INFRARED FIBER TECHNOLOGY: ITS PROMISE AND STATUS

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ABSTRACT

Optical fibers with attenuations much lower than those attainable in present-day silicate waveguides are possible in theory if mid-infrared operating wavelengths are used. The loss mechanisms, materials, and problems inherent in obtaining such fibers are discussed. Among several candidates, heavy metal fluoride glasses are suggested as being most suited to low and moderate loss fiber applications in the 2-5 micrometer spectral region.

INTRODUCTION

The successful development of optical fibers based on silicate glasses has recently prompted interest in the extension of this technology to longer wavelengths in the infrared. A variety of communications and non-communications applications have been envisioned for such fibers, many based on the ultra-low optical absorption (perhaps 0.01 to 0.001 dB/km) which may theoretically be achieved in certain non-silicate materials. Very low attenuations offer the prospects of transoceanic or transcontinental fiber links, as well as waveguides for infrared power transmission, IR imaging, and sensing (e.g., remote pyrometry). Although efforts in this area are still very much in the research and development stage, a number of appropriate fiber materials have been identified and are under active examination at laboratories worldwide. This paper endeavors to briefly assess the state of the art in IR fiber technology, and examines the mechanisms, materials, and problems inherent in achieving long wavelength lightguides.

LOSS MECHANISMS

Fibers which operate at wavelengths in excess of about 2 micrometers could in principle exhibit very low optical loss (for a review, see Ref. 1). The reasoning behind this argument is schematically illustrated in Fig. 1. The total intrinsic attenuation of light observed in a transparent solid such as a glass as a function of wavelength is the result of three mechanisms. Overall, the theoretical transparency curve exhibits a "vee" shape; in practice it may be distorted by various extrinsic sources of attenuation such as transition metal or rare earth impurities, or contamination from hydroxyl (OH) species. At short wavelengths, usually in the ultraviolet, optical absorption is due to electronic transitions from the valence to the conduction band in the solid. The intensity of this absorption is seen to decrease rapidly with increasing wavelength (Fig.1, dashed line), but in some materials it can extend into the infrared. Although the atoms in a glass are considered to be randomly arranged, localized microscopic fluctuations in the refractive index are frozen into the material when it is cooled from a liquid state. This small-scale "granularity" causes Rayleigh scattering of light. The amount of Rayleigh scattering decreases with the reciprocal fourth power of the wavelength and can reach very low values in the mid-infrared (Fig.1, dotted line). The vibrations of cations and anions in the glass structure at very long wavelengths, and the overtones and combinations of these fundamental vibrations at shorter wavelengths, give rise to an infrared vibrational or "multiphonon" absorption edge. In many materials the intensity of this infrared edge is observed to decrease in a roughly exponential fashion with decreasing wavelength (Fig. 1, dash-dot line). The position of the infrared edge depends on a first approximation, on the atomic weight of the anions and cations which form the material. Substances which contain, e.g., "heavy" halide anions (Cl, F, Br) exhibit transmission to longer wavelengths than materials (such as silicate glasses) based on comparatively "light" species such as oxygen.

3.6.1

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FIGURE 1: Schematic illustration of the three intrinsic loss-inducing mechanisms which govern the total attenuation observed in a transparent solid or optical fiber. Absorption due to electronic transitions, which is strongest in the ultraviolet for many materials, decreases rapidly with increasing wavelength. Small localized fluctuations in the refractive index of the material lead to Rayleigh scattering of light. The intensity of this effect decreases with the reciprocal fourth power of the wavelength. At very long wavelengths, vibrations of the atoms in the material's structural framework or "lattice" lead to high absorption. Combinations and overtones of these fundamental vibrations give rise to the infrared vibrational or "multiphonon" edge, whose intensity decreases with decreasing wavelength. The conjunction of these three factors leads to an overall attenuation curve which exhibits a "vee" shape. The wavelength of minimum attenuation is governed by the slopes and separation of the three loss-inducing mechanisms which in turn are a function of materials properties.

3.6.2
The wavelength of minimum attenuation is governed by the slopes and separation of the parts of the curve due to the three loss-inducing mechanisms, which in turn depend on the composition of the material. To obtain very low loss fibers it is necessary to choose materials with infrared edges at long wavelengths and thus take advantage of the rapid decrease in intrinsic Rayleigh scattering with increasing wavelength. Vitreous materials are favored in this regard over polycrystalline substances, where grain boundaries often lead to non-Rayleigh scattering behavior.

**CANDIDATE MATERIALS**

Among the fiber materials considered to date are the chalcogenide glasses (e.g., vitreous arsenic triselenide or arsenic trisulfide), single crystals of various halides (e.g., silver bromide), and polycrystalline substances such as thallium bromoiodide (i.e., KRS-5). Each has advantages and drawbacks for infrared fiber applications. A variety of chalcogenide fibers with losses between 35 and 150 dB/km in the 2-3 micrometer region have been prepared by Japanese workers. Single crystal fibers are potentially very transparent, but fabrication problems have prevented preparation of multikilometer lengths. Scattering processes in polycrystalline materials have limited the attainable attenuation to the vicinity of 1000 dB/km. Nevertheless, all the materials cited above can exhibit reasonable transparency in the 6-11 micrometer region, and are thus potentially suited for short distance applications such as optical power transmission or IR imaging via fibers.

A consensus now appears to be emerging in the optical materials community that a recently discovered family of multicomponent glasses derived from the fluorides of heavy metals may be the source for future mid-IR fibers with very low attenuations (for a review, see Ref. 2). These materials are now under intense scrutiny at industrial and government laboratories in the U.S., Europe, and Japan, and numerous compositions have been examined. At present, glasses of the fluorozirconate type appear most suited for optical fiber applications. Zirconium tetrafluoride is the primary constituent (about 60%), with fluorides of barium, lanthanum, aluminum, lead or sodium constituting the remainder. The heavy metal fluoride glasses exhibit a broad range of high transparency which spans the ultraviolet to the midinfrared. In the vicinity of 2-4 micrometers, they show a minimum in absorption coefficient; fiber losses of less than 10.0 dB/km have been demonstrated and are expected to decrease further.

The current status of infrared optical fiber technology can be examined by comparing the loss levels found in experimental fibers and bulk glasses with the attenuations predicted by theory on the basis of material properties. This has been done in Fig. 2, which summarizes data taken from a variety of sources (3-10). The theoretical "vee" curves for heavy metal fluoride glasses, chalcogenide glasses such as arsenic trisulphide, and thallium bromoiodide (KRS-5) crystals (all shown as dashed lines in the bottom of Fig. 2) suggest that losses of 0.01 to 0.001 dB/km could in principle be obtained in the 3 to 7 micrometer region (4,5,9). Only with silicate glasses, however, have fibers with experimental attenuations (solid line) near the theoretical limit of about 0.2 dB/km been prepared (9). This is due in part to the availability of high purity glass by precipitation and sintering of silicate "soots" from gas phase reactions. Data obtained from bulk silicate glass show the fundamental vibrational absorption in the 8-15 micrometer region decreasing rapidly along the infrared edge to meet with fiber data at shorter wavelengths (10). The best heavy metal fluoride fibers, prepared by workers at the U.S. Naval Research Laboratory, have losses of 4 dB/km near 2.5 micrometers. In the example shown in Fig. 2 (dashed line), a minimum attenuation of 8.5 dB/km was observed (7). The disparity between these results and the theoretical prediction is due to extrinsic absorptions from transition metal, rare earth and hydroxyl impurities in the starting materials, and to non-Rayleigh scattering from crystallites and other defects. As was the case with silicates, the infrared edge data (8) suggests that improvements could be made through materials purification. Despite the presence of hydrogen impurities, arsenic trisulphide chalcogenide glass fibers with losses of about 35 dB/km near 2.4 micrometers have been fabricated (dotted line); their long wavelength behavior shows good agreement with theory. It has recently been suggested, however, that a weak intrinsic electronic absorption tail which extends into the infrared may limit the minimum attainable attenuation in chalcogenide fibers to about 10 dB/km (6). Fibers of thallium bromoiodide (KRS-5), while very transparent in theory, exhibit high attenuation (dash-dot line) because they are polycrystalline (3). The granular structure scatters light readily and limits such materials to short distance applications such as optical power
FIGURE 2: Attenuation versus wavelength for a number of prospective infrared transmitting fiber materials, based on data contained in Refs. 3-10. The theoretical intrinsic attenuation attainable in each material is indicated by the dashed "vee" curves at the bottom of the figure. Above them, experimental data for fibers and bulk glasses are shown. These data represent the "best" values reported in the literature for a given material as of June, 1985. With the exception of silica-based fibers, the loss levels in all the materials are far above the intrinsic limit. In large part, this is due to the presence of extrinsic impurities and non-Rayleigh scattering effects.
transmission; their range of transparency, however, exceeds that of the other candidates.

It is clear from Fig. 2 that heavy metal fluoride glasses have exhibited the lowest experimental attenuations at wavelengths beyond 2 micrometers. Despite their promise, these materials are still in a fundamental stage of development and a considerable amount of basic and applied research remains to be done. Problems include glass stability, the preparation of large fiber preforms and long fiber lengths, light scattering behavior, chemical durability and the reduction of impurities such as transition metals, rare earths, and hydroxyl and oxide species. The wavelength position and absorptivities of various metallic species, for example, have been determined and it is now recognized that such contaminants must be reduced to the parts-per-billion level. Successful efforts to reduce hydroxyl and oxide impurities have focused on high temperature glass processing or the use of reactive atmospheres such as carbon tetrachloride. Fibers and bulk glasses have been prepared whose Rayleigh scattering behavior closely follows the predictions shown in Fig. 2. While current mid-IR loss levels in the fluoride glasses are adequate for many short length applications, the progression towards ultra-low optical absorption is presenting a considerable challenge to the applied sciences.

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