Infrared Fiber Optics†

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1. Introduction

Infrared (IR) optical fibers may be defined as fiber optics transmitting radiation with wavelengths greater than approximately 2 μm. The first IR fibers were fabricated in the mid-196[1]0's from chalcogenide glasses such as arsenic trisulfide with losses in excess of 10 dB/m.[1] During the mid-1970's, the interest in developing an efficient and reliable IR fiber for short-haul applications increased partly in response to the need for a fiber to link broadband, long wavelength radiation to remote photodetectors in military sensor applications. In addition, there was an ever-increasing need for a flexible fiber delivery system for transmitting CO_2 laser radiation in surgical applications. Around 1975, a variety of IR materials and fibers were developed to meet these needs. These included the heavy metal fluoride glass (HMFG) and polycrystalline fibers as well as hollow rectangular waveguides. While none of these fibers had physical properties even approaching that of conventional silica fibers, they were, nevertheless, useful in lengths less than 2 to 3 m for a variety of IR sensor and power delivery applications.[2]

IR fiber optics may logically be divided into three broad categories: glass, crystalline, and hollow waveguides. These categories may be further subdivided based on either the fiber material or structure or both as shown in Table 1. Over the past 25 years many novel IR fibers have been made in an effort to fabricate a fiber optic with properties as close to silica as possible, but only a relatively small number have survived. A good source of general information on these various IR fiber types may be found in the literature.[3,4,5,6] In this review only the best, most viable and, in most cases, commercially available IR fibers are discussed. In general, both the optical and mechanical properties of IR fibers remain inferior to silica fibers and, therefore, the use of IR fibers is still limited primarily to non-telecommunication, short-haul applications requiring only tens of meters of fiber rather than kilometer lengths common to telecommunication applications. The short-haul nature of IR fibers results from the fact that most IR fibers have losses in the few dB/m range. An exception is fluoride glass fibers which can have losses as low as a few dB/km. In addition, IR fibers are much weaker than silica fiber and, therefore, more fragile. These deleterious features have slowed the acceptance of IR fibers and restricted their use today to applications in chemical sensing, thermometry, and laser power delivery.

Main	Subcategory	Examples
Glass	Heavy metal fluoride-HMFG Germanate Chalcogenide	ZBLAN - (ZrF_4-BaF_2-LaF_3-AlF_3-NaF) GeO_2-PbO As_2S_3 and AsGeTeSe
Crystal	Polycrystalline –PC Single crystal – SC	AgBrCl Sapphire
Hollow waveguide	Metal/dielectric film Refractive index < 1	Hollow glass waveguide Hollow sapphire at 10.6 μm

Table 1 Categories of IR fibers with a common example to illustrate each subcategory.

A key feature of current IR fibers is their ability to transmit wavelengths longer than most oxide glass fibers. In some cases the transmittance of the fiber can extend well beyond 20 μm, but most applications do not require the delivery of radiation longer than about 12 μm. In Figure 1 we give the attenuation for some of the most common IR fibers as listed in Table 1. From the data it is clear that there is a wide variation in range of transmission for the different IR fibers and that there is significant extrinsic absorption which degrades the overall optical response.

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Most of these extrinsic bands can be attributed to various impurities, but, in the case of the hollow waveguides, they are due to interference effects resulting from the thin-film coatings used to make the guides.

Some of the other physical properties of IR fibers are listed in Table 2. For comparison, the properties of silica fibers are also listed. The data in the table and in Figure 1 reveal that, compared to silica, IR fibers usually have higher loss, larger refractive indices and dn/dT, lower melting or softening points, and greater thermal expansion. For example, chalcogenide and polycrystalline Ag-halide fibers have refractive indices greater than 2. This means that the Fresnel loss exceeds 20% for two fiber ends. The higher dn/dT and low melting or softening point leads to thermal lensing and low laser induced damage thresholds for some of the fibers. Finally, a number of these fibers do not have cladding analogous to clad oxide glass fibers. Nevertheless, core-only IR fibers such as sapphire and chalcogenide fibers can still be useful because their refractive indices are sufficiently high. For these high index fibers, the energy is largely confined to the core of the fiber as long as the unprotected fiber core does not come in contact with an absorbing medium.[7]

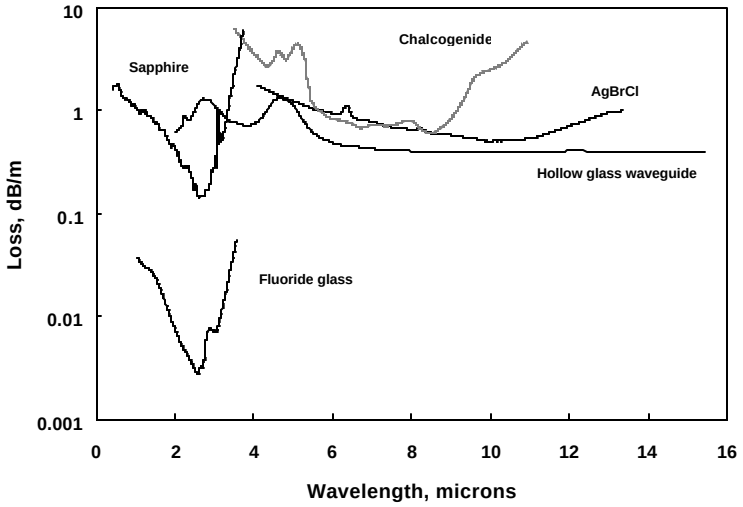

Figure 1 - Composite loss spectra for some common IR fiber optics: ZBLAN fluoride glass,[12] SC sapphire,[19] chalcogenide glass,[17] PC AgBrCl,[23] and hollow glass waveguide.[37]

	Glass			Crystal		Hollow
Property	**Silica**	**HMFG ZBLAN**	**Chalcogenide AsGeSeTe**	**PC AgBrCl**	**SC Sapphire**	**Hollow Silica Waveguide**
Glass transition or melting point, ^{o}C	1175	265	245	412	2030	150 (useable T)
Thermal conductivity, W/m ^{o}C	1.38	0.628	0.2	1.1	36	1.38
Thermal expansion coefficient, $10^{-6}\,^{o}C^{-1}$	0.55	17.2	15	30	5	0.55
Young's modulus, GPa	70.0	58.3	21.5	0.14	430	70.0
Density, g/cm^3	2.20	4.33	4.88	6.39	3.97	2.20
Refractive index (λ, μm)	1.455 (0.70)	1.499 (0.589)	2.9 (10.6)	2.2 (10.6)	1.71 (3.0)	NA
dn/dT, $10^{-5}\,^{o}C^{-1}$ (λ, μm)	+1.2 (1.06)	-1.5 (1.06)	+10 (10.6)	-1.5 (10.6)	+1.4 (1.06)	NA
Fiber transmission, range, μm	0.24-2.0	0.25-4.0	4-11	3-16	0.5-3.1	0.9-25
Loss† at 2.94 μm, dB/m	~800	0.08	5	3	0.4	0.5
Loss† at 10.6 μm, dB/m	NA	NA	2	0.5	NA	0.4

Table 2 Selected physical properties of key IR fibers compared to conventional silica fiber.

The motivation to develop a viable IR fiber stems from many proposed applications. A summary of the most important current and future applications and the associated candidate IR fiber that will best meet the need is given in Table 3. We may note several trends from this table. The first is that hollow waveguides are an ideal candidate for laser-power delivery at all IR laser wavelengths. The air core of these special fibers or waveguides gives an

inherent advantage over solid-core fibers whose damage threshold is frequently very low for these IR transmissive materials. The high refractive index of chalcogenide fibers is ideal for chemical sensing via evanescent wave coupling of a small portion of the light from the core into an IR absorbing medium. For the measurement of temperature through the simple transmission of blackbody radiation, IR fibers which transmit beyond about 8 μm, such as the Ag halide, chalcogenide, and hollow waveguides, are excellent candidates for use in measuring temperatures below 50 ^{o}C. This is because the peak for room temperature blackbody radiation is about 10 μm.

Application	Comments	Suitable IR fibers
1. Fiber optic chemical sensors	Evanescent wave principle - liquids	AgBrCl, sapphire, chalcogenide, HMFG
2. Fiber optic chemical sensors	Hollow core waveguides - gases	Hollow glass waveguides
3. Radiometry	Blackbody radiation, temperature measurements	Hollow glass waveguides, AgBrCl, chalcogenide, sapphire
4. Er:YAG laser power delivery	3 μm transmitting fibers with high damage threshold	Hollow glass waveguides, sapphire, germanate glass
5. CO_2 laser power delivery	10 μm transmitting fibers with high damage threshold	Hollow glass waveguides
6. Thermal imaging	Coherent bundles	HMFG, chalcogenide
7. Fiber amplifiers and lasers	Doped IR glass fibers	HMFG, chalcogenide

Table 3 Examples of IR fiber candidates for various sensor and power delivery applications.

2. Non-oxide and heavy-metal oxide glass IR fibers

There are two IR transmitting glass fiber systems that are relatively similar to conventional silica-containing glass fibers. One is the HMFG and the other is heavy-metal germanate glass fibers based on GeO_2. The germanate glass fibers generally do not contain fluoride compounds; instead they contain heavy metal oxides to shift the IR absorption edge to longer wavelengths. The advantage of germanate fibers over HMFG fibers is that germanate glass has a higher glass transition temperature and, therefore, higher laser-damage thresholds. But the loss for the HMFG fibers is lower. Finally, chalcogenide glass fibers made from chalcogen elements such as As, Ge, S, and Te contain no oxides or halides. They are a good fiber for non-laser power delivery applications.

HMFG fibers

Property	Fluorozirconate ZBLAN	Fluoroaluminate AlF_3-ZrF_4-BaF_2-CaF_2-YF_3
Glass transition temperature, ^{o}C	265	400
Durability	Medium	Excellent
Loss at 2.94 μm, dB/m	0.01	0.1
Er:YAG laser peak output energy, mJ	300 300-μm core	850 500-μm core

Table 4 Comparison between fluorozirconate and fluoroaluminate glasses of some key properties which relate to laser power transmission and durability of the two HMFG fibers. Other physical properties are relatively similar.

Poulain and Lucas discovered HMFGs or fluoride glasses accidentally in 1975 at the University of Rennes.[8] In general, the typical fluoride glass has a glass transition temperature, T_g, four times less than silica; is considerably less stable; and has failure strains of only a few percent compared to silica's greater than 5%. While an enormous

number of multicomponent fluoride glass compositions have been fabricated, comparably few have been drawn into fiber. This is because the temperature range for fiber drawing is normally too small in most HMFGs to permit fiberization of the glass. The most popular HMFGs for fabrication into fibers are the fluorozirconate and fluoroaluminate glasses of which the most common are ZBLAN (ZrF_4-BaF_2-LaF_3-AlF_3-NaF) and AlF_3-ZrF_4-BaF_2-CaF_2-YF_3, respectively. The key physical properties which contrast these glasses are summarized in Table 4. An important feature of the fluoroaluminate glass is its higher T_g which largely accounts for the higher laser damage threshold for the fluoroaluminate glasses compared to ZBLAN at the Er:YAG laser wavelength of 2.94 μm.

The fabrication of HMFG fiber is similar to any glass-fiber drawing technology except that the preforms are made using some type of melt-forming method rather than by a vapor deposition process common with silica fibers. Specifically, a casting method based on first forming a clad glass tube and then adding the molten core glass is used to form either multimode or single-mode fluorozirconate-fiber preforms. The cladding tube is made either by a rotational casting technique in which the clad tube is spun in a metal mold or by merely inverting and pouring out most of the molten clad glass contained in a metal mold to form a tube.[9] The clad tubing is then filled with a higher index core glass. Other preform fabrication techniques include rod-in-tube and crucible techniques. The fluoroaluminate-fiber preforms have been made using an unusual extrusion technique in which core and clad glass plates are extruded into a core/clad preform.[10] All methods, however, involve fabrication from the melt glass rather than from the more pristine technique of vapor deposition used to form SiO_2-based fibers. This process creates inherent problems such as the formation of bubbles, core-clad interface irregularities, and small preform sizes. Most HMFG fiber drawing is done using preforms rather than the crucible method. A ZBLAN preform is drawn at about 310 ^oC in a controlled atmosphere (to minimize contamination by moisture or oxygen impurities which significantly weaken the fiber) using a narrow heat zone compared to silica. Either UV acrylate or Teflon coatings are applied to the fiber. In the case of Teflon, heat shrink FEP fluoride is generally applied to the glass preform prior to the draw.

The attenuation in HMFG fibers is predicted to be about 10 times less than that for silica fibers.[11] Based on extrapolations of the intrinsic losses resulting from Rayleigh scattering and multiphonon absorption, the minimum in the loss curves or V-curves is projected to be about 0.01 dB/km at 2.55 μm. Recent refinements of the scattering loss have modified this value slightly to be 0.24 dB/km or about 8 times less than that for silica fiber.[12] In practice, however, extrinsic loss mechanisms still dominate fiber loss. In Fig. 2 losses for two ZBLAN fibers are shown. The data from British Telecom (BTRL) represents state-of-the-art fiber 110 m in length.[12] The other curve is more typical of commercially available (Infrared Fiber Systems, Silver Spring, MD) ZBLAN fiber. The lowest measured loss for a BTRL, 60-m-long fiber is 0.45 dB/km at 2.3 μm.

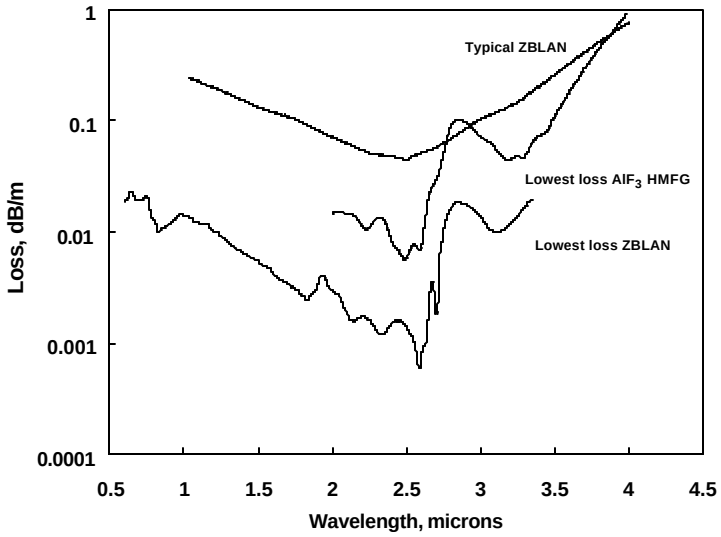

Figure 2 - Losses in the best BTRL[12] and typical (Infrared Fiber Systems, Silver Spring, MD) ZBLAN fluoride glass fibers compared to fluoroaluminate glass fibers.[10]

Some of the extrinsic absorption bands that contribute to the total loss shown in Fig. 2 for the BTRL fiber are; Ho^{3+} (0.64 and 1.95 μm), Nd^{3+} (0.74 and 0.81 μm), Cu^{2+} (0.97 μm), and OH^- (2.87 μm). Scattering centers such as crystals, oxides, and bubbles have also been found in the HMFG fibers. In their analysis of the data in Fig. 2, the BTRL group separated the total minimum attenuation coefficient (0.65 dB/km at 2.59 μm) into an absorptive loss component equal to 0.3 dB/km and a scattering loss component equal to 0.35 dB/km. The losses for the fluoroaluminate glass fibers are also shown for comparison in Fig. 2.[10] Clearly the losses are not as low as for the BTRL-ZBLAN fiber, but the AlF_3-based fluoride fibers do have the advantage of higher glass transition temperatures and, therefore, are better candidates for laser power delivery.

The reliability of HMFG fibers depends on protecting the fiber from attack by moisture and on pretreatment of the preform to reduce surface crystallization. In general, the HMFGs are much less durable than oxide glasses. The leach rates for ZBLAN glass ranges between 10^{-3} and 10^{-2} g/cm^2/day. This is about 5 orders of magnitude higher than the leach rate for Pyrex glass. The fluoroaluminate glasses are more durable with leach rates that are more than three times lower than the fluorozirconate glasses. The strength of HMFG fibers is less than that for silica fibers. From Table 2 we see that Young's modulus *E* for fluoride glass is 51 GPa compared to 73 GPa for silica glass. Taking the theoretical strength to be about 1/5 that of Young's modulus gives a theoretical value of strength of 11 GPa for fluoride glass. The largest bending strength measured has been about 1.4 Gpa, well below the theoretical value. To estimate the bending radius R we may use the approximate expression $R = 1.198 r \frac{E}{\sigma_{\max}}$, where σ_{max} is the maximum fracture stress and *r* is the fiber radius. [13]

Germanate fibers

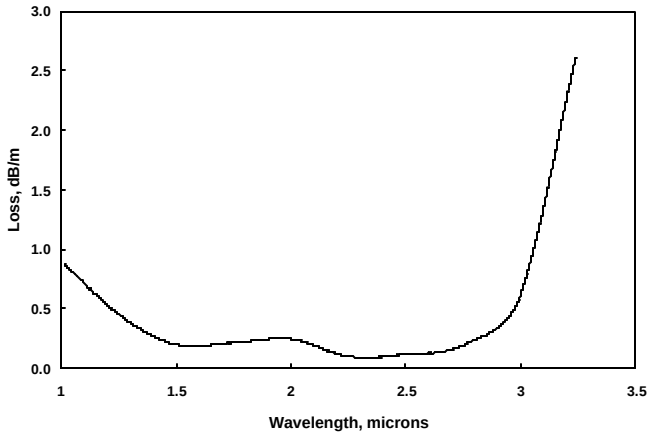

Figure 3 - Germanate glass fiber manufactured by Infrared Fiber Systems, Silver Spring, MD.

Heavy metal oxide glass fibers based on GeO_2 have recently shown great promise as an alternative to HMFG fibers for 3 μm laser power delivery. [14] Today, GeO_2-based glass fibers are composed of GeO_2 (30-76%) – RO (15-43%) – XO (3-20%) where R represents an alkaline-earth metal and X represents an element of Group IIIA. [15] In addition, small amounts of heavy metal fluorides may be added to the oxide mixture. The oxide-only germanate glasses have glass transition temperatures as high as 680 ^oC, excellent durability, and a relatively high refractive index of 1.84. In Fig. 3, loss data is given for a typical germanate glass fiber. While the losses are not as low as they are for the fluoride glasses shown in Fig. 2, these fibers have an exceptionally high damage threshold at 3 μm. Specifically, over 20 W (2J at 10 Hz) of Er:YAG laser power has been launched into these fibers.

Chalcogenide fibers

Chalcogenide glass fibers were drawn into essentially the first IR fiber in the mid 1960s.[1] Chalcogenide fibers fall into three categories: sulfide, selenide, and telluride. [16] One or more chalcogen elements are mixed with one or more elements such as As, Ge, P, Sb, Ga, Al, Si, etc. to form a two or more component glass. From the data in Table 2 we see that the glasses have low softening temperatures more comparable to fluoride glass than the oxide glasses. They are very stable, durable, and insensitive to moisture. A distinctive difference between these glasses and the other IR fiber glasses is that they do not transmit well in the visible region and their refractive indices are quite high. Additionally, most of the chalcogenide glasses, except for As_2S_3, have a rather large value of dn/dT. [17] This fact limits the laser power handling capability of the fibers. In general, chalcogenide glass fibers have proven to be an excellent candidate for evanescent wave fiber sensors and for IR fiber image bundles.[18]

Chalcogenide glass is made by combining highly purified (>6 nines purity) raw elements in an ampoule which is heated in a rocking furnace for about 10 hours. After melting and mixing, the glass is quenched and a glass preform fabricated using rod-in-tube or rotational casting methods. Preform fiber draws involve drawing a core/clad preform or a core-only preform. For the core-only preform draw either a soft chalcogenide cladding can be extruded over the fiber as it is drawn or the preform can be Teflon clad. Crucible drawing is also possible.

The losses for the most important chalcogenide fibers are given in Fig. 4. Arsenic trisulfide (As_2S_3) fiber, one of the simplest and oldest chalcogenide fibers, has a transmission range from 0.7 to about 6 μm. [16] This fiber is red in

color and, therefore, transmits furthest into the visible region but cuts off in the long wavelength end well before the heavier chalcogenide fibers. [17] Longer wavelengths are transmitted through the addition of heavier elements like Te, Ge, and Se as shown in the figure. A key feature of essentially all chalcogenide glasses is the strong extrinsic absorption resulting from contaminants such as hydrogen, H_2O, and OH^- bonding to the elemental cations. In particular, absorption peaks between 4.0 and 4.6 μm are due to S-H or Se-H bonds and those at 2.78 μm and 6.3 μm are due to OH^- (2.78 μm) and/or molecular water. The hydride impurities are often especially strong and can be deleterious when using these fibers in chemical sensing applications where the desired chemical signature falls in the region of extrinsic absorption. Another important feature of most of the chalcogenide fibers is that their losses are in general much higher than the fluoride glasses. In fact at the important CO_2 laser wavelength of 10.6 μm, the lowest loss is still above 1 dB/m for the Se-based fibers. [16]

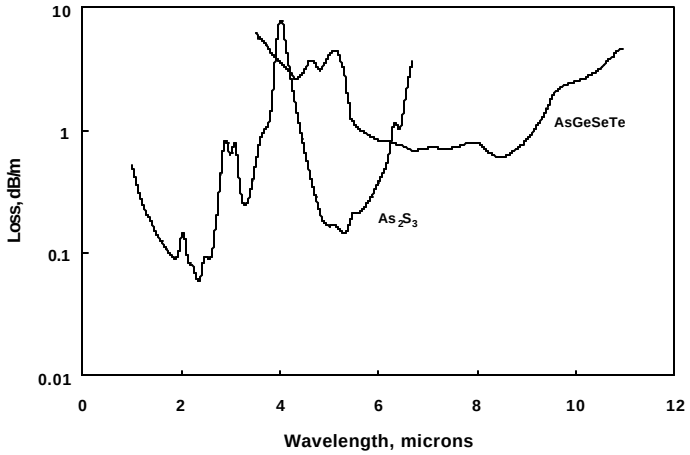

Figure 4 - Two common chalcogenide glass fibers: As_2S_3 and an AsGeSeTe fiber.[17] Note the many impurity bands pervasive in these fiber systems.

3. Crystalline fibers

Crystalline IR fibers are an attractive alternative to glass IR fibers because most non-oxide crystalline materials can transmit longer wavelength radiation than IR glasses and, in the case of sapphire, exhibit some superior physical properties as well. [2] The disadvantage is that crystalline fibers are difficult to fabricate. There are two types of crystalline fiber; single-crystal (SC) [19] and polycrystalline (PC) fiber. [20,21] Historically, the first crystalline fiber made was hot-extruded, KRS-5 fiber fabricated at Hughes Research Labs in 1975. [22] KRS-5 or TlBrI was chosen because it is very ductile and because it can transmit beyond the 20 μm range required for the intended military surveillance satellite application. In fact, crystalline fibers such as KRS-5 and other halide crystals were initially thought to hold great potential as the next generation ultralow loss fibers because their intrinsic loss was predicted to be as low as 10^{-3} dB/m. [22] Unfortunately, this loss was not only never achieved but not even approached experimentally.

PC fibers

There are many halide crystals which have excellent IR transmission but only a few have been fabricated into fiber optics. The technique used to make PC fibers is hot extrusion. As a result, only the silver and thallium halides have the requisite physical properties such as ductility, low melting point, and independent slip systems to be successfully extruded into fiber. In the hot extrusion process, a single-crystal billet or preform is placed in a heated chamber and the fiber extruded to net shape through a diamond or tungsten carbide die at a temperature equal to about ½ the melting point. The final PC fibers are usually from 500 to 900 μm in diameter with no buffer jacket. The polycrystalline structure of the fiber consists of grains on the order of 10 microns or larger in size. The billet may be clad using the rod-in-tube method. In this method, a mixed silver halide such as AgBrCl is used as the core and then a lower index tube is formed using a Cl^- rich AgBrCl crystal. The extrusion of a core/clad fiber is not as easy to achieve as it is in glass drawing, but Artjushenko and his colleagues [23] at the GPI in Moscow have achieved clad Ag-halide fibers with losses nearly as low as the core-only Ag-halide fiber. Today, the PC Ag-halide fibers represent the best PC fibers. KRS-5 is no longer a viable candidate due largely to the toxicity of Tl and the greater flexibility of the Ag-halide fibers.

The losses for the Ag-halide fibers are shown in Fig. 5. Both the core-only and core/clad fibers are shown and as with the other IR fibers, we again see that there are several extrinsic absorption bands. Water is often present at 3

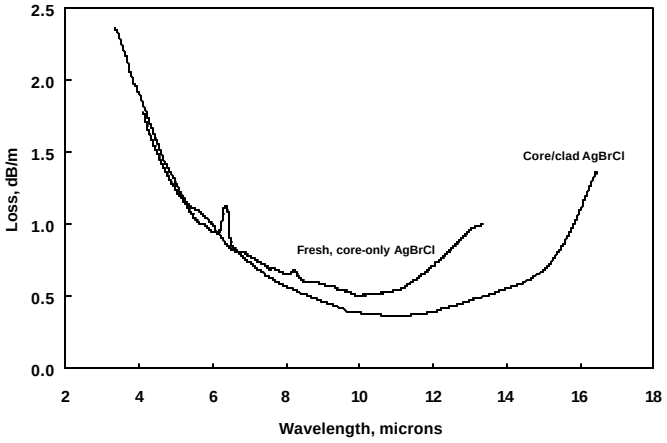

Figure 5 - Losses in a typical PC silver halide fiber[20] compared to recently developed core-clad silver halide fiber.[23]

and 6.3 μm and there is sometimes a SO_4^{--} absorption near 9.6 μm. Furthermore, we note the decreasing attenuation as the wavelength increases. This is a result of λ^{-2} scattering from strain-induced defects in the extruded fiber. An important feature of the data is that the loss at 10.6 μm can be as low as 0.2 dB/m for the core-only fiber and these fibers will transmit to almost 20 μm. These fibers have been used to transmit about 100 W of CO_2 laser power but the safe limit seems to be 20 to 25 W. [24] This is due to the low melting point of the fibers.

There are several difficulties in handling and working with PC fibers. One is an unfortunate aging effect in which the fiber transmission is observed to decrease in time. [25] Normally the aging loss, which increases uniformly over the entire IR region, is a result of strain relaxation and possible grain growth as the fiber is stored. Another problem is that Ag halides are photosensitive and exposure to visible or UV radiation creates colloidal Ag which in turn leads to increased losses in the IR. Finally, the AgBrCl is corrosive to many metals. Therefore, the fibers should be packaged in dark jackets and connectorized with materials such as Ti, Au, or ceramic materials.

The mechanical properties of these ductile fibers are quite different from those of glass fibers. The fibers are weak with ultimate tensile strengths of about 80 MPa for a 50/50 mixture of AgBrCl. The main difference, however, between the PC and glass fibers is that the PC fibers plastically deform well before fracture. This plastic deformation leads to increased loss as a result of increased scattering from separated grain boundaries. Therefore, in use, the fibers should not be bent beyond their yield point; too much bending can lead to permanent damage and a high loss region in the fiber.

SC fibers

Meter-long lengths of SC fibers have been made from only a small number of the over 80 IR transmissive crystalline materials. Initially some SC fibers were grown by zone-refining methods from the same metal halides used to extrude PC fibers. The idea was that removal of the grain boundaries in the PC fibers would improve the optical properties of the fiber. This did not occur so most of the crystalline materials chosen today for SC fiber fabrication have been oxides. Oxide materials like Al_2O_3 (sapphire) have the advantage over halides of high melting points, chemical inertness, and may be conveniently melted and grown in air. Currently, sapphire is the most popular SC fiber. [19,26,27]

Sapphire is an insoluble, uniaxial crystal (trigonal structure) with a melting point over 2000 ^oC. It is an extremely hard and robust material with a usable fiber transmission from about 0.5 to 3.2 μm. Other important physical properties from Table 2 include the refractive index equal to 1.75 at 3 μm, a thermal expansion about 10 times higher than silica, and a Young's modulus approximately 6 times greater than silica. These properties make sapphire an almost ideal IR fiber candidate for applications less than about 3.2 μm. In particular, this fiber has been used to deliver over 10 W of average power from an Er:YAG laser operating at 2.94 μm.[28]

Sapphire fibers are fabricated using either the edge-defined, film-fed growth (EFG) or the laser heated pedestal growth (LHPG) techniques. [29] In either method some or all of the starting sapphire material is melted and a SC fiber is pulled from the melt. In the EFG method, a capillary tube is used to conduct the molten sapphire to a seed fiber, which is drawn slowly into a long fiber. Multiple capillary tubes, which also serve to define the shape and diameter of the fiber, may be placed in one crucible of molten sapphire so that many fibers can be drawn at one time. The LHPG process is a crucibleless technique in which a small molten zone at the tip of a SC sapphire source rod (<2 mm diameter) is created using a CO_2 laser. A seed fiber slowly pulls the SC fiber as the source rod continuously moves into the molten zone to replenish the molten material. Both SC fiber growth methods are very slow (several

mm/min) compared to glass fiber drawing. The EFG method, however, has an advantage over LHPG methods because more than one fiber can be continuously pulled at a time. LHPG methods, however, have produced the cleanest and lowest loss fibers owing to the fact that no crucible is used which can contaminate the fiber. The sapphire fibers grown by these techniques are unclad, pure Al_2O_3 with the C axis usually aligned along the fiber axis. Fiber diameters range from 100 to 300 μm and lengths are generally less than 2 m. Post cladding techniques mostly involve a Teflon coating using heat shrink tubing.

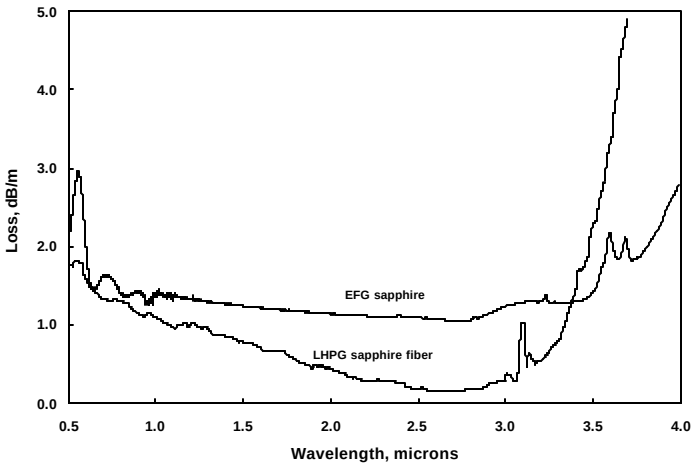

Figure 6 - SC sapphire fibers grown by the EFG[29] (Saphikon, Inc., Milford, NH) and LHPG methods.[28]

The optical properties of the as-grown sapphire fibers are normally inferior to those of the bulk starting material. This is particularly evident in the visible region and is a result of color-center type defect formation during the fiber draw. These defects and the resulting absorption can be greatly reduced if the fibers are post annealed in air or oxygen at about 1000 °C. In Fig. 6 the losses for LHPG fiber grown at Rutgers University[19] and EFG fiber grown by Saphikon, Inc. (Milford, NH) are shown. Both fibers have been annealed at 1,000 °C to reduce short wavelength losses. We see that the LHPG fiber has the lowest overall loss. In particular, LHPG fiber loss at the important Er:YAG laser wavelength of 2.94 μm is less than 0.3 dB/m compared to the intrinsic value of 0.15 dB/m. There are also several impurity absorptions beyond 3 μm which are believed due to transition metals like Ti or Fe. Sapphire fibers have also been used at temperatures up to 1400 °C without any change in their transmission.

4. Hollow waveguides

The first optical frequency hollow waveguides were similar in design to microwave guides. Garmire, et al. [30]made a simple rectangular waveguide using aluminum strips spaced 0.5 mm apart by bronze shim stock. Even when the aluminum was not well polished, these guides worked surprisingly well. Losses at 10.6 μm were well below 1 dB/m and Garmire early demonstrated the high power handling capability of an air-core guide by delivering over 1 kW of CO_2 laser power through this simple structure. These rectangular waveguides, however, never gained much popularity primarily because their overall dimensions (about 0.5 x 10 mm) were quite large in comparison to circular cross section guides and also because the rectangular guides cannot be bent uniformly in any direction. As a result, hollow circular waveguides with diameters of 1 mm or less fabricated using either metal, glass, or plastic tubing are the most common guide today. In general, hollow waveguides are an attractive alternative to conventional solid-core IR fibers for laser power delivery because of the inherent advantage of their air core. Hollow waveguides not only enjoy the advantage of high laser power thresholds but also low insertion loss, no end reflection, ruggedness, and small beam divergence. A disadvantage, however, is a loss on bending which varies as $1/R$ where R is the bending radius. In addition, the losses for these guides vary as $1/a^3$ where a is the radius of the bore and, therefore, the loss can be arbitrarily small for a sufficiently large core. The bore size and bending radius dependence of all hollow waveguides is a characteristic of these guides not shared by solid-core fibers. Initially these waveguides were developed for medical and industrial applications involving the delivery of CO_2 laser radiation, but more recently they have been used to transmit incoherent light for broadband spectroscopic and radiometric applications.[31,32,33] They are today one of the best alternatives for power delivery in IR laser surgery and industrial laser delivery systems with losses as low as 0.1 dB/m and transmitted cw laser powers as high as 2.7 kW.[34]

Hollow-core waveguides may be grouped into two categories: 1.) those whose inner core materials have refractive indices greater than one (leaky guides) and 2.) those whose inner wall material has a refractive index less than one (attenuated total reflectance, i.e. ATR, guides). Leaky or n>1 guides have metallic and dielectric films deposited on the inside of metallic, [35]plastic, [36] or glass tubing. [37] ATR guides are made from dielectric materials

with refractive indices less than one in the wavelength region of interest.[38] Therefore, n<1 guides are fiber-like in that the core index ($n \approx 1$) is greater than the clad index. Hollow sapphire fibers operating at 10.6 μm ($n = 0.67$) are an example of this class of hollow guide.[39]

Hollow metal and plastic waveguides

The earliest circular cross section hollow guides were formed using metallic and plastic tubing as the structural members. Miyagi and his group in Japan used sputtering methods to deposit Ge, [40]ZnSe, and ZnS [35]coatings on aluminum mandrels. Then a final layer of Ni was electroplated over these coatings before the aluminum mandrel was removed by chemical leaching. The final structure was then a flexible Ni tube with optically thick dielectric layers on the inner wall to enhance the reflectivity in the infrared. Croitoru and his group at Tel Aviv University applied Ag followed by AgI coatings on the inside of polyethylene and Teflon tubing to make a very flexible waveguide. [41] Similar Ag and Ag-halide coatings were deposited inside Ag tubes by Morrow, et al.[42]

Hollow glass waveguides

The most popular structure today is the hollow glass waveguide (HGW) developed initially at Rutgers University. [43] The advantage of glass tubing is that it is much smoother than either metal and plastic tubing and, therefore, the scattering losses are less. HGWs are fabricated using wet-chemistry methods to first deposit a Ag layer on the inside of silica glass tubing and then to form a dielectric layer of AgI over the metallic film by converting some of the Ag to AgI. The silica tubing used has a polymer coating of UV acrylate or polyimide on the outside surface to preserve the mechanical strength. The thickness of the AgI is optimized to give high reflectivity at a particular laser wavelength or range of wavelengths. Using these techniques, HGWs have been fabricated with lengths as long as 13 m and bore sizes ranging from 250 to 1,300 μm.

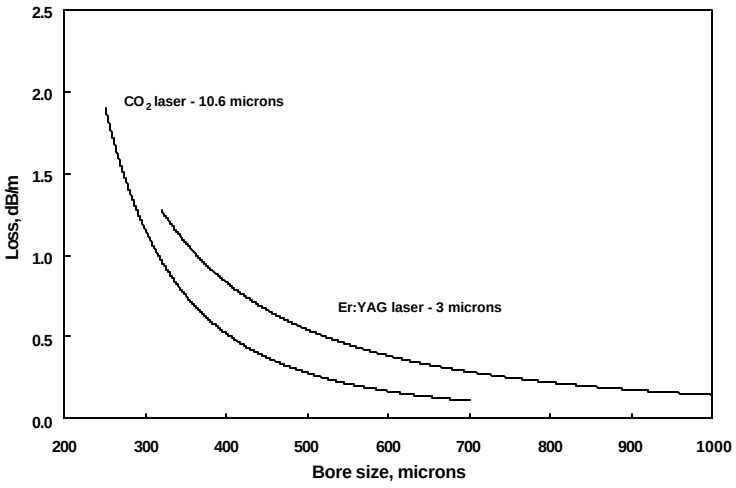

Figure 7 - Straight losses measured in hollow glass waveguides with Ag/AgI films. The guide labeled CO_2 laser was designed for optimal transmission at 10.6 μm while that labeled Er:YAG laser was designed for optimal transmission at 3 μm. Note that the loss varies approximately as $1/a^3$.

The spectral loss for a 530-μm-bore HGW is given in Fig. 2. This HGW was designed for an optimal response at 10 μm. The peaks at about 3 and 5 μm are not absorption peaks but rather interference bands due to thin film optical effects. For broadband applications and shorter wavelength applications, a thinner AgI coating would be used to shift the interference peaks to shorter wavelengths. For such HGWs the optical response will be nearly flat without interference bands in the far IR fiber region of the spectrum. The data in Fig. 7 shows the straight loss measured using a CO_2 and Er:YAG laser for different bore sizes. An important feature of this data is the $1/a^3$ dependence of loss on bore size predicted by theory of Marcatili and Schmeltzer. [44] In general, the losses are less than 0.5 dB/m at 10 μm for bore sizes larger than ~400 μm. Furthermore, the data at 10.6 μm agrees well with the calculated values but at 3 μm the measured losses are somewhat above those predicted by Marcatili and Schmeltzer. This is a result of increased scattering at the shorter wavelengths from the metallic and dielectric films. The bending loss depends on many factors such as the quality of the films, the bore size, and the uniformity of the silica tubing. A typical bending loss curve for a 530-μm bore HGW measured with a CO_2 laser is given in Fig. 8. The losses are seen to increase linearly with increasing curvature as predicted. It is important to note that

while there is an additional loss on bending for any hollow guide, it does not necessarily mean that this restricts their use in power delivery or sensor applications. Normally most fiber delivery systems have rather large bend radii and, therefore, a minimal amount of the guide is under tight bending conditions and the bending loss is low. From the data in Fig. 8 one can calculate the bending loss contribution for a HGW link by assuming some modest bends over a small section of guide length. An additional important feature of hollow waveguides is that they are nearly single mode. This is a result of the strong dependence of loss on the fiber mode parameter. That is, the loss of high order modes increases as the square of the mode parameter so even though the guides are very multimode, in practice only the lowest order modes propagate. This is particularly true for the small bore (<300 μm) guides in which virtually only the lowest order HE_{11} mode is propagated.

HGWs have been used quite successfully in IR laser power delivery and, more recently, in some sensor applications. Modest CO_2 and Er:YAG laser powers below about 80 W can be delivered without difficulty. At higher powers, water-cooling jackets have been placed around the guides to prevent laser damage. The highest CO_2 laser power delivered through a water-cooled, hollow metallic waveguide with a bore of 1,800 μm was 2,700 W and the highest power through a water-cooled, 700-μm-bore HGW was 1,040 W. [45] Sensor applications include gas and temperature measurements. A coiled HGW filled with gas can be used in place of a more complex and costly White cell to provide an effective means for gas analysis. Unlike evanescent wave spectroscopy in which light is coupled out of a solid-core-only fiber into media in contact with the core, all of the light is passing through the gas in the hollow guide cell making this a sensitive, quick response fiber sensor. Temperature measurements may be aided by using a HGW to transmit blackbody radiation from a remote site to an IR detector. Such an arrangement has been used to measure jet engine temperatures.

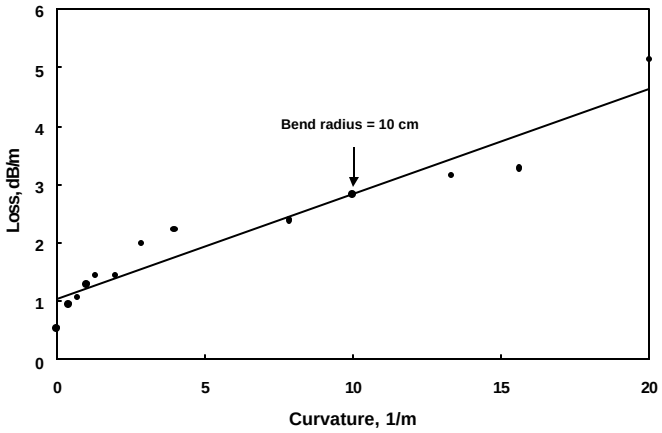

Figure 8 - Additional loss on bending a 530-μm-bore HGW measured at 10.6 μm. The loss is seen to increase as the curvature increases.

5. Summary and conclusions

During the past 25 years of the development of IR fibers there has been a great deal of fundamental research designed to produce a fiber with optical and mechanical properties close to that of silica. We can see that today we are still far from that Holy Grail but some viable IR fibers have emerged which as a class can be used to address some of the needs for a fiber which can transmit greater than 2 μm. Yet we are still limited with the current IR fiber technology by high loss and low strength. Nevertheless, more applications are being found for IR fibers as users become aware of their limitations and, more importantly, how to design around their properties.

There are two near-term applications of IR fibers; laser power delivery and sensors. An important future application for these fibers, however, may be more in active fiber systems like the Er and Pr doped fluoride fibers and emerging doped chalcogenide fibers. As power delivery fibers, the best choice seems to be hollow waveguides for CO_2 lasers and either SC sapphire, germanate glass, or HGWs for Er:YAG laser delivery. Chemical, temperature, and imaging bundles make use mostly of solid-core fibers. Evanescent wave spectroscopy (EWS) using chalcogenide and fluoride fibers is quite successful. A distinct advantage of an IR fiber EWS sensor is that the signature of the analyte is often very strong in the infrared or fingerprint region of the spectrum. Temperature sensing generally involves the transmission of blackbody radiation. IR fibers can be very advantageous at low temperatures especially near room temperature where the peak in the blackbody radiation is near 10 μm. Finally, there is an emerging interest in IR imaging using coherent bundles of IR fibers. Several thousand chalcogenide fibers have been bundled by Amorphous Materials (Garland, TX) to make an image bundle for the 3 to 10 μm region.

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