Photons in Fibers for Telecommunication

Glass fibers may replace copper wires for carrying voice, data, or video signals in telecommunications systems.

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The prospective use of glass fibers in telecommunications is no accidental result or byproduct of another interest in electronics. Schawlow and Townes reported (*1*) the conception of a coherent oscillator or amplifier in the visible or near infrared region in 1958. It was based on stimulated emission and was related to a centimeter-wave device that was described 4 years earlier (*2*). The coherent visible source, which became known as the laser, was unique. No other highly coherent source existed in the visible region, and its potential usefulness in telecommunications was immediately recognized. The optical carrier (*3*), with a frequency 10^4 times higher than microwave carriers, could have superimposed on it an information bandwidth also larger by orders of magnitude.

Maiman built the first solid-state laser in 1960 (*4*), and Javan *et al.* (*5*) devised the gaseous laser in 1961. These and other developments had broad applications possibilities to communications, and led to rapid research on materials, optical devices, and optical transmission media. This research was reviewed by Kompfner in 1965 (*6*).

During the next 5 years a great deal of progress was made (*7*). Intercity communications proved technically feasible with a transmission medium consisting of periodically placed glass lenses, periscopic mirrors, or gas lenses, enclosed in an underground conduit system. However, large initial costs for such installations needed the support of large service requirements (over 10^{11} bit/second on an individual route) in order to make the system economics attractive. The glass-lens or periscopic-mirror beam waveguides were not adaptable to use through crowded conduits in the city. Either more refined gas-lens guides or an alternative was required.

Point-to-point radiolike transmission through the atmosphere was studied with the conclusion that reliable path lengths are limited to a few hundred meters by snow, fog, and rain. Such paths may become useful for special-purpose applications.

Glass fibers were seen as a conceptually attractive but unfortunately highly lossy transmission medium [typically over 1000 db (*8*) per kilometer]; the light-wave signal became "lost" in the noise after only a few meters of travel in existing fibers. An early publication by Kao and Davies (*9*) indicated very much lower losses in bulk fused silica, and this stimulated a concerted effort to make low-loss fibers by several groups. In Japan, workers proposed making a continuously focusing medium by grading the transverse index distribution in a glass fiber; they called it "Selfoc" and made a series of novel distributed image-focusing elements as well as a fiber transmission line (*10*). Theoretical work in this area came as early as 1965 (*11*), and a U.S. patent covering a graded-index fiber was issued in 1969 (*12*). In England, a consortium was formed to explore fibers for transmission, spurred by speculation that lower losses might be achievable. In all, four groups—Bell Laboratories, an English consortium, Nippon Sheet Glass–Nippon Electric, and Corning Glass Works—put forth strong efforts in parallel to try to bring losses down from values typical of fibers in medical instruments (1 db/m) to values of potential viability for telecommunications. The Corning group achieved significant results in 1970, producing a single-mode fiber hundreds of meters long in which light-wave loss is less than 20 db/km (*13*).

Later, MacChesney *et al.* (*14*) announced a new fabrication process, a modified chemical vapor deposition (MCVD) process which led to lower losses and improved fiber-design parameters. Numerous industrial and university groups are now making fibers in which losses are 2 db/km or less. The general size, physical flexibility, and cost of glass-fiber (fiberguide) cables resemble those same features of wire cables, and fiberguides are seen as potentially applicable wherever wire-pairs or coaxials are now employed. I shall show that light-emitting diodes (LED's) as well as lasers can be used as optical carrier generators; LED's are an attractive low-cost candidate for short-distance transmission in on-premises or aircraft or shipboard applications, while lasers make possible systems with much higher information rates such as might be used between cities or between central offices in the metropolitan area telephone plant.

Elementary Fiber Link

The optical portions of all such systems are similar and simple; they consist of a carrier generator (laser or LED), fiberguide cable, envelope detector [simple semiconductor-junction (PIN) or avalanching photodiode], and conventional electronics to drive the carrier generator and to follow the detector. The information rate or bandwidth required on the link, in combination with the desired link length, lead to the choice between laser or LED and to selection of one of the fiber types described below.

Two slightly different kinds of glass are used for the core and the cladding of fibers, giving the core a slightly higher index of refraction than the cladding. The electromagnetic-wave modes guided in the core have fields that decay radially in the cladding; with appropriate cladding thickness, very little influence on core modes is produced by the wave properties of the jacket or regions exterior to the jacket. Single-mode guidance is obtained with a core diameter of about 5 micrometers and an index difference between core and cladding of about 0.5 percent. Multimode fibers are necessary for carrying significant amounts of power from a LED; typical core diameters are in the 50- to 75-μm range with an index difference of 1 or 2 percent.

In the multimode fiber case there are subtleties associated with the transverse index distribution (Fig. 1) which have profound effect on the pulse-spreading or "delay distortion" property of the fibers. For so-called step-index fibers (uniform core index, $g \rightarrow \infty$ in Fig. 1), the

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←*Courtesy Bell Laboratories*

various core modes travel with markedly different group velocities. By grading the index the relative group velocities of the core modes can be made much more nearly equal, resulting in less pulse broadening. These effects can be stated in terms of digital transmission capability; for step-index fibers with $\Delta = 1$ percent (Fig. 1), the fiber capability is a bit-rate-distance product of 18 megabit-kilometers (Mb-km). This means that a fiber 1 km in length could carry digital signals at an 18-Mb rate without significant error, or alternatively, a 500-m-long fiber could carry signals at a 36-Mb rate. A near optimum grading of the transverse index distribution (a g value of about 2 in Fig. 1) raises this capability theoretically to around 14,000 Mb-km, or almost 1,000 times the capability of the step-index fiber (*15, 16*). Graded-index fibers having a transmission capability of 75 to 100 times the step-index fiber have been made in the laboratory, and research continues.

The largest transmission capability is theoretically available with single-mode fibers, in which wavelength dispersion proves to be limiting. Here with an 0.8-μm laser having a spectral width of 1 angstrom, the capability in fused silica is about 50,000 Mb-km.

The simplest and least expensive carrier generator for the fiber link is a LED; the message is imposed as a driving current variation, resulting in an emission brightness variation. The efficiency of coupling to the fiber is low, because of the incoherent nature of the emission; however, anywhere from 100 microwatts to a few milliwatts can be coupled into a telecommunications fiber, depending on the value of Δ (Fig. 1).

The semiconductor injection laser, in which stimulated electron-hole recombination emission is used, is a far more efficient carrier generator. With special care the laser can be made to oscillate in a single transverse mode, and most of the output can be coupled into the fiber. Continuous operation at outputs near 1 mw and pulsed low-duty-cycle output on the order of 1 watt have been achieved. At present, the materials used in such lasers are aluminum, gallium, and arsenic (AlGaAs system), with emission at 0.82 or 0.85 μm wavelength (*17*).

Attempts are being made to develop carrier generators with emission wavelengths of 1.0 to 1.5 μm, because (i) the fiber loss is lower at longer wavelengths (see Fig. 2), and (ii) fibers have less wavelength dispersion in the 1.0 to 1.5 μm region. Wavelength dispersion is still being studied, but it is known that the dispersion of pure fused silica has a minimum near 1.25 μm, and the dopants added move this optimal wavelength only slightly. At 0.82 μm the spectral width of the AlGaAs LED (about 350 Å) leads to pulse spreading in pure fused silica of about 4 nanoseconds per kilometer; this gives the LED-fiber combination a transmission capability of about 100 Mb-km as limited by wave-length dispersion. The AlGaAs injection laser typically has a spectral width of about 20 Å, leading to pulse spreading at 250 picoseconds per kilometer.

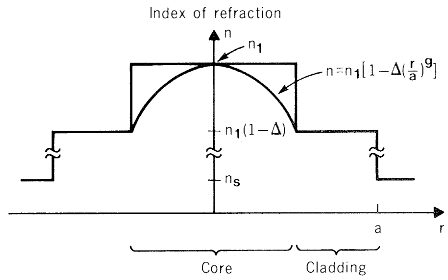


Fig. 1. Profiles of index versus radius for graded-index and step-index ($g = \infty$) fibers (fiber diameter = 2a). Symbols: a, fiber radius; r, distance from core center; g, parameter determining profile shape; n_s surrounding refractive index).

A new laser has been developed that has both longer emission wavelength (1.06 or 1.3 μm) and narrower spectral width (1 or 2 Å); this is the single-crystal Nd:YAG (neodymium doped yttrium aluminum garnet) fiber laser, pumped by an AlGaAs LED. Other contenders for future fiber systems use are the GaAsSb injection laser (*18*) and the InGaAsP injection laser (*19*), both of which have been operated as continuous wave oscillators.

The final optical element in the elementary fiber link is the detector. Either the simple PIN silicon diode or the avalanching photodiode is employed; the hole-electron pairs created by the incident photons are swept out by a static applied field, yielding a conduction current carrying the modulation of the incident light intensity. The PIN is less expensive, but yields a weak signal which may be obscured by thermal noise in the following amplifiers. The avalanching detector yields a current larger by 10 to 100 times, and this rides above the thermal noise of following amplifiers. The avalanching detector is more complex and therefore more expensive, and also requires a precisely set bias potential which must be reset to follow ambient temperature changes. The net result is to reserve the higher-cost high-performance avalanching detector for those applications where the performance of the PIN detector is inadequate (or where the incremental cost of the avalanching detector assembly results in system savings elsewhere).

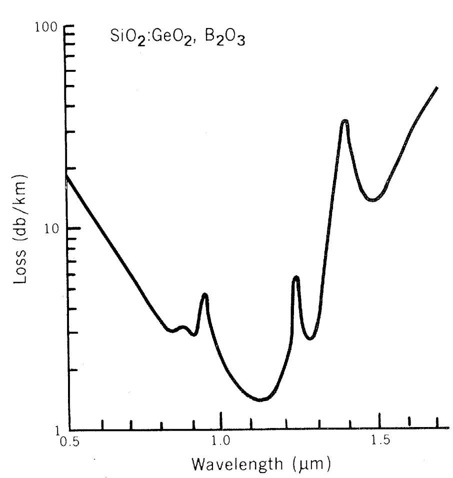


Fig. 2. Loss plotted against wavelength for a good multimode silica fiber in which GeO_2 and B_2O_3 were used as dopants. [From Kaiser and MacChesney (*37*)].

Silicon detectors are useful at wavelengths up to about 1.06 μm; beyond that the absorption falls off catastrophically and either germanium or one of the semiconductor compounds must be used. Only silicon detectors meet all performance requirements now (such as low dark current and reproduceability), but with the interest in the 1.0- to 1.5-μm region already noted investigators are looking for other satisfactory materials.

Fiber and Cable Fabrication

One of the most novel aspects of fiber-guide transmission is the science and technology of telecommunications fiber and cable fabrication. But let us consider first the carry-over of older techniques. The rather remarkable formability of glass is utilized in a very straightforward way (Fig. 3), which also shows enlarged view. The preform is on the order of 1 or 2 cm in diameter and 40 to 100 cm long, and is a scaled-up model of the fiber desired. The center of the preform is made of the glass composition desired in the fiber core, usually nearly pure silica with a few percent of an additive, or dopant, such as germanium, boron, phosphorus, or combinations of these elements. The outer shell of the preform is made of the glass desired as the fiber cladding, frequently silica with boron as the dopant. Then in a single operation the fiber is drawn, a 100 to 1 diameter-reduction ratio and a fiber-pulling velocity of 1 m per second being typical. New techniques for controlling diameter (on-line measurement plus feedback) and for preserving high strength have been added to the system as a consequence of the potential telecommunications applications of these fibers.

The preform needed is a recent development. The preferred graded-index distribution of Fig. 1 required a new approach, as did the need for glass purity of a new order. There are of course two broad classes of losses to be minimized: absorption loss, caused in part by electronic transitions in impurity ions, and scattering losses caused by inhomogeneities. Figure 4 shows the added bulk losses to be expected in pure fused silica with the impurities noted. In order to get down near the intrinsic Rayleigh scattering limit one needs no more than one part in 10^6 of the OH radical, three parts in 10^9 of Cu^{2+}, or one part in 10^8 of Fe^{2+}, for example. Other transition elements are similarly troublesome. Systems containing high concentrations of silica have proved most practical. Two methods of fabricating high-silica preforms have appeared; the first is the soot-deposition process (*20*) and the second is the modified chemical vapor deposition (MCVD) process. Both methods have produced fibers in which light-wave losses are very low, although the MCVD process appears to have been more widely adopted because of its simplicity and because it can inject higher percentages of dopants. Adjustment of the doping level of the successive layers of glass according to a programmed plan can yield the transverse index profile desired. In Fig. 2, the fiber doped with Ge and B shows peaks near 0.95 μm, 1.2 μm, and 1.4 μm which are all due to the presence of OH^-. Even greater purity has been reported (*21*) by several Japanese workers, with material losses dipping below 1 db/km near 1.2 μm.

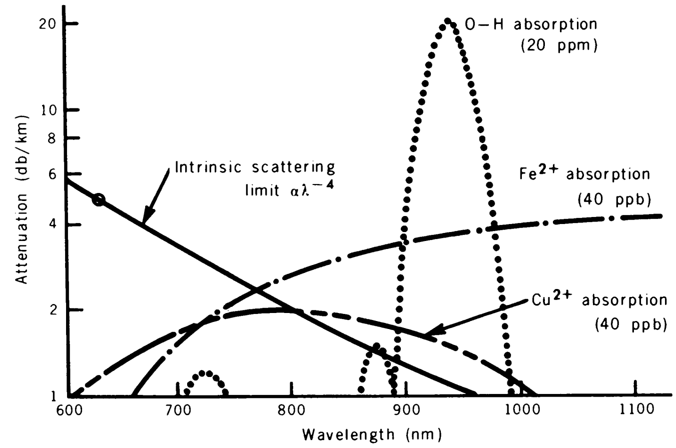


Fig. 4. Typical loss contributions for fused silica. Concentrations of impurity ions for O–H, Fe^{2+} and Cu^{2+} lead to the absorptions shown. For pure fused silica the intrinsic Rayleigh scattering loss, varying as λ^{-4}, is also shown.

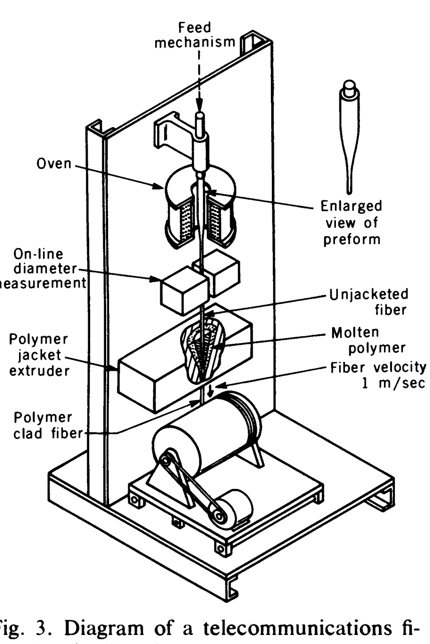


Fig. 3. Diagram of a telecommunications fiber-drawing bench.

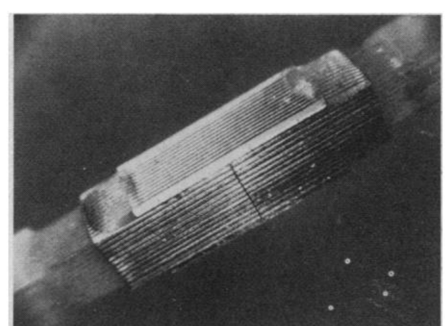
However, a low-loss fiber is just the beginning of achieving a low-loss fiberguide cable. The most novel aspect of cabling optical fibers stems from an electromagnetic wave propagation effect: axial kinks, or minute changes in direction at length intervals of the order of 1 mm, such as can be created by winding a fiber tightly on a drum having a rough surface, can cause coupling from the core-guided modes to a radiation field and can easily result in added losses in the 5 to 50 db/km range (*22*). A solution, proposed by Gloge (*23*), is to form a minute composite structure which isolates the fiber from external mechanical influences. However it is done, the fiberguide must be constructed in such a way as to avoid "microbending" losses, as they are called.

In the most common form of cable, the communications fibers are protected by plastic jackets and strengthening components, and the communications fibers are handled individually at the cable ends. Such cables have been made at Bell Laboratories, where another approach has also been explored. The fibers are first grouped into ribbon-like arrays (*24*) so that all subsequent splicing and handling can be done on the ribbon assembly. Figure 5 shows a ribbon assembly (12 fibers per ribbon, 12 ribbons per cable) in end view and in a completed splice. Here the 144 fibers were first aligned in grooved chips (preferentially etched silicon chips) and faced off to form a solid array which was mass spliced to an identical mate (*25*). A 658-m section of this cable was used in a fiberguide system experiment at Atlanta. In that section, 138 of the 144 fibers survived the cable-making process; no fiber breakage occurred during installation in ducts reasonably typical of commercial installations; and the final mean loss of all surviving fibers was 6.0 db/km at 0.82 μm, an increase of 1.3 db/km over the mean uncabled loss of the same fibers, the change being attributed to microbending (*25*).

Fiber Connectors and Splicing

More new structures are required in fiberguide transmission systems to provide both permanent splices and fiberguide connections which can be disengaged. The background of theory can be summarized as follows: The requirement on transverse alignment of the fiber ends is about 0.2 core radius for approximately 0.2 db loss. For single-mode fibers, 0.2 core radius is about 1 μm, a requirement that is likely to be expensive to meet. For that reason, single-mode fibers are likely to be used only where the single-mode performance is essential.

Longitudinal end separation can be on the order of a core radius for about 0.1 db loss (with a bridging fluid or solid at the joint), so this requirement is not as critical as that for the transverse align-



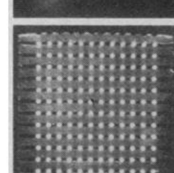


Fig. 5. (Top) Completed splice showing two connectorized ends aligned by grooved chips. (Bottom) End view of twelve tapes assembled in grooved chips for use as a prefabricated connector (*38*). [Courtesy of M. I. Schwartz]

ment, especially for multimode fibers where the core radius is about 25 μm.

In a splice or demountable connector it is essential to have a properly prepared fiber end. A refinement of the "score-and-break" technique, in which the fiber is subjected to simultaneous tension and controlled-radius bending, yields ends that are smooth and perpendicular to the axis. This has been demonstrated not only on single fibers (*26*), but also on tape arrays of fibers (*27*) wherein the entire array is prepared in a single step.

Single-fiber splices have been accomplished by several groups. Such splicings were achieved by slipping the two ends into a close-fitting round sleeve and gluing them together as a butt joint. This yielded rather high losses when fiber diameter tolerances were accommodated. In an innovation of this method, the ends are assembled within a square tube in the presence of a bending moment. The fibers align themselves accurately in one of the corners, and losses on the order of 0.1 db are reproducibly achieved (provided that the fiber diameters are comparable).

Figure 6 shows a single fiber connector that has found application not only in "patch cord" applications but also as a plug-in fiber connector on plug-in electronic circuit assemblies. A molded male with tapered end mates with a biconical female; a compliant solid bridges the gap across the fiber ends. Mean connection losses under 0.4 db have been achieved (*28*).

The splicing of an entire tape array of fibers has been accomplished in a single step by aligning the fibers in an embossed chip and sealing them with epoxy glue (*29*).

Transmitter-Receiver Electronics

In a fiber-optic telecommunication system, the electronic circuits which drive the laser-LED or which follow the detector are mostly conventional, but there are a few critical points to note. The laser has a sharp threshold of oscillation, and must not be driven very far above that point or damage may result. Furthermore, the threshold current changes during the life time of the laser and is sensitive to ambient temperature changes. As a result, stabilizing electronics is required to control the laser's operating point. Similarly, the avalanching photodiode detector (APD) requires a static bias critically related to avalanching gain and signal-to-noise ratio; this bias must also be changed as the ambient temperature changes. The solution is another auxiliary circuit. For the above reasons the receiver electronics is less expensive for LED-transmitter and simple photodiode-receiver arrangements than for the laser-APD arrangement; the latter is likely to be used only where the larger signal-to-noise range is required.

Initial fabrication of repeater assemblies has combined the current technology, in which plug-in circuit boards and thin-film or integrated circuit assemblies are used, with the optical elements. Further integration of the fiber connector with the associated electronics will probably be achieved in the future, so that the result will be a single package (*24*).

Modulation Format

The modulation format is usually dictated by the signal being transmitted, and either analog or digital transmission can be used. It is noteworthy that the photodiode detector yields electrons for photons received, so the output modulation current is directly proportional to lightwave power input—a square-law relationship. This works out to favor a signal format with a large peak factor for favorable ratio of signal to thermal noise.

For digital signals, Fig. 7 shows the required number of photoelectrons per bit (or received signal power level) as a function of bit rate (*15, 30*). The upper band implies simple photodiode (PIN) detectors, and the lower band implies APD detectors with optimal avalanche gain ranging from 25 to 100 as indicated on Fig. 7. Research model receivers performing within these bands have been built with both PIN and APD detectors at 6.3 Mb/second, 45 Mb/second, and 274 Mb/second (*15*).

Digital transmission can be advantageous, not only where the customer's signal is digital (as with computers or data processing), but also where an analog (continuously varying) signal such as voice or video is to be transmitted. The analog signal is periodically sampled, and each sample value sent as a coded group of on-off pulses. Hence the name pulse-code modulation (PCM). A major advantage is that the PCM signal can be regenerated to eliminate accumulated noise at each amplification point, permitting far longer systems than is feasible with analog transmission. The disadvantage of PCM is the cost of the coder-decoder which is required.

A preferred form of analog transmission for lightwave systems is pulse-posi-

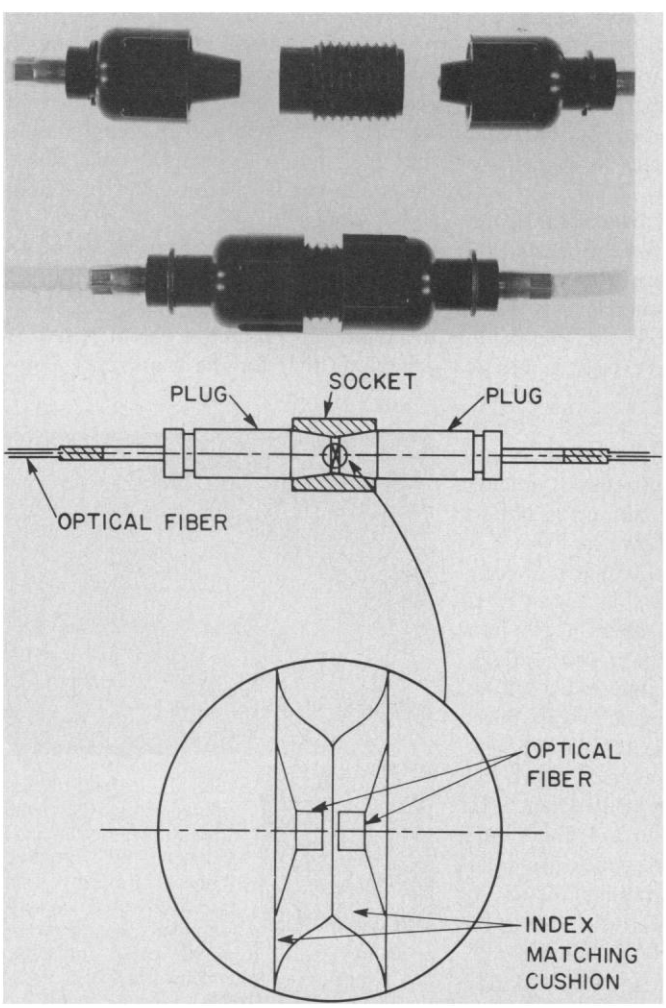


Fig. 6. Single-fiber connector designed by P. K. Runge of Bell Laboratories. The two identical males mate with a biconical female and yield a mean connection loss under 0.4 db. Fabrication of both males and female is by transfer molding, an inexpensive process (*28*).

tion modulation (PPM); here the spacing between pulses is continuously modulated by the analog signal, thus eliminating the need for the coder-decoder. The PPM system has been shown capable of transmitting a voice channel at 70 db peak ratio of signal to r.m.s. noise ratio (where r.m.s. is root mean square) through a fiberguide loss of 70 db with a LED transmitter and PIN detector (*31*), or more than about 100 db fiber loss with a pulsed laser. At today's low fiber losses, this implies that very long fiber spans might be used.

In the system noted above, PPM uses expanded bandwidth on the fiber to gain a signal-to-noise advantage, and since fibers have broad bandwidths, this is advantageous. Waveform sampling is required for PPM, with some associated complexity. An alternative way of using bandwidth expansion and avoiding the linearity requirements of simple intensity modulation is to use a frequency-modulated (f-m) subcarrier to modulate the LED or laser. This technique should be useful, particularly where an f-m analog signal may be necessary or convenient for other reasons.

Comparison with Wire-Pairs or Coaxial Cables

Lightwave transmission on fiberguide has several advantages over other means of telecommunication. (i) Small size (smaller and lighter than either wire pairs or coaxials). (ii) The fibers are tolerant of bends in the centimeter range. (iii) The fibers are nonconducting and noninductive. This is valuable in avoiding spurious ground currents, the interference effects of lightning, and possibly also the damage effect of lightning. The fiberguides do not radiate in the usual radio spectrum, that is, they are not generators of interference, nor do they pick it up. (iv) The fibers have lower losses than wire pairs or coaxials, at least for bandwidths above a few megacycles. (v) Much wider bandwidths are available with these fibers than with wire pairs at (prospectively) modest extra cost. (vi) Negligible signal interaction (or cross talk) occurs between adjacent fibers in the same cable.

Cost, the final element of comparison, is all important but difficult to pin down. Cost is extremely sensitive to volume of production. Because the principal components of fibers are abundant, in the long range at large-volume production they should become inexpensive. They are now produced in small volume and are quite expensive (approximately $10 per meter for a six-fiber cable).

Short Length Applications

There are numerous applications for short lengths of these fibers under consideration. In mid-1973, an experimental 16-Mb 30-m fiberguide link was installed in a laboratory model digital switching machine (No. 4 ESS) with a Burrus LED, a plastic-clad fused-silica fiber made at BTL Crawford Hill, and PIN receiver. Potential for satisfactory performance was established and an exploratory development is now under way (*32*). There are numerous 30-m to 400-m coaxial-cable links in the present design No. 4 ESS machine; the fiberguide alternative would be smaller, lighter, and free of interference pickup or generation. For military applications similar short links have been used on aircraft and on board ships (*33*). The use of fiberguide links in computing machines and in commercial measuring apparatus is also being considered.

For all of these links it is anticipated that LED-PIN technology is most appropriate, and once they are produced in volume these elements will be inexpensive. For some of these applications, the lifetime of the device may not be too critical, but in the No. 4 ESS machine, for example, the lifetime of the fiber links should be in the region of 10^8 to 10^9 hours to keep failure rate within system requirements. Reliability of this type is generally difficult to achieve with an infant technology.

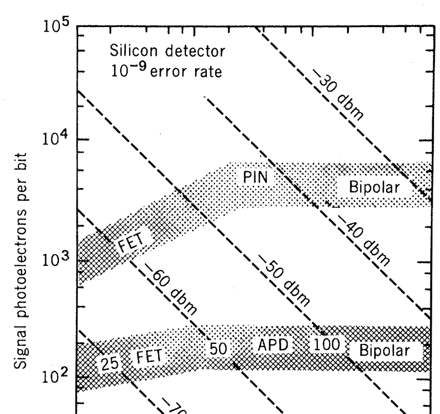


Fig. 7. Theoretical prediction of the required photons per bit for binary digital transmission at the abscissa rate with an error incidence of 10^{-9}. The dashed lines show the corresponding power level of the received signal. The band labeled PIN corresponds to use of PIN detector and low-noise electronics. The band labeled APD corresponds to use of an avalanching photodiode detector. The labels FET (field effect transistor) and "bipolar" refer to the preferred type of transistor amplifier following the detector. [Chart conceived by T. Li, based on theory of Personick (*30*)]

Fiberguide System Experiment at Atlanta

As part of Bell Laboratories' broad research effort on optical communications and to provide a focus for certain key specific development activities, planning for a fiberguide system experiment began in 1974 (*34*). Of the several prospective Bell System uses, the one selected for this exploratory effort was transmission between switching centers. Currently, extensive use is made of a pulse code modulation system which transmits 24 voice channels on a single pair of wires. The lightwave system alternative could employ any one of a number of channel groupings on a single fiber, depending on service requirements and economic tradeoffs. The Atlanta experiment was carried out initially with a 672-channel format and a 44.7 Mb/sec pulse rate.

A 144-fiber cable was fabricated in a 1-km length and cut down to fit into an existing standard underground plastic duct (*25*). Studies of fiber loss and bandwidth were made on the fibers before cabling, after cabling, and after installation in the duct. This experience serves as a foundation for any future cable design and, indeed, the initial performance fully met the designers' expectations. Further research and development will be beneficial in the areas of index profile control, structures for minimizing cabling loss, and processes for maximizing the strength of individual fibers (*35*).

The Atlanta experiment included electronics to control the avalanche photodiode and amplify its output, to perform the digital decision and retiming function, and to drive the injection laser. By using optical patch cords (short sections of fiber) a new fiberguide distributing frame containing 288 connectors, each associated with a fiber end, permits one to connect any of the various fibers of the 144-fiber cable to any of the repeater assemblies on an adjacent bay. Some of the best fibers were patched in series with 11 repeater assemblies to form a fiberguide path 64 km long with error-free transmission. The results from the Atlanta experiment have been extremely encouraging (*32*, *34*).

Other Applications

There are other prospective applications for fiberguide. One is in the local loop, the connection between the customer and the central office. Increased bandwidth, at much less increased cost than would be necessary if wires were used, is anticipated.

In intercity installations, high-capacity fibers may some day find a place; the biggest questions are probably economic rather than technologic, although research is needed to clarify which of the alternative pathways to attaining high capacity is to be preferred.

Fiberguide might also be used to provide control and communication for electrical power companies, where the insulating properties and noninductive nature of fiberguide would be great assets (*36*).

Although the United States has held a leading position in this technology, much research into the use of fibers for telecommunications is being conducted in Japan, where the service to power companies has received great emphasis (*36*). There is also considerable interest in the art in England, Germany, and France.

The Future

The pace of activity is feverish, expectations are high, and economics continues to regulate the ultimate usage of glass fibers in telecommunications. With so many fiberguide potentialities and so much effort to find economically viable applications, photons in fibers seem certain to flourish.

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$$\text{Power loss in decibels} = 10 \log_{10}\left(\frac{\text{input power}}{\text{output power}}\right)$$

The maximum tolerable power loss between amplifiers in a communication system is usually about 50 db, or a factor of 10^5.
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New Technologies for Signal Processing

Charge-transfer and surface acoustic-wave phenomena are used in advanced signal processing devices.

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The signal processors discussed here—the charge-transfer device (CTD) and the surface acoustic-wave (SAW) device—are based on new electronic design principles. Charge-transfer and SAW devices use an analog representation of information which moves along a path on a planar surface: in the CTD charge packets move in a semiconductor, and in the SAW device elastic wave energy propagates. Short-term storage of charge is possible in the CTD, and the speed of motion of charge through the device can be controlled externally, providing the opportunity to accept information at one rate and output it at another. In both the CTD and the SAW, simple means exist for sensing the moving charge or wave frequently along its path; with either technology this permits one to realize new types of signal processors based on the concept of the transversal filter, which is discussed below.

Charge-transfer and SAW devices are in similar stages of evolution. Their development until recently has been primarily in research laboratories which were perfecting the technologies. Both technologies are now sufficiently well understood that designers are beginning to incorporate them in complex electronic systems. A few of these new system applications and the advantages obtained by using either a CTD or an SAW are presented in this article. We expect that an accelerating use of these devices will be seen as system designers become more familiar with them and the devices themselves become more readily available.

Charge-Transfer Device Delay Lines

A CTD is an array of closely spaced capacitors fabricated by using metal oxide semiconductor (MOS) technology. Its operation involves the movement of a charge packet which is stored on one

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