OPTICAL FIBERS FOR COMMUNICATIONS

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INTRODUCTION

A new transmission medium is about to emerge as a competitor to copper media in many communications applications. It is the optical fiber, 100 μm or so in diameter and made principally of silica, one of the most abundant materials on earth. When suitably engineered, optical-fiber cables may be used in a variety of applications where twisted copper- wire pairs, coaxial cables, and metallic waveguides are now used for the transmission of information; these applications range from short data links and equipment interconnections within a building to long telecommunications trunk circuits connecting switching offices within a city or between cities. The small size of the individual fiber, the allowable small bending radius of the fiber cables, the large information capacity, the flexibility of system growth, the freedom from electromagnetic interference, the immunity from ground-loop problems, and the potential economy are some of the features that make optical-fiber systems appear more attractive than copper systems.

RECENT ADVANCES AND PROGRESS

Advances in research on optical fibers and cables in the past few years have been accompanied by similar progress in research on optical devices and components and on optical repeater techniques and systems.[1] Signal attenuation in fibers as low as a fraction of a decibel per kilometer and pulse dispersion as small as a few hundred picoseconds per kilometer have been reported for multimode fibers.[2,3] Several methods for coating and jacketing fibers to preserve their intrinsic strength have been applied successfully, and various techniques for cabling, splicing, and connectorizing have been developed.[4] The Burrus-type high-radiance light-emitting diode (LED) and the stripe-geometry injection laser have proved their suitability and reliability in many laboratory tests and field experiments. These aluminum-gallium-arsenide (AlGaAs) devices emit in the spectral region of 0.8–0.9 μm, where currently produced fibers have low loss. Temperature-accelerated-aging tests on a large number of such devices indicate a projected mean life of 10^6 h for the laser and 10^7 h for the LED at room temperature.[5,6]

Various optical repeaters and terminals involving LED's, lasers, photodetectors, amplifiers, and digital electronics have been built and tested at data rates up to 800 Mb/sec; their performances were measured and found to be close to theory.[7,8] During 1976 a field experiment involving optical-fiber cables in underground ducts, cable splices, fiber connectors, and optical repeaters operating at 45 Mb/sec was conducted to obtain information on the performance and reliability of an integrated system under simulated field conditions. Overall results were extremely encouraging.[9] A data-bus system using optical-fiber bundles also was tested successfully in a military aircraft.[10] Trial systems with fiber cables and repeaters carrying voice, data, and video signals have been installed in standard telephone company ducts, manholes, and central offices in the United States; similar tests are being conducted in Europe and Japan. At the same time, vital economic studies are being pursued to ferret out applications that are not only technically sound but also economically viable. With such rapid progress in research and promising results from field experiments, there is good reason to believe that optical-fiber technology will begin to have a substantial impact on the telecommunications field in the near future.

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TRANSMISSION PROPERTIES AND APPLICATIONS

Two important transmission properties of the optical-fiber cable that will strongly influence the economic viability and the areas of application of potential fiber systems are its optical loss and signal distortion (pulse spreading or dispersion). In general, low loss means long repeater spans, and small dispersion implies large transmission bandwidth over long distances. These properties also will influence the selection of system components and configurations.

For many short-distance applications, such as data links within a building where fiber runs are likely to be less than a few hundred meters, loss and dispersion need not be very low. Loss as high as several tens of decibels per kilometer and pulse spreading of a few tens of nanoseconds per kilometer are tolerable. Multimode fibers satisfying these moderate requirements now are available commercially.

The situation is different for intracity applications where the distances between telephone central offices are several kilometers and the transmission rates may range from a few to tens of megabits per second. Especially if no repeaters are to be used in manholes between central offices, loss should be less than 10 dB/km, and pulse spreading below a few nanoseconds per kilometer. Experimental cables containing multimode fibers with graded-index profiles and satisfying these criteria have been produced in research laboratories.

Requirements are most stringent for long-haul, high-capacity intercity systems. There, loss must not exceed a few decibels per kilometer and pulse spreading must fall below 1 nsec/km. The low-dispersion requirement dictates the use of either multimode fibers with a tightly controlled graded-index profile or single-mode fibers. Pulse spreading as low as 200 psec/km has been observed in experimental graded-index multimode fibers.[3] Single-mode fibers with 0.75-dB/km loss also have been produced.[11]

OPTICAL LOSS

The very-low-loss fibers of today are produced by the method of chemical vapor-phase deposition (CVD). It is one of the methods by which extremely pure glass materials (with impurity levels of transition metals less than one part in 10^8) can be obtained to satisfy the requirements of low loss. In this method, silicon tetrachloride ($SiCl_4$) gas reacts with oxygen at high temperature to form silica (SiO_2) on the inside of a quartz tube. Other suitable gases, such as $GeCl_4$, BCl_3, or $POCl_3$, for example, can be introduced at the same time to deposit dopant oxides, such as GeO_2, B_2O_3, or P_2O_5, for varying the refractive index of the deposit. After sufficient material has been deposited, the tube is collapsed at a higher temperature into a solid rod, or preform, which is then drawn into a fiber. Several kilometers of fiber can be drawn from a single preform.

The lowest loss observed to date in CVD-produced doped-silica multimode fibers is about 0.5 dB/km.[2] These low-loss fibers, which have doped-silica ($GeO_2 \cdot SiO_2$ and $P_2O_5 \cdot SiO_2$) cores and borosilicate ($B_2O_3 \cdot SiO_2$) claddings, exhibit rather wide transmission "windows" in their loss spectra, as shown in Fig. 1. The loss in the visible part of the spectrum is determined by Raleigh scattering, which is due to the frozen-in density and compositional fluctuations in the material, and by the tail of the inherent absorption band of the glass constituents in the ultraviolet region. The absorption edge on the longer-wavelength side is determined by the absorption of the OH

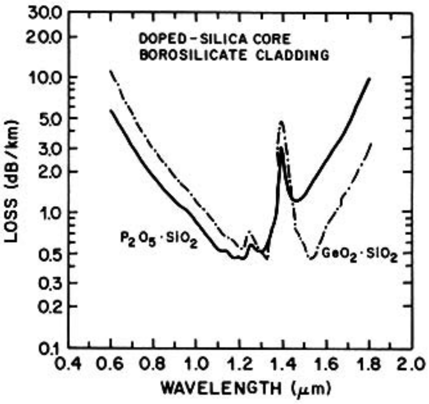

Figure 1. Loss spectra of multimode optical fibers with doped silica ($GeO_2 \cdot SiO_2$ and $P_2O_5 \cdot SiO_2$) core and borosilicate ($B_2O_3 \cdot SiO_2$) cladding (from Ref. 2).

ions present as an impurity and by the tail of the inherent absorption band of the glass constituents in the infrared region. The absorption peak near 1.4 μm is the first overtone of the fundamental stretching vibration of the OH bond at 2.72 μm.

Besides absorption and Raleigh-scattering losses, which are intrinsic to glass materials, additional losses may be introduced during fiber drawing and cable manufacturing and during actual usage of the fiber cable in the field. Factors such as macroscopic imperfections in the bulk, irregularities at the core-cladding interface, insufficient cladding thickness, microbends (minute but sharp curvatures in individual fibers) introduced during cabling, severe cable bends in usage, and imperfect splices all can cause additional loss and must be avoided. Fiber-drawing techniques now are well developed, so that geometric variations and waveguide imperfections in fibers are under control. When a coating of pliant material is applied to the fiber, which is then suitably jacketed and packaged in a cable, the excess cabling loss due to microbends can be made very small (<1 dB/km), as has been demonstrated in several experimental cables with overall losses of 4–6 dB/km.[4] It is conceivable that the loss of future fiber cables may fall below 3 dB/km in the longer wavelength region of 1–1.5 μm, making them well suited for high-capacity, long-haul applications.

DISPERSION AND BANDWITH

The information-carrying capacity of optical-fiber waveguides is limited by signal distortion in the form of pulse spreading. Pulse spreading within a single mode, or intramodal dispersion, occurs when the group velocity v_g of the mode varies with the wavelength λ. Thus intramodal dispersion is a chromatic effect that increases with the spectral width of the optical signal source. In particular, $v_g(\lambda)$ is a function of the refractive index $n(\lambda)$ and of the dimensions of the waveguide relative to λ.[12] Pulse spreading due to the variation of $dn/d\lambda$ is referred to as material dispersion. In single-mode fibers, material dispersion usually dominates over the dispersion associated with waveguide effects.[13]

Pure silica exhibits zero material dispersion near $\lambda = 1.27\,\mu m$.[14] Dispersion in borosilicate ($B_2O_3 \cdot SiO_2$) and germanium borosilicate ($GeO_2 \cdot B_2O_3 \cdot SiO_2$) glasses used for low-loss fibers has been measured in the bulk and found to be not too different from that of pure silica, as shown in Fig. 2.[14, 15] The extrapolated zero dispersion near 1.3 μm has been verified experimentally in several doped-silica fibers.[16] It is fortuitous and indeed fortunate that these fibers also exhibit their lowest loss in the vicinity of 1.3 μm. Naturally, intense research interest is now focused on optical sources and detectors that will work efficiently at these wavelengths.

Significant pulse spreading can occur in multimode fibers even if monochromatic sources are used. This is because the group velocities of the various modes differ from one another, causing group delay spread, or intermodal dispersion. Intermodal dispersion is usually measured in terms of σ_m, the root-mean-square (rms) value of the delay spread per unit length of the fiber. A multimode fiber of uniform (step) index profile has an intermodal dispersion given by $2\sigma_m = n_0\Delta/\sqrt{3}c$, where n_0 is the refractive index of the core, $\Delta(<<1)$ is the relative index difference between the core and the cladding, and c is the velocity of light in vacuum. Grading the index profile

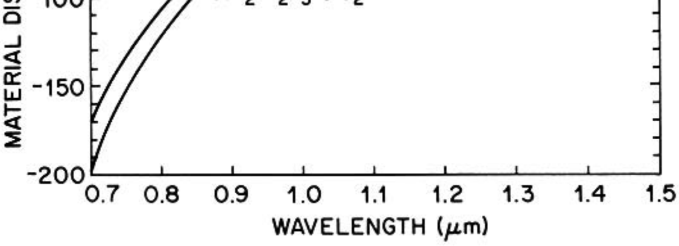

Figure 2. Material dispersion of silica (SiO_2), borosilicate (13 mol% B_2O_3 · 87 mol% SiO_2), and germanium borosilicate (10 mol% GeO_2 · 4 mol% B_2O_3 · 86 mol% SiO_2) glasses commonly used for making low-loss fibers. The ordinate is measured in psec/km of pulse delay spread per nanometer of source spectral width. The solid curves are taken from Refs. 13 and 14; the dashed portion is extrapolated. Material dispersion of silica and borosilicate glasses are very close to each other.

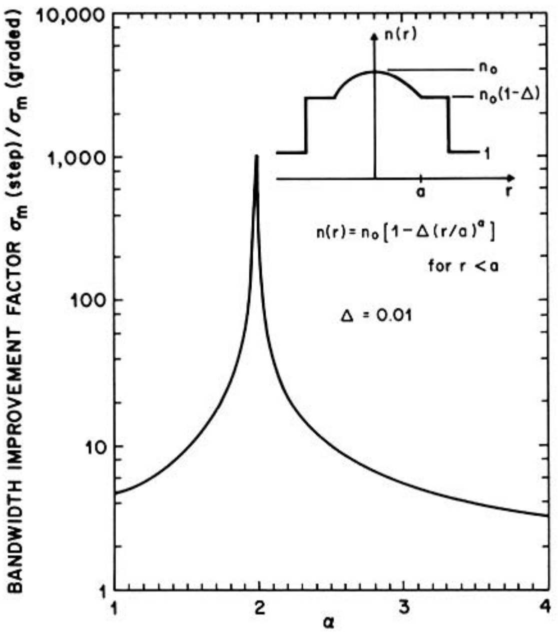

Figure 3. Bandwidth improvement factor versus α for a multimode fiber of graded-index profile described by $n(r) = n_0[1 - \Delta(r/a)^{\alpha}]$, with $\Delta = 0.01$. The improvement factor is the ratio of the rms value of the pulse delay spread for the step-index fiber, σ_m (step), to that for the graded-index fiber, σ_m (graded).

in the core tends to equalize group velocities and reduce intermodal dispersion. For the class of graded-index profiles defined by $n(r) = n_0[1-\Delta(r/a)^{\alpha}]$, where α is the radius of the core and $r < \alpha$, intermodal dispersion is minimized when α is approximately 2.[17] In particular, if the variation of Δ with respect to the wavelength is neglected, one obtains a minimum pulse spreading given by $2\sigma_m = n_0\Delta^2/10\sqrt{3}c$ when α is $\alpha_{opt} = 2(1 - 1.2\Delta)$.[18] The intermodal dispersion of the optimally graded fiber is therefore $10/\Delta$ times smaller than that of the step-index fiber; for $\Delta = 0.01$, the improvement factor is 10^3. As shown in Fig. 3, this impressive improvement is sharply peaked over a very narrow range of α values, implying the necessity for precision control of the index profile in high-performance multimode fibers.

Actually, because refractive indices of different materials vary differently with λ, the variation of Δ with respect to λ is not zero, and therefore $d\Delta/d\lambda$ should not be neglected in determining α_{opt} The corrected optimal α, assuming a linear relationship between n and dopant concentrations, is given by $\alpha_{opt} = 2[1 - P - \Delta(2 - P)(3 - 2P)/(5 - 4P)]$, where $P \equiv (\lambda/\Delta)d\Delta/d\lambda$ is called profile dispersion.[18] Hence, the peak of the bandwidth improvement curve in Fig. 3 shifts with wavelength, although the shape remains approximately the same. Because of profile dispersion and because of the critical dependence of the bandwidth on α, a fiber that is optimized for operation at one wavelength may not have a large bandwidth at another. This effect is material dependent and is more pronounced for certain material combinations than for others.[15,19] It is possible to reduce profile dispersion by specifying independently the concentration profiles of the components of a multicomponent glass in order to obtain a relatively flat dependence of α_{opt} on λ.[20]

In a study of dispersion in multimode borosilicate ($B_2O_3 \cdot SiO_2$) fibers of variously graded index profiles, maximum bandwidth was observed to occur for $\alpha = 1.77$, which agrees well with the value predicted from bulk-sample measurements.[15,21] The observed maximum bandwidth was 75 times that of the step-index fiber of the same Δ, but still a factor of 23 below the theoretical maximum, thus indicating the difficulty of obtaining a perfect optimal profile in practice.

A phenomenon that has been predicted and observed to reduce pulse spreading is mode mixing.[22, 23] Index variations or perturbations of the fiber geometry, with longitudinal periodicities equal to the beat wavelengths of the propagating modes, will cause power in a pulse to transfer from mode to mode and to arrive at the output end with a group delay that is averaged over all modes. When the mode-mixing effect dominates, pulse spreading will not increase with fiber length L but will increase with $\sqrt{LL_c}$, where L_c is a coupling length over which mode mixing has resulted in a steady-state distribution of energy among modes. Unfortunately, mode mixing introduces additional loss because power also transfers to radiation modes.[24] Thus the very desirable reduction in pulse spreading is accompanied inevitably by an added loss, which may not be tolerable in many situations.

In order to illustrate the foregoing discussion on dispersion, pulse spreading at three wavelengths of interest is compared in Fig. 4 for three fibers: a multimode fiber with step-index profile, $GeO_2 \cdot B_2O_3 \cdot SiO_2$ glass, $\Delta = 0.01$; a multimode fiber with a non-optimally graded index profile (bandwidth improvement factor of 100), $GeO_2 \cdot B_2O_3 \cdot SiO_2$ glass, $\Delta = 0.001$; and a single-mode fiber, $B_2O_3 \cdot SiO_2$ glass, $\Delta = 0.001$. Material dispersion data for the above glasses are taken from

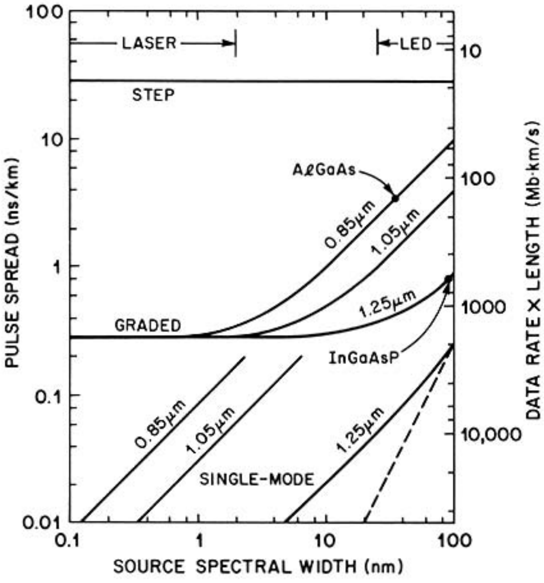

Figure 4. Pulse spreading ($2\sigma_m$) and bandwidth (data rate × fiber length) versus source spectral width ($2\sigma_s$) for three types of optical fibers at λ = 0.85, 1.05, and 1.25 μm (σ_m and σ_s are rms values). The three fibers are: multimode fiber with step-index profile, $GeO_2 \cdot B_2O_3 \cdot SiO_2$ glass, $\Delta = 0.01$; multimode fiber with non-optimally graded-index profile (the assumed bandwidth improvement factor of 100 is close to the best value observed to date), $GeO_2 \cdot B_2O_3 \cdot SiO_2$ glass, $\Delta = 0.01$; and single-mode fiber, $B_2O_3 \cdot SiO_2$ glass, $\Delta = 0.001$. The dashed line in the lower-right corner represents the lower limit to pulse spreading in silica fibers.

Refs. 14 and 15. Both pulse-delay spread and source spectral width are given by their double rms values, $2\sigma_m$ and $2\sigma_s$, respectively.

As illustrated in Fig. 4, the bandwidth of the step-index multimode fiber is completely dominated by intermodal dispersion in the range of the source spectral width shown. The operation of the graded-index fiber is governed by intermodal dispersion if lasers are used ($2\sigma_s < 2$nm) and by material dispersion if LED's are used (e.g., for AlGaAs LED's operating at $\lambda = 0.85\,\mu$m, $2\sigma_s \simeq$ 35 nm; for InGaAsP LED's operating at $\lambda = 1.25\,\mu$m, $2\sigma_s \simeq 90$ nm, as indicated in the figure by the two dots). Pulse spreading in single-mode fibers follows closely material dispersion and is less than 10 psec/km for laser sources operating near $\lambda = 1.3\,\mu$m.

Pulse spreading at the wavelength where material dispersion vanishes is proportional to the square of the source spectral width.[25] This is shown in Fig. 4 (in the lower right-hand corner) as the dashed line of slope two for fused silica at λ = 1.27 μm. It imposes a fundamental limit on the duration of the shortest pulse that can be transmitted through silica fibers. For a monochromatic source it is about 1 psec/km.

In order to relate dispersion to transmission bandwidth of the fiber, it is necessary to consider how pulse spreading degrades system performance. In a pulse-code-modulation communication system, pulse spreading causes intersymbol interference which increases the error probability (when the signal is regenerated) above that set by the signal level and the receiver noise. This degradation can be removed by first increasing the level of the received optical signal at the detector and then passing the distorted electrical signal through a filter that equalizes the response of the fiber. The required increase in signal power, for an error probability of 10^{-9}, is approximately 1 dB when $2\alpha_m L$ is about one hal the time slot T assigned to each pulse, that is, when $2\alpha_m L = T/2$, where $1/T$ is the data rate.[8] Using this 1-dB signal-power penalty as the criterion, it is possible to define a transmission bandwidth in terms of the allowable data rate for a given fiber length L. This data-rate-times-length product ($DR \cdot L$) is given as the right-hand ordinate in Fig. 4. The example of the graded-index multimode fiber with an AlGaAs LED operating at 0.85 μm shows that material dispersion limits $DR \cdot L$ is about 140 Mb · km/sec, whereas with an InGaAsP LED operating at 1.25 μm $DR \cdot L$ is about 600 Mb·km/sec. A single-mode fiber operating with a laser of $2\alpha_s = 1$ nm at 1.25 μm is capable of transmitting 25,000 Mb/sec for 10 km, a very impressive bandwidth indeed!

CURRENT RESEARCH ACTIVITIES

Although optical-fiber cables of various configurations are now available on an experimental basis and already have demonstrated satisfactory performance in several applications trials, current research work continues to push toward the achievement of higher strength, lower cost, lower loss, larger bandwidth, greater reliability, and other desirable features. For example, some of these activities are: examination of different glass materials for lower loss and lower cost, improvement of preform-fabrication and fiber-drawing techniques, investigation of various plastic materials for coating and jacketing of fibers, implementation of new and sophisticated measurement techniques for characterizing fibers and preforms, evaluation of environmental effects on fiber strength and optical loss, exploration of better cabling and splicing methods, and development of connectors and couplers with lower loss and greater reliability.[4] In addition, technologies relating to single-mode fibers are now beginning to receive attention. Promising results have been obtained already in the areas of low-loss single-mode fibers and

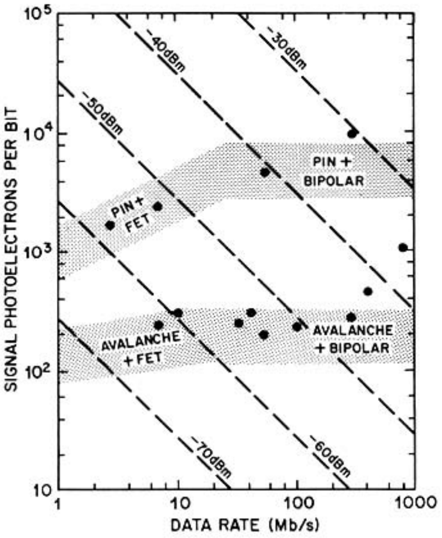

Figure 5. Repeater performance chart. This chart summarizes theoretical and experimental performance of optical digital repeaters. [7,8] The ordinate is the average number of primary photoelectrons generated in the photodetector by the received optical signal in an interval $T = 1/(\text{bit rate})$ required to achieve a 10^{-9} error probability; it is proportional to the required energy per bit. The abscissa is the bit rate. The two bands represent theory based on current device parameters for silicon field-effect transistors (FET) and silicon bipolar transistors that are used in the preamplifiers immediately following the detectors.[8] The upper band is for PIN photodiode detectors and the lower band is for avalanche photodiode detectors with optimal gain (ranging from about 20 at 1 Mb/sec to about 100 at 100 Mb/sec). The dots represent experimental results. The dashed diagonal lines help to determine performance values in terms of the average optical power required at the receiver.

splices.[11,26] The more demanding requirements of single-mode operation and small core dimensions ($\sim$10-μm diameter) will present new and interesting challenges.

For operation near $\lambda = 0.85\ \mu$m, AlGaAs LED's and lasers and silicon PIN and avalanche photodiodes are commercially available and have been used in many laboratory tests and field experiments. Reliability of these devices is no longer a major concern. Current research interests in AlGaAs devices center around investigations of various techniques for achieving single-frequency and single-mode operation, lower threshold, greater temperature stability, higher modulation bandwidths, etc., and for integrating devices of different functions on a single semiconductor chip.[27]

The potential of optical-fiber cables with low loss and low dispersion in the spectral region of 1–1.5 μm has stimulated intense interest in materials and device research on sources and detectors that will work efficiently and reliably at these wavelengths. Examples of sources that show promise are InGaAsP lasers and LED's and a single-crystal neodymium fiber laser end-pumped by a single LED.[28-30] The problem of making a low-noise avalanche photodiode with low dark current remains to be solved.

Rather intensive work on optical repeaters and terminals during the last few years has produced results that cover a wide range of data rates.[7] As illustrated in Fig. 5, agreement between theory and experiment is rather good. Current repeater-research interest is directed toward pushing the frontiers of high-capacity systems and broadening the base of various areas of application.

CONCLUSIONS

Optical-fiber transmission is looming as a major innovation in the field of telecommunications. Its technical feasibility is being demonstrated in many ongoing field experiments and trials. The impact of this new technology on the communications field will depend on the economic viability of fiber systems compared to conventional and alternative systems in various applications.

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