The Search for Very Low Loss Fiber-Optic Materials

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The propagation of light through glass fibers is rapidly becoming the preferred mode of transmitting audio and visual information, and meeting demands for even higher capacity, speed, and reliability is an ever present challenge. The recent success of lightwave systems has already led to operating telecommunications systems within more than 50 U.S. cities, and long-distance transcontinental and even transoceanic systems are scheduled to go into service within the present decade.

Summary. Today's fiber-optic communications systems are fused-silica–based fibers for which signals require reamplification every 30 kilometers. Repeaterless long-haul (transcontinental and transoceanic) links can only be envisaged if a new fiber material with intrinsic power losses significantly lower than those of silica can be identified and developed. This article reviews the development of silica-based systems, details the physical mechanisms which produce signal attenuation in fiber materials in general, and identifies that class of materials from which ultralow loss glasses are most likely to be developed in the future.

There are many advantages in transmitting information by photons through fibers rather than by electrons in metallic cables. First, the much higher carrier frequencies, which, at $\sim 3 \times 10^{14}$ cycles per second (or hertz), are some 100,000 times the ultrahigh frequencies used for television communications, promise an enormously increased carrying capacity, or bandwidth. Second, transmission losses are much smaller, requiring far fewer amplifiers, or repeaters, per unit distance of transmission. Third, since optic fibers are electrical insulators, they are not affected by stray electrical fields from other neighboring systems to anything like the same extent as metals. They are therefore comparatively free of "interference" and are essentially immune to electronic spying. Finally, and perhaps most obviously, they are small (typical fiber diameters being a tenth of a millimeter), leading to enormous cost savings over the much larger conventional cables.

In spite of the impressive advances already made, a potential problem remains concerning the expense and efficiency of long-distance transmission. The present generation of optic fibers, which are based on fused silica (SiO_2), have intrinsic material (and therefore unavoidable) power losses which, at least with present-day technology, require reamplification of the carrier lightwave about every 30 km. The necessary repeaters and regenerators, whose installation represents perhaps the major expense for proposed silica-based fiber long-haul systems, can be significantly reduced in number (or even, ideally, eliminated completely) only if a new generation of non-silica-based fibers with significantly reduced losses can be developed.

Excluding right-of-way charges (which are, however, far from negligible for most overland routes), the cost factor is governed by the product of carrying capacity and repeater length. Carrying capacity is determined by the dispersion characteristics of the fiber and is measured as a data rate, megabits per second, each 100 Mb/sec corresponding to about 1500 voice circuits. Dispersion, which is a measure of pulse spreading and overlapping on propagation along the fiber, is therefore one possible limit to fiber efficiency. The other, repeater length, is governed by attenuation, or power loss. Planned long-haul silica fiber operations, such as the 274 Mb/sec (4200 voice circuits), 30-km repeater length undersea cable system, are attenuation-limited, and it is consequently this aspect of power loss on which we focus for a possible major cost breakthrough in the years ahead.

This article will discuss the search, now seriously under way, for new materials which have the potential for exhibiting material losses significantly (at least one and possibly two or more orders of magnitude) lower than those of silica. The word potential is used above since none of the candidate materials can yet be produced with levels of defects and impurities which even come close to enabling their ultimate intrinsic limits of optical transparency to be probed by direct measurement. Nevertheless, from among these candidates, and after an exhaustive examination of the many other materials characteristics which affect viability in the context fiber communication (such as ease of fiber fabrication; optical, chemical, and mechanical stability; strength; durability; and many others), it is hoped that at least one suitable ultralow-loss fiber will be found on which a new repeaterless generation of long-haul telecommunications systems can be based.

History

The possibility of guiding light within the confines of a long narrow cylinder of dielectric is an idea with a surprisingly lengthy history. As far back as 1854 the British physicist John Tyndall demonstrated before the Royal Society of London the fact that light could be guided within a jet of water (*1*). In 1880, very shortly after the invention of the telephone, Alexander Graham Bell discussed the feasibility of telecommunications with light waves (*2*), although his original patent for the "Photophone" (*3*) contemplated the free propagation of light through the atmosphere. Unfortunately, Bell's concept was ahead of the technology since he lacked a powerful steady source of light, and atmospheric disturbances, even on clear days, severely limited the distances which his light beams could travel.

The first documented examples of theoretical study of the problem of guiding electromagnetic waves, by internal reflection, within long cylinders of dielectric appeared in 1910 (*4*) and the first quantitative experimental investigations in 1920 (*5*). Although laboratory interest in the propagation of light within glass rods continued through the intervening years, it was the first laboratory demon-

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stration of a laser in 1960 (*6*) which finally triggered in earnest the quest for a viable lightwave communications system.

Shortly thereafter came the first serious efforts to devise shielded waveguide structures. Since the absorption and scattering losses from the glasses available at that time were still prohibitively large, the earliest waveguides were simply gas-filled underground conduits, about 20 cm in diameter, housing lenses at intervals to refocus the light and change its direction when required. The system was bulky, expensive, and extremely sensitive to temperature and misalignment. The next advance followed with the realization that the high losses hitherto experienced in silica-based glasses were very dominantly of extrinsic (that is, impurity and growth imperfection) origin. In 1966 (*7*) the proposal was made that silica-based fibers could in principle be made to transmit light with losses low enough to make a communications technology feasible. The first laboratory examples of such low-loss fibers were actually produced at Corning in 1970 (*8*).

With the subsequent development of reliable ways to generate rapid pulses of light, to periodically redefine and reamplify them, and finally to detect and interpret them, the technology developed rapidly through the 1970's. An essential ingredient was the improvement in manufacturing process for the fabrication of high-quality fibers achieved at Bell Laboratories in 1974 (*9*), which led eventually to the achievement in 1979 of a silica-based fiber with losses close to its intrinsic theoretical limit (*10*). Finally, after a research stage of barely more than a decade, lightwave telecommunication blossomed into commercial reality and was in worldwide use by the early 1980's, the first longer-haul intercity applications beginning in 1983.

Light Propagation in Fibers

Mathematically, the simplest optical waveguide would consist of a core region of straight cylindrical symmetry encased in a cladding of infinite thickness. It would be composed of two completely lossless dispersionless dielectric component materials, the one with the larger refractive index, n_1, forming the core, the other (with refractive index n_2) the cladding. In this theoretical limit of perfection, the equations for the propagation of electromagnetic radiation are exactly solvable, and a class of solutions exists which transports energy along the cylinder without loss.

In the simpler, but less exact, language of "light rays" these solutions (finite in number) represent rays which travel at specific "quantized" values of angle with respect to the core axis, and which are subject to total internal reflection at the boundary between the core and cladding. They are therefore confined entirely to the core region in this picture. More exactly, within the wave representation, they possess an exponentially decaying tail within the cladding so that, for each allowed ray or mode, energy is transported along the cylinder in both the core and the cladding.

The number of allowed solutions (or propagating modes) for a fixed value of the core-cladding refractive index difference $n_1 - n_2$ decreases with the diameter d of the core and eventually, when d becomes of the same order of magnitude as the wavelength of the propagating radiation, only a single mode remains confined. We correspondingly refer to single-mode and multimode waveguides in this context. Since different allowed propagating rays make different angles with the rod axis, a path length difference exists between them per unit length traveled along the axis. This gives rise to an undesirable pulse spreading or multimode dispersion due to the different times taken for the different modes to travel the same distance along the rod. For this reason future generations of long-haul fibers are likely to be of single-mode design in spite of the increased technological problems imposed by the small-diameter restriction.

Power Losses

Following the development of laser and light-emitting diode sources in the early 1960's it was soon recognized (*7*) that light-carrying glass fiber waveguides could be a practical transmission medium if power losses could be sufficiently reduced. These losses are of two types: material losses (arising from the fact that neither core nor cladding can in actuality be composed of glasses which approximate very closely our theoretical ideal of lossless dielectrics) and fiber design losses. The latter, which we shall not dwell upon in any detail in this article, include losses incurred at joins and splices and at light insertion, as well as scattering losses induced by any variations in core-cladding interface radius or in core-cladding refractive index difference. Further, such losses can arise as the result of finite cladding thickness (that is, at the cladding-jacket boundary, since some mode energy necessarily propagates within the cladding), and from any deviations of the fiber from linearity (bending losses).

Material losses are those sources of power attenuation which are present in the bulk materials from which the core and cladding are to be constructed. No solid, whether crystalline or glass, approximates very closely the theoretical ideal of a lossless dispersionless medium. Even ideally pure real materials are atomistically discreet and possess electronic band structures and atomic vibrational (phonon) modes which vary in detail from material to material, and which can absorb electromagnetic radiation in a manner that is dependent on the frequency (or, equivalently, vacuum wavelength λ) of the propagating radiation. These effects also introduce a chromatic material dispersion (that is, a wavelength dependence of refractive index) which necessarily exists quite independently of any waveguide-generated dispersion.

In addition to these intrinsic material absorption losses and other absorption and scattering losses from impurities and atomic defects (which can never be entirely removed), further unavoidable losses arise because of radiative scattering from intrinsic static or dynamic local fluctuations in refractive index. Any physical processes which give rise to index modulation on the scale of the wavelength of light (and many will be detailed below) contribute to these intrinsic scattering losses, which, in turn, add to the various absorption losses to produce the total resultant material attenuation.

Thus, regardless of fiber design, an intrinsic material loss is necessarily incurred which sets a lower limit to the possible attenuation achievable by use of that material as the core-cladding dielectric in any associated fiber communications system. It is an understanding of these ultimate material loss limits and the nature of their variation from glass to glass which is the prime concern of this article. Since values of $(n_1 - n_2)/n_1$ in telecommunications fibers are typically of the order of 1 percent, core and cladding are usually based on modifications of the same basic glass-forming composition.

In order to appreciate the problem of material attenuation in a quantitative fashion, we shall first get an idea of the numbers involved by considering a piece of traditional glass of optical quality.

Power losses are measured most frequently in decibels per unit length (usually 1 km). A loss of α dB/km is defined as a ratio of power output P_o to power input P_i over a length L (kilometers) of the form

$$P_o/P_i = 10^{-\alpha L/10} \quad (1)$$

Good-quality optical glass has bulk material losses which are typically of the order 1000 dB/km, implying from Eq. 1 a power loss of about 10^{-100} after transmission through 1 km of material. No practically viable communications system could be constructed with such high attenuation. Since reamplification of the signal becomes necessary when the power level has dropped about 10^{-5}, such a system would require repeater installation every 50 m or so.

However, in 1968 losses of the order of a few tens of decibels per kilometer were obtained (*11*) in samples of high-purity fused silica, and 2 years later a silica fiber with a loss of 20 dB/km was reported by Corning Glass Works (*8*). By 1979, by continuing improvements in growth techniques and impurity removal, silica-based glasses with losses as low as 0.2 dB/km (at a wavelength of about 1.55 μm) were available (*10*) and the age of optical fiber communications was at hand. With current technology, and a figure of the order of 1 dB/km when all losses (material and waveguide) are included, repeaters are necessary every 50 km or so (actually 30 km in commercial networks), although recent research at Bell Laboratories has suggested that improved technology could possibly extend this distance to ≳100 km in future silica-based systems.

The dramatic improvements in optical transparency for silica-based fibers transpired primarily through the progressive elimination of metallic impurities (particularly transition metals ions such as Fe^{2+}, Ni^{2+}, and Cu^{2+}) and water contaminants, all of which absorb strongly in the 1 to 2 μm (vacuum) wavelength range, for which low intrinsic material attenuation obtains in silica-based glasses (*12*). For many contaminants a reduction to levels of concentration of a few parts per billion is necessary. This achievement, combined with the simultaneous development of reliable low-cost semiconductor light sources and detectors in this same wavelength range, has made silica-based fibers the present-day standard for fiber-optic communications.

Nevertheless, as stated earlier, even lower-loss fibers are desirable for future long-distance (particularly inter- and intracontinental) communications systems in order to decrease, or even eliminate altogether, the number of repeaters required for the transmission. If, for example, a reduction in overall attenuation to values of the order of 0.01 dB/km could be obtained, then repeater distances would be measured in thousands of kilometers. Ignoring for the moment the tremendous advances in waveguide technology which this might demand, the first essential ingredient for such a future fiber-optic system would be a core-cladding dielectric with material losses at or below this level.

It is now widely believed that any significant improvement over the best silica value of ≈0.16 dB/km achieved at this writing (*13*), let alone the one to two orders of magnitude improvement contemplated above, requires a fundamental movement away from silica-based glasses. This belief arises since theory indicates that the minimum attenuation possible for even ideal pure and defect-free silica is still of order 0.1 dB/km. It therefore seems very likely that present-day technology has already attained a fiber communication system quite close to the ultimate which can possibly be achieved with silica-based core and cladding materials.

Intrinsic Loss Mechanisms

Two approaches can now be used in a search for new glass compositions which might potentially have significantly lower losses than fused silica. One explores directly the minimum attenuation characteristics of other known glass formers. This seemingly obvious approach, however, is seriously flawed at present, since the available purity of all non-silica-based materials is insufficient to approach the minimum intrinsic loss limits under any experimental circumstances. The other, which will be set out below, attempts to determine by calculation the theoretical limits for a wide selection of possible glass compositions whether or not they are known to be achievable, and to set out semiquantitative trends as a function of the most basic physical and chemical characteristics such as valence, bond lengths, molecular weight, and density. In this manner the regions of the periodic table which seem most promising in the quest for ultralow losses can be sketched and estimates given of the relevant ideal intrinsic low-loss capabilities together with the associated wavelengths for which these minima occur.

In order to understand the latter approach we must first set out the separate forms which the intrinsic (and therefore unavoidable) loss mechanisms take in ideally pure and defect-free materials. First, at shorter (normally ultraviolet) wavelengths, attenuation is dominated by absorption due to electronic excitations from valence to conduction band. Though largest for photon energies of the order of the actual valence-conduction band gap, an associated tail of exponential form $Ce^{c/\lambda}$ (in which C and c are wavelength-independent material parameters) extends significantly to longer visible and near-infrared wavelength regimes. Referred to as the Urbach tail (*14*), its precise physical origin is complex and, even for crystalline materials, is not well understood despite extensive experimental and theoretical studies over several decades.

At the far-infrared end of the optical frequency spectral range the attenuation is dominated by absorption from cation-anion polar modes of lattice vibrations. Extending to shorter wavelengths from these intense single-phonon absorption bands is another basically exponential tail, this time of the form $Ae^{-a/\lambda}$, where A and a are wavelength-independent material parameters. The origin of this tail is well understood in principle (*15*) and results from multiphonon excitations, which are overtones and combinations of the far-infrared fundamental vibrational frequencies. These overtones occur because the individual vibrational modes are not perfectly harmonic but couple to each other through various anharmonicities. Although pronounced structure, reflecting any sharp phonon band-structure characteristics, is sometimes found on this multiphonon edge at longer wavelengths, it usually decreases as one progresses further out along the edge to regimes dominated by three, four, and five phonons and, particularly for glasses, can probably be neglected in the window region of lowest total absorption where the Urbach and multiphonon tails meet (Fig. 1).

In this window region a third contribution to optical attenuation is no longer negligible when compared to absorption losses. It is the intrinsic material scattering loss from local fluctuations in refractive index. Theoretically, it has a wavelength dependence of the so-called Rayleigh form, B/λ^4 (*16*), where B is a wavelength-independent material parameter. Any physical process which can modulate the refractive index can in principle contribute to the Rayleigh scattering through B. In general, these can include local fluctuations in temperature, densi-

ty, bond polarizability, electronic or ionic carriers, concentration (for multicomponent systems), and molecular orientation (for materials containing markedly anisotropic molecules).

In single-component glasses at room temperature the dominant Rayleigh scattering is usually assumed to be that resulting from local density fluctuations which were in dynamic thermal equilibrium in the melt, but which became frozen in on cooling through the temperature region of glass formation. The associated fixation temperature T_F for this density fixation process has not been well studied but is usually associated loosely with the glass transition temperature T_g, at which certain macroscopic properties (such as heat capacity and specific volume) exhibit a discontinuous change, or at which the viscosity reaches about 10^{13} poise.

For glass systems composed of grossly anisotropic molecular constituents (B_2O_3, As_2S_3, and so on) the orientational fluctuation scattering may be significant (*17*) and for multicomponent glasses the concentration scattering (which results when different microscopic scattering volumes contain different relative concentrations of the various components) is always a potential source of significant attenuation (*18*).

The total attenuation is therefore the sum of the Urbach, Rayleigh, and multiphonon contributions. As sketched in Fig. 1, the minimum total attenuation normally occurs in the region of competition between Rayleigh scattering and multiphonon absorption, where the Urbach contribution is negligibly small. We may therefore write

$$\alpha = Ae^{-a/\lambda} + B/\lambda^4 \qquad (2)$$

to represent the attenuation near its minimum. Direct differentiation of Eq. 2 with respect to wavelength then formally locates the minimum absorption α_{min} and its associated wavelength λ_{min} in terms of the material parameters A, a, and B. Although A and a can be fairly accurately obtained in known glasses by direct measurement in the multiphonon-dominated region of Fig. 1, the parameter B (due to extraneous scattering and absorption in the window region) must be estimated theoretically at present. Assuming density fluctuation scattering to be the dominant Rayleigh source, this can be accomplished by using well-established thermodynamic techniques (*16*) and B expressed in terms of measurable quantities (*17–19*).

Using the resulting A, a, and B data for 33 single-component crystals and glasses (where density fluctuations for crystals are of dynamic origin through the thermal excitation of long-wavelength acoustic phonons), we find that the weak (essentially logarithmic) dependence of λ_{min} on B and A is so small that, to a root-mean-square accuracy of better than 10 percent, we can write

$$\lambda_{min} \approx 0.030a \qquad (3)$$

in terms of the multiphonon exponent a alone. The corresponding minimum attenuation is

$$\alpha_{min} \approx 1.1\ B/\lambda_{min}^4 \qquad (4)$$

with the overwhelmingly dominant (90 percent) contribution coming from Rayleigh scattering.

The Role of Valence and Reduced Mass

In order to use these equations for predictive purposes on hypothetical materials it is necessary to associate the material parameters a and B with simple physical and chemical concepts. The exponent a is essentially an inverse measure of the mean frequency of the lattice vibrations involved in the absorption process. Through the concepts of effective anion and cation charges (q_A and q_C), mean volume per ion v, and reduced mass μ [where for a simple anion-cation pair of masses m_A and m_C, $\mu = m_A m_C/(m_A + m_C)$], it is anticipated from an elementary theory of polar lattice vibrations that this frequency should be proportional to $(q_A q_C/\mu v)^{1/2}$. Guided by this we find empirically that, if the effective charges q_A and q_C are put equal to the square roots of their formal valence charges Z_A and Z_C, then the expected scaling, $a \propto (\mu v/Z_A^{1/2} Z_C^{1/2})^{1/2}$, is obeyed with a root-mean-square error of only 8 percent over all 36 single-component crystal and glassy materials for which data on the exponent a are available.

The Rayleigh parameter B, through its known theoretical form for density scattering (*18, 19*), can also be probed for its dependence on these fundamental quantities μ, v, Z_A, and Z_C. We find that B is approximately proportional to $Z_A^3 Z_C v^2 \mu^0$. Since, from Eqs. 3 and 4, α_{min} is proportional to B/a^4, it follows directly that the minimum attenuation

$$\alpha_{min} \propto Z_A^4 Z_C^2 v^0/\mu^2 \qquad (5)$$

Although more subtle factors related to lattice coordination, cations with shallow electron cores, and fixation temperature have been omitted for simplicity, this relationship is extremely informative in implying a dominant role of valency. In short, ultralow-loss glasses should be formed from components of the lowest possible valence, and particularly anion valence.

This dominant role of valence in the present context has not been generally appreciated. By contrast, the other dictate of Eq. 5, namely the advantage of moving to heavier ions, has long been recognized. This situation has led to an active interest in germania-based glasses containing heavy metals (Pb, Tl, Bi, and so on) and in chalcogenide glasses like As_2S_3 and As_2Se_3. Equation 5 suggests that these materials can never compete with halide glasses in capacity for ultralow loss.

Since the alkali halides ($Z_A = Z_C = 1$) are not glass formers, the most favorable attainable situation is with $Z_C = 2$ and $Z_A = 1$. The only known good single-component glass formers in this category are BeF_2 and $ZnCl_2$. For them we have predicted minimum losses of 0.008 and 0.001 dB/km, respectively (*20*), $ZnCl_2$ being favored over BeF_2 by its larger reduced mass μ. These values are respectively one and two orders of magnitude lower than the minimum anticipated for SiO_2. Both BeF_2 and $ZnCl_2$ have for some time been discussed as possible candidates for ultralow-loss fibers (*21, 22*). Unfortunately, they each have other characteristics which make them very difficult to work with in the fiber context, BeF_2 being extremely toxic and $ZnCl_2$ one of the most deliquescent substances known.

Multicomponent Halide Glasses

Given this situation, it seems that a further search for ultralow-loss glass materials should center on multicomponent halide compositions. One such family, based on heavy-metal fluorides containing primarily zirconium (or isoelectronic hafnium) and barium in relative concentrations ZrF_4:$BaF_2 \approx 2:1$, has already received prominent attention in the literature (*23*). It was first discovered accidentally in 1974 by M. Poulain during mineralogical crystallization experiments (*24*), and glass formation has since been demonstrated in numerous multicomponent embellishments of the basic composition.

Theory (*20*) indicates values λ_{min} of order twice the range (1.3 to 1.6 μm) currently used with silica-based fibers, and a potential for intrinsic minimum attentuation α_{min} below 0.01 dB/km. To date, the best values obtained experimentally are barely below 10 dB/km, or some 1000 times the anticipated limit. Further reduction will depend on significant improvements in glass purity and

quality. In this longer wavelength regime many rare-earth impurities absorb strongly and must eventually be removed to the part-per-billion (ppb) level. In addition, hydroxyl impurities exhibit a strong fundamental absorption centered at 2.8 μm and must be removed to comparable low concentrations. Oxide impurities are a further source of concern since their vibrational overtones give rise to significant absorption bands on the multiphonon edge.

Although several other families of multicomponent heavy-metal fluoride glasses are now known to exist (*23*), little detail is yet available about their potential for ultralow-loss fiber purposes. Of particular interest are cadmium fluoride–based glasses such as the CdF_2-BaF_2-ZnF_2 systems (*25*) since, being systems with $Z_C = 2$ and $Z_A = 1$, they have excellent valence credentials for ultralow loss through Eq. 5. They would have λ_{min} values in the range 3.0 to 3.5 μm and may well be superior to the fluorozirconates in potential for low loss.

One persistent problem for almost all these glasses is the fact that, with the exception of the fluoroberyllates, fluorides appear to be relatively poor glass formers. In general, they form glasses only on rapid cooling and tend to recrystallize. Since fiber drawing itself is a rapid quench process, with cooling rates of 1000 degrees per second or larger, it is the recrystallization aspect which is of major concern. The problem can be countered to some extent by the "confusion principle" of introducing large numbers of components into the glass. This works well for the fluorozirconates (*26*), although the addition of even a small concentration of a light cation component (such as AlF_3) may, through its small reduced mass μ, raise the intrinsic minimum loss α_{min} to a surprisingly large degree. The latter results theoretically from a shift of λ_{min} to shorter wavelengths through a change in slope of the multiphonon edge near the attenuation minimum. No significant change in multiphonon edge in the regions of higher attenuation is anticipated or observed.

The drawing of fibers from these glasses based on heavy-metal fluorides is complicated by their susceptibility to attack from atmospheric moisture and oxygen, with devitrification spreading from the surface inward. Nevertheless, significant progress has been made with a method pioneered in Japan by Nippon Telegraph and Telephone, in which halide "preforms" are jacketed with Teflon and the resulting composite is drawn into fiber in an electric furnace (*27*). It is thought that some fluorine may be released by the Teflon during drawing, thus providing a reactive atmosphere which inhibits crystallization.

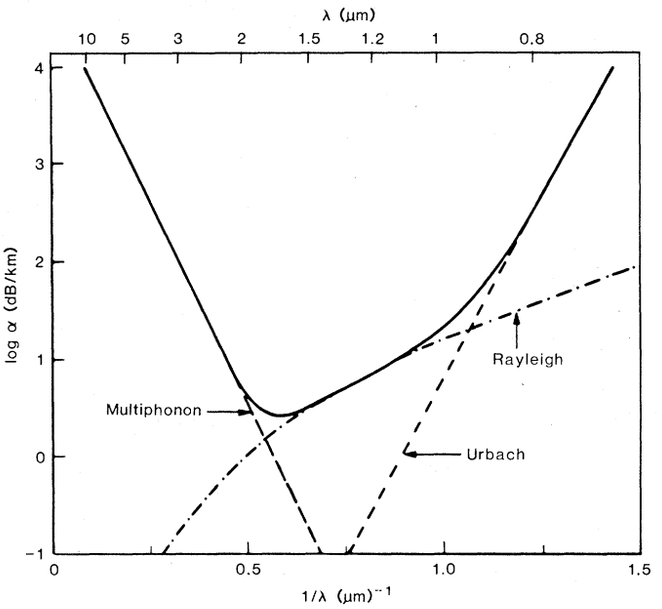

Fig. 1. Schematic of the attenuation α as a function of reciprocal wavelength 1/λ on a log-linear plot, emphasizing the separate component contributions from the Urbach tail ($Ce^{c/\lambda}$), Rayleigh scattering (B/λ^4), and multiphonon tail ($Ae^{-a/\lambda}$) and the parts of the spectrum over which each dominates. The scale is typically representative for an oxide glass.

Refinement of preparation methods for ZrF_4-based halide fibers has reduced the published mid-infrared (~2.5 μm) fiber losses from ~500 dB/km in 1980 to about 8 dB/km at this writing. Losses will no doubt continue to decrease, but the development of alternative (and cleaner) methods of glass and fiber preparation (similar to that achieved for silica-based fiber) will probably be required before intrinsic ultralow loss limits can be approached in practice.

Although multicomponent glasses are also known to exist in the heavier halides, bromides and particularly iodides have low cohesive energies and relatively low stabilities and are unlikely to be first-line candidates for communications fibers. Chloride glasses based on each of the binary combinations $ThCl_4$-KCl, $BiCl_3$-KCl, and $CdCl_2$-$BaCl_2$ have been prepared, although very little information is yet available about their properties. Theoretically, they should have λ_{min} near or just beyond 5 μm with ideal intrinsic attenuation limits perhaps as low as 0.001 dB/km. Like the fluorides, however, they appear to be poor glass formers and many have the additional complication of high water solubility. Both these problems are alleviated to a significant degree by forming mixed fluoride-chloride glasses (*28*).

Conclusions

Although we can now locate that broad category of materials—namely the halide glasses—on which any new generation of repeaterless long-haul optical communications systems seems likely to be based, we are clearly still at an extremely early stage of development of that system. First, no choice of the best halide composition has yet been made. This choice must include an examination of the physical and chemical as well as optical characteristics of candidate materials, and a number of trade-offs in desirable and less desirable features will clearly be necessary.

Only fibers based on the toxic beryllium fluoride would operate in the same frequency regime as the present generation of silica-based fibers and could therefore take advantage of much of the existing technology. All the others would operate at markedly longer wavelengths for which high-power source lasers and efficient photodetectors have yet to be developed. The glass purity required to get down to intrinsic material losses near or below 0.01 dB/km would generally involve degrees of purification beyond any which have yet been attained or required for silica. In addition, waveguide and coupling losses of the kinds detailed earlier would have to be markedly reduced from their present levels before the advantages of ultralow-loss material characteristics could be translated into correspondingly low-loss long-haul fibers. The ultrapurification problem may be particularly severe for the halides vis-à-vis silica, with respect to both starting material quality (silica of exceptional purity is commercially available from the semiconductor industry) and the techniques required.

On the positive side, operating at longer wavelengths would allow for larger fiber diameters for single-mode opera-

tion, easing the problems of efficient power launch and fiber-splicing. Also, mode dispersion characteristics, which in single-mode systems are set by the sum of chromatic and waveguide contributions, do not appear to present insuperable limitations. Chromatic dispersion, which is a material property, occurs because different spectral components radiating from a source laser travel with slightly different velocities. The effect is predicted (*29*) to be significantly smaller in most halide-based materials than in silica. Moreover, near λ_{min} it can be largely canceled by introducing tailored waveguide contributions of the opposite sign. It is therefore unlikely that ultralow-loss halide fibers would be seriously dispersion-limited.

Finally, it should be mentioned that the total emphasis on glass fiber materials in this article arises only because of the immense technological problems involved in drawing high-quality single-crystal fibers. Theoretically, some single-crystal halides have bulk intrinsic material attenuation far lower than any of the glass materials discussed. However, the fabrication rate is so slow and imperfections introduced in the drawing process are at present so severe that, barring a major breakthrough in technique, they are not considered realistic alternatives to glass fibers for any commercial applications in the foreseeable future.

Organizations currently involved in halide fiber materials research within the United States include industrial laboratories (Hughes, AT&T, and Corning), government facilities (Rome Air Development Center and Naval Research Laboratory), and universities (University of California at Los Angeles, Purdue, and Rensselaer Polytechnic Institute). Overseas, major efforts are being made in France (Université de Rennes and the Centre National L'Etude des Telecommunications Laboratories at Lannion), Japan (Nippon Telegraph and Telephone), and the U.S.S.R. (Lebedev Physics Institute, Moscow).

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