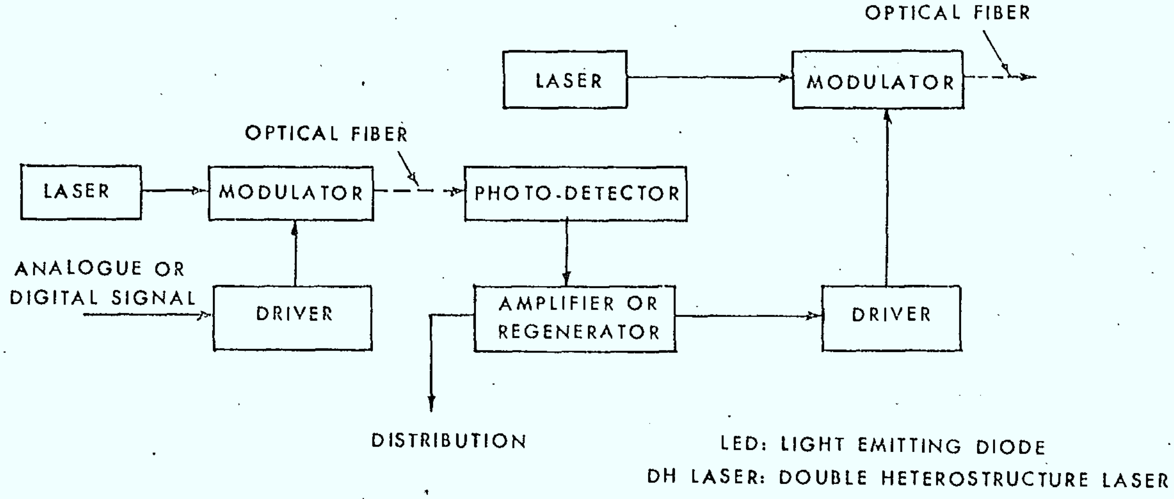
Fig. 3

The Attenuation Factor

The attenuation of a coaxial cable increases with frequency. In comparison, the optical fiber waveguide has essentially a constant frequency response over a comparable bandwidth. The attenuation values for the fiber are for the infrared wavelength of 0.9 μm.



(a)



(b)

Fig. 4

Optical Communication Systems

(a) Direct modulation of the light source is employed.

(b) An external modulator is employed.

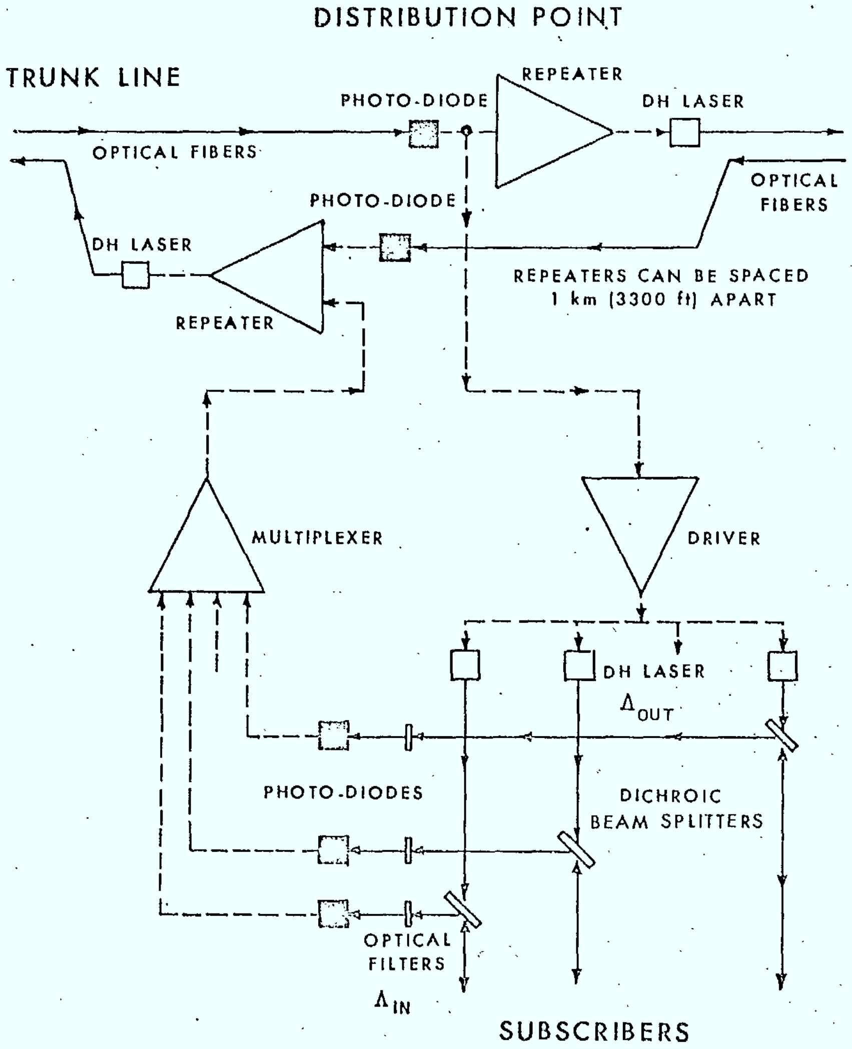


Fig. 5

Distribution Point

The solid lines represent optical signals and the dashed lines represent radio signals.
The trunk line is bidirectional through spatial multiplexing.
The subscriber lines are bidirectional through wavelength multiplexing.

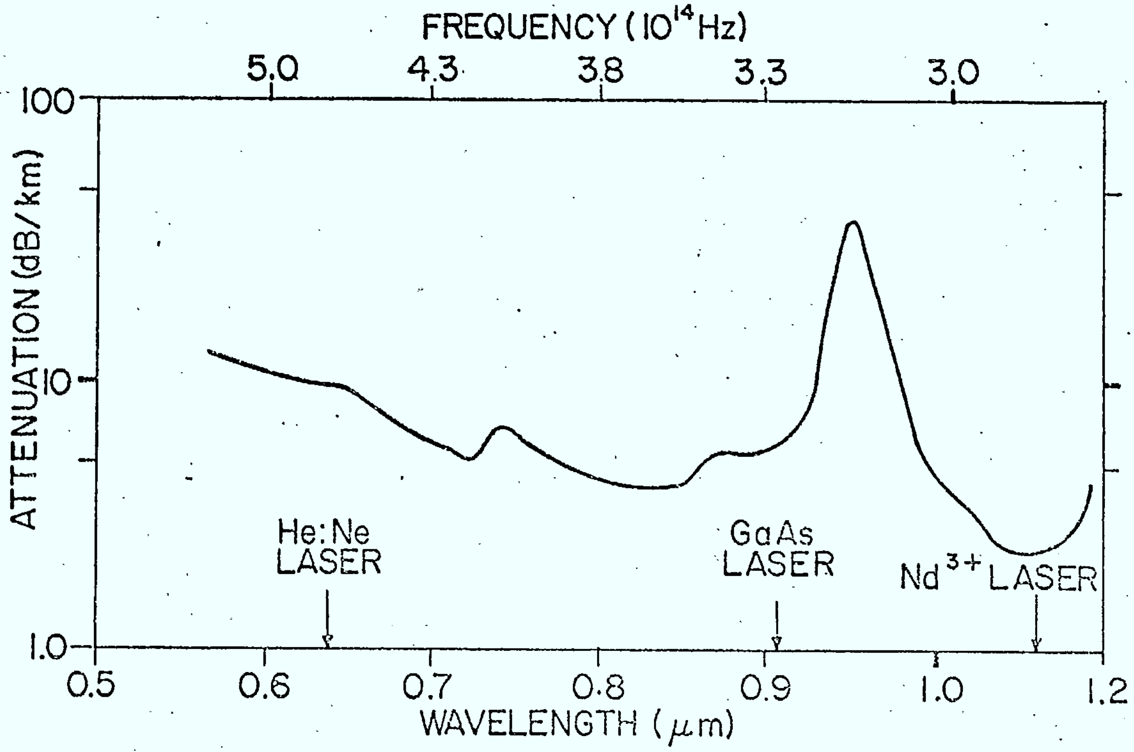


Fig. 6

Optical Fiber Waveguide Attenuation

The attenuation decreases with increasing wavelength except for the large peak in the neighbourhood of 0.95 μm which is caused by water. The Nd^{3+}:YAG laser and the GaAs semiconductor DH laser emits at wavelengths where the attenuation is low. The LEDs also emit wavelengths that correspond to regions of low attenuation between 0.8 μm to 0.9 μm.

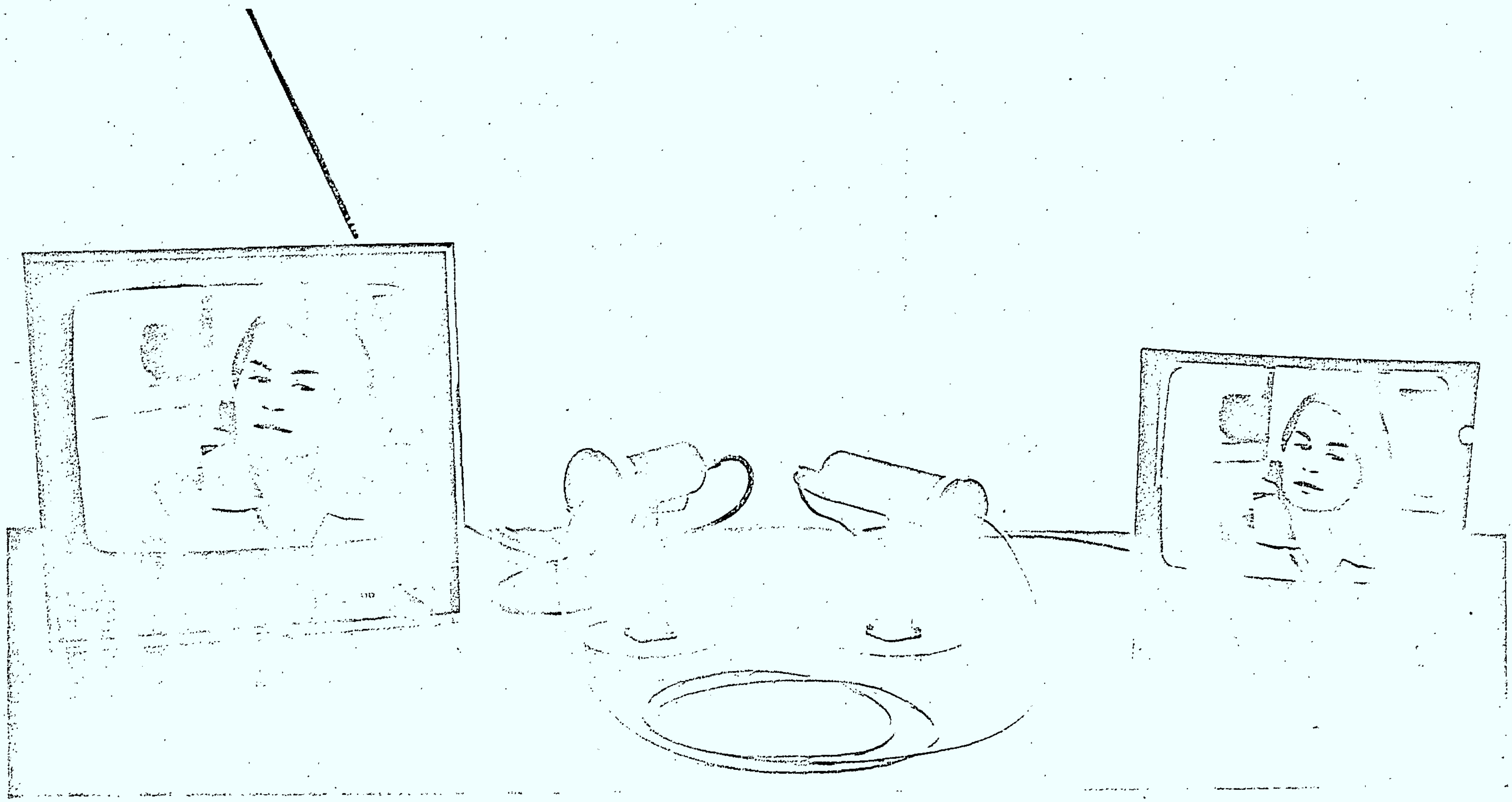


Fig. 7

Optical Fiber Waveguide Television Link

A television broadcast signal is received by the TV set on the lefthand side of the figure and the baseband video signal is transmitted through an optical fiber bundle to the monitor TV set on the righthand side.

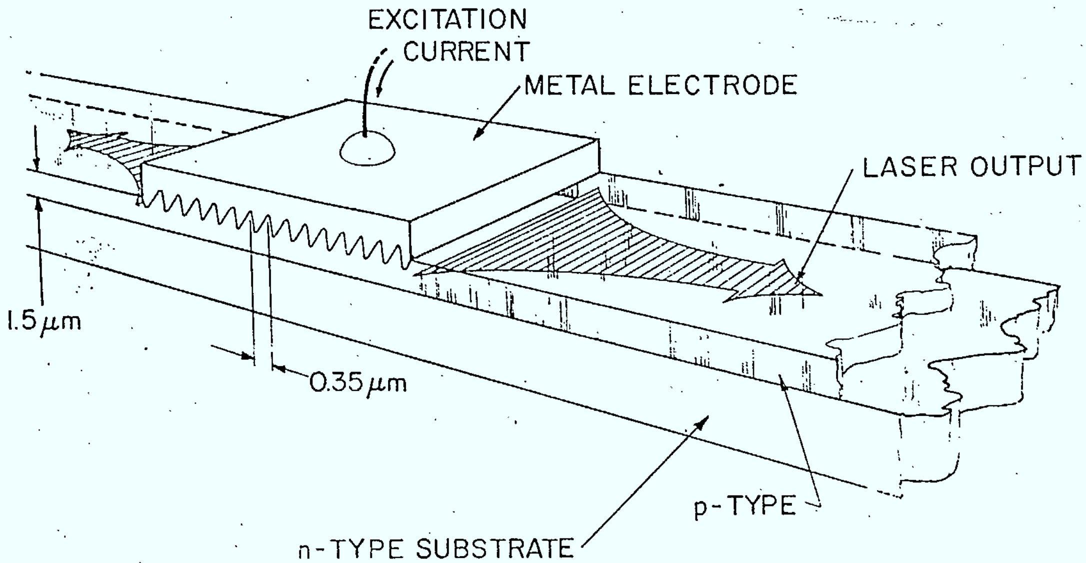


Fig. 8

<u>Distributed Feedback Laser</u>

The corrugated structure establishes a feedback condition which corresponds to a high Q resonator.