A Look at the Future of Infrared Fibers

By James A. Harrington

Since the development of the first polycrystalline infrared fibers more than seven years ago at Hughes Research Laboratories,[1] there have been a wide variety of infrared transmissive waveguides fabricated for sensor, power delivery, and future long-distance communication links.[2] These fibers transmit wavelengths between 2 and 25μm, but their losses are well above those of conventional silica-based fibers; thus, the near-term applications involve fibers 1 to 10 m in length. In the future, these waveguides may be suitable for long-distance applications if their losses can be reduced to the theoretical minimum of 10^{-3} dB/km.

Types of IR fibers

There are three categories of IR fibers:

1. PC and single-crystal fibers made from crystalline materials such as the thallium and silver halides.
2. Non-oxide glasses composed of metal fluorides or chalcogenides.
3. Hollow waveguides.

Table 1 lists the basic properties of each type of fiber, including a representative composition and the range of transmission. The loss values reported are the lowest values so far obtained for the particular waveguide.

Fibers made from crystalline materials have the advantage of a very large IR bandpass, but they are weak and less stable than the IR glasses (see Table 1). The most widely studied crystalline fibers are the extruded PC fibers made from KRS-5 (thallium bromoiodide) and AgC1. The transmission of KRS-5 fiber[3] is shown along with that for the As_2S_3[4] and fluoride glass[5] fibers in Figure 1. The attenuation is high at the short wavelengths but decreases as λ^{-2} to a value of 190 dB/km at 10.6 μm in the best fiber. These fibers are thus very useful for CO_2 laser applications, in contrast to the fluoride glasses that are not useful at 10.6 μm because of their high intrinsic absorption at this wavelength.

SC fibers are less well studied but lately their potential use in applications requiring nonlinear and electro-optic fiber materials is very exciting. Work has been done on fabricating fibers from both linear and nonlinear materials including the thallium, silver, and oxide materials. In general, linear SC fibers tend to be very soft, and the losses are higher than the corresponding PC fiber. The greatest usefulness of SC fibers will undoubtedly be as nonlinear fibers where short (<30 cm) lengths are suitable. The linear PC fibers will remain the fiber of choice for the passive applications requiring 1 to 10 m lengths.

The non-oxide glass fibers receiving the greatest attention, and those with the lowest loss, are composed of metal fluorides. Since the discovery of fluoride glass in 1977 by Lucas and his coworkers,[6] fibers have been made from mixed fluorides such as ZrF_4, BaF_2, GdF_4, and AlF_3 with losses as low as 8.5 dB/km at 2.1 μm. The attenuation of this fiber (see Figure 1), which was made by NTT,[5] shows the characteristic extrinsic absorption bands that result from small concentrations of cations such as Fe^{2+}, Cu^{2+}, and Ni^{2+} at the short wavelengths and from water near 3 μm. Presently, these fibers exhibit the lowest loss of all the IR fibers but their transmission appears limited to wavelengths shorter than 5 or 6 μm.

Chalcogenide glass fibers are perhaps the oldest of the IR fibers. Simple glasses such as As_2S_3 and As_2Se_3 are the most common chalcogenide fiber materials although other glasses composed of Ge, Se, and Te have also been made. The transmission spectrum[4] of As_2S_3 (see Figure 1) also has a rich extrinsic absorption spectrum characteristic of these glasses. The minimum attenuation is 78 dB/km at 2.4 μm but other minima of 92 and 164 db/km occur at 1.85 and 5.3 μm, respectively. The peaks in the spectrum may be linked to OH ion contamination at 3 and 6 μm, the SH ion at 4.1 μm, and oxygen impurities in the 8 to 9 μm region. These fibers have the greatest usefulness for wavelengths shorter than 10 μm but even in the practical 3 to 5 μm region, the chalcogenide fibers are likely to be replaced by the potentially lower loss fluoride glass fibers.

Hollow waveguides developed for use at 10.6 μm are either rectangular or circular in cross section. Most work has been done by Garmire and her coworkers[7] on the rectangular waveguides. By launching in a linearly-polarized, single Gaussian mode they are able to transmit over 800 watts of power for waveguides about 1 m in length. Furthermore, the mode remains pure even through moderate bending and twisting of the guide. The disadvantage of these hollow wave-

TABLE 1
Properties of IR Fibers

	CHALCOGENIDE	FLUORIDE GLASS	POLYCRYSTALLINE	SINGLE CRYSTAL	HOLLOW WAVEGUIDE
FABRICATION	Drawing	Drawing	Extrusion	Pull From Melt	Mechanical
EXAMPLE	As_2S_3	ZrF_4:BaF_2 :GdF_4:AlF_3	KRS−5 (T1BrI)	Cs1	Rectangular
LOWEST LOSS	78 dB/km at 2.4 μm	8.5 dB/km at 2.1 μm	190 dB/km at 10.6 μm	300 dB/km at 10.6 μm	1000 dB/km at 10.6 μm
TRANSMISSION	1 to 10 μm	1 to 6 μm	5 to 20 μm	5 to 20 μm	0.8 μm and longer
FEATURES	Glass Easily Drawn	Glass Cladding Easy Strong Low Loss	CO Transmission Large IR Bandpass	Nonlinear Fibers Ultralow Loss	Large Power Threshold

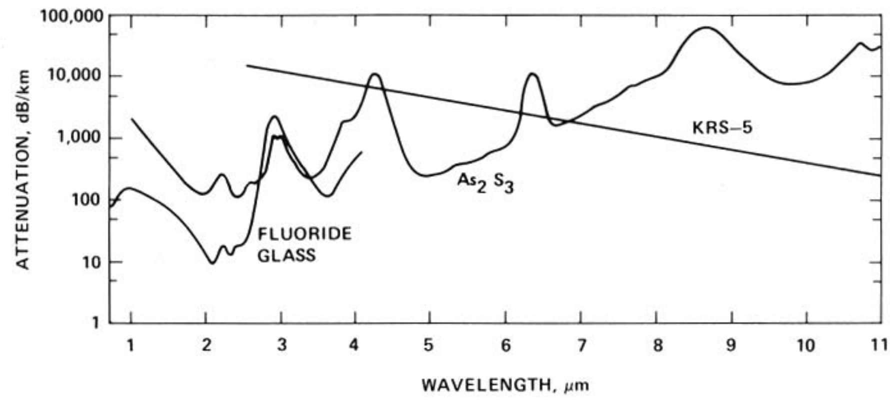
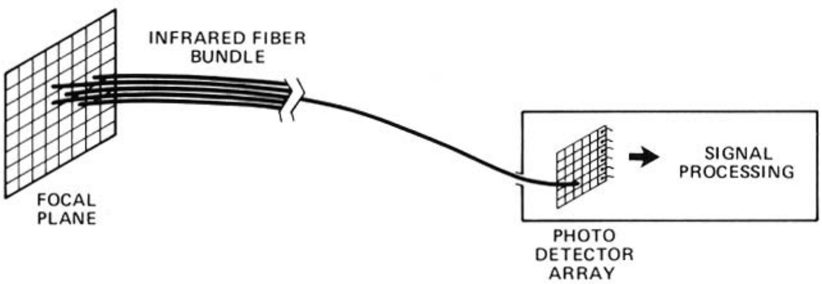
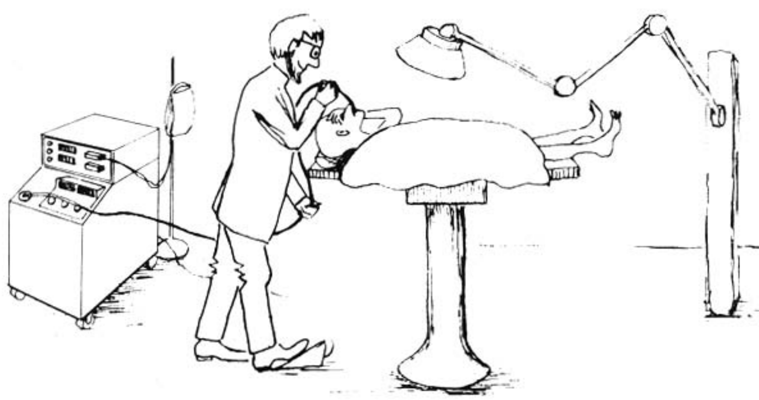


Figure 1 Comparison of the best glass and PC fibers.



- RELAY INFORMATION FROM REMOTE AREAS TO PHOTODETECTORS
- IR FIBER RECEIVERS/TRANSMITTERS FOR IFF, COUNTERMEASURES
- PYROMETRY–MEASURE TEMPERATURES LESS THAN 200°C
- REMOTE IR SPECTROSCOPY–DETECT POLLUTANTS, GASES

Figure 2 Use of IR fibers to transfer information from an image plane to a remote photodetector.



- CO_2 LASER SURGERY
- MULTIPOINT MATERIALS PROCESSING: LASER ANNEALING, ELECTRICAL CONTACTS, ETC.
- POWER OUT: 10 WATTS, CO_2 LASER, 500 μm–DIAMETER FIBER

Figure 3 Power delivery is an important application especially in laser surgery where CO_2 lasers are useful for cutting tissue.

guides is that they are larger—about 1 mm by 5 mm—than dielectric guides and they tend to develop rather large losses when they are bent or twisted. They will have their greatest usefulness in very high power applications.

Applications of IR fiber

The applications of IR fibers are most easily discussed in terms of three general categories: sensors, power delivery, and long-distance communications. Because the present fibers have rather high loss, the near-term applications involve sensors and power delivery, while the future long-distance communication links await the development of ultra low-loss IR fibers.

In the short length sensor applications, fibers are used to relay information from one area, such as a focal plane, to a remote photodetector. Figure 2 illustrates how a bundle of fibers may be used to dissect a focal plane and relay the IR image to a photodetector array. We have used KRS-5 fiber bundles with as many as 10 fibers up to 5 m in length to transfer 10.6 μm information to liquid nitrogen cooled HgCdTe detectors.[8] In these particular applications, the fibers were part of an early-warning receiver for the detection of 10.6 μm radiation. In one instance, the fiber bundles would be installed in an aircraft to detect and transmit CO_2 laser radiation that would illuminate the skin of the aircraft from, for example, ground-based laser rangefinders.

Other sensor applications include the detection of blackbody radiation and remote IR spectroscopy. Using a fiber-detector combination, it is possible to measure temperatures well below 200°C °C because at these low temperatures the blackbody radiation is peaked near 10 μm. The spectroscopic application involves using the fibers to monitor the IR absorption of gases such as CO_2 or common pollutants.

The delivery of laser power by IR fibers is of great importance in such fields as medicine. Fibers have already been used to deliver up to 100 watts of 1.06 μm radiation from Nd:YAG lasers for laser surgical applications. We are now developing IR fibers that will reliably deliver 10 to 20 watts from fibers that are as small as 250 μm in diameter. Figure 3 shows an endoscopic application for an IR fiber, but other surgical modalities such as gynecology, urology, and ophthalmology are also good candidates for laser surgery.

Other power delivery applications include multipoint soldering and cutting. So far, IR fibers such as KRS-5 have power thresholds that vary from 10 to 80 watts so that cutting and soldering operations would be limited to small amounts of softer materials.

The theoretical attenuation in these waveguides is near 10^{-3} dB/km. While the current IR fibers have losses well above this level, when IR fiber losses are reduced to this level we can look for a major advance in communication systems. With a loss of 10^{-3} dB/km, it would be possible to construct communication links thousands of kilometers in length without repeaters. This would be particularly useful in undersea links between shore and submarine where the use of repeaters would be inconvenient. This application and a comparison of the various repeaterless lengths for wire and fibers are shown in Figure 4.

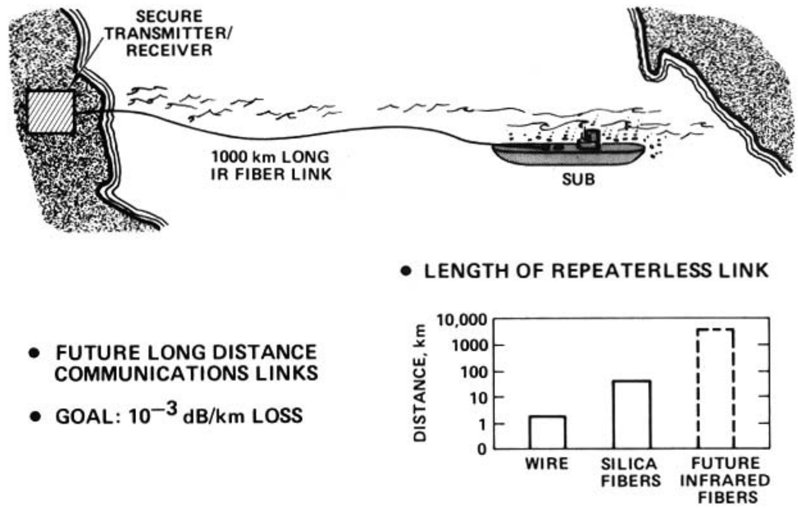


Figure 4 Future application for ultralow loss IR fibers is in repeaterless, long-distance communications.

Polycrystalline KRS-5 fibers

PC fibers made from the thallium and silver halides are fabricated using a hot extrusion technique. The extrusion temperatures are generally between 200 and 350 °C and the extrusion force may be as high as 40 kN for billets 1.5 cm in diameter.[9] Fibers have been extruded with diameters ranging from 75 to 1000 μm and with lengths as long as 200 m. The fiber grain size is typically 3 to 10 μm with the smallest grain size fiber having the greatest tensile strength.

All KRS-5 fibers made to date have had no conventional cladding. For most applications, the fibers are placed in loose fitting polyethylene tubing that, for lengths less than 10 m, has been found to induce no extra loss.

The attenuation at 10.6 μm in KRS-5 fibers is typically 1 dB/m, which is about 1,000 times greater than the intrinsic loss. To understand this large extrinsic loss, we studied[3] the total attenuation, α_T, and the attenuation due to scattering, α_S, as a function of wavelength. In general, α_T can conveniently be written in the form

$$\alpha_T(\lambda) = A\lambda^{-4} + B + C\lambda^{-2} + \alpha_A(\lambda),$$

where λ is the vacuum wavelength. In silica-based fibers, measurements of both α_T and α_S are in excellent agreement with theories based on the first (Rayleigh) and second (geometrical optics) terms. In contrast, we find that in our PC fibers the λ^{-2} term dominates the fiber attenuation. To explain these results, we developed a model[3] showing that this λ^{-2} attenuation results from the combination of bulk scattering from large-scale, optically thin imperfections and surface scattering and absorption. In KRS-5 fibers, the imperfections that may lead to a λ^{-2} scattering loss are believed to be because of residual strains in the fibers and surface irregularities. The strain is induced in the extrusion process and results in a large birefringence that causes scattering. The surface of the fiber is also rough compared with a drawn-glass fiber surface.

Figure 5 shows the λ^{-2} dependence of α_T for two KRS-5 fibers approximately 1 m long. One fiber (No. 1) has a loss of 0.74 db/m at 10.6 μm, whereas the other (No. 2) has a higher attenuation coefficient of 2.1 dB/m at 10.6 μm. The higher-loss fiber exhibits several impurity bands, which may result from impurities on the fiber's surface; for example, the 6.1 μm band is due to water.

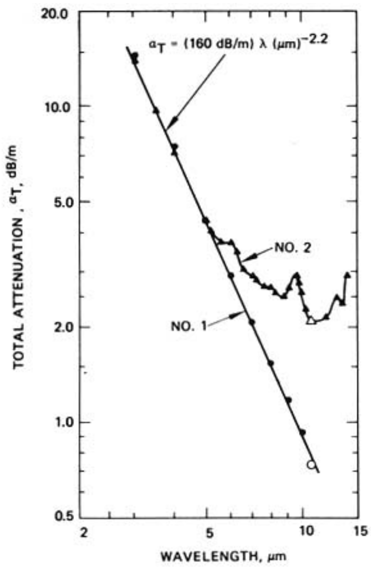


Figure 5 The attenuation in KRS-5 fibers decreases as λ^{-2}, in sharp contrast to the situation in glass fibers.

Finally, we note that there have been several attempts to commercialize KRS-5 fibers. The first was by Horiba Limited in Japan and now by Infrared Fiber Industries in California. The fibers made by Horiba were very expensive, more than $10,000 per cable 1.2 m in length, and, to the best of the author's knowledge, they are no longer available. The reason for this may be, in part, an aging problem in which the transmission of the KRS-5 fiber decreases with time. Since the Horiba fibers appeared, there has been more progress on solving the aging problem, and fibers available in the future should show minimal aging.

Single-crystal fibers

The losses of PC fiber result from the absorption and scattering of light from defects that may be impurities decorating grain boundaries, residual strain induced during the fiber's extrusion, and poor surface quality. SC fibers have the potential of eliminating these deleterious effects because they can be grown with smoother surfaces and less fiber strain than PC fibers. We have developed at Hughes a new method of SC fiber fabrication in which PC fiber is converted into SC fiber using a traveling zone growth technique. Using this method we have made 1-m long lengths of silver and thallium halide SC fibers with losses as low as 6.6 dB/m at 10.6 μm.

Previous SC fiber fabrication techniques have most generally relied on a capillary shaper or edge definer to configure the fiber diameter. Bridges[10] at AT&T Bell Labs and Ota[11] at KDD in Japan uses shapers to make SC fibers from the silver, thallium, and cesium halides. In these cases, a molten reservoir of material was used as the source. In the traveling zone method, we do not use a shaper and, therefore, no part of the molten zone contacts a surface. In this way, we eliminate a potential impurity source that occurs when the melt contacts the container walls. Another advantage of our method is that the melt zone is very small—approximately one fiber diameter.

The heart of the traveling zone technique is shown in Figure 6. Two sets of synchronously driven drive wheels move extruded PC fiber through a small heater coil that is used to form a melt zone with a length between 0.1 and 4 fiber diameters. As the fiber exits the

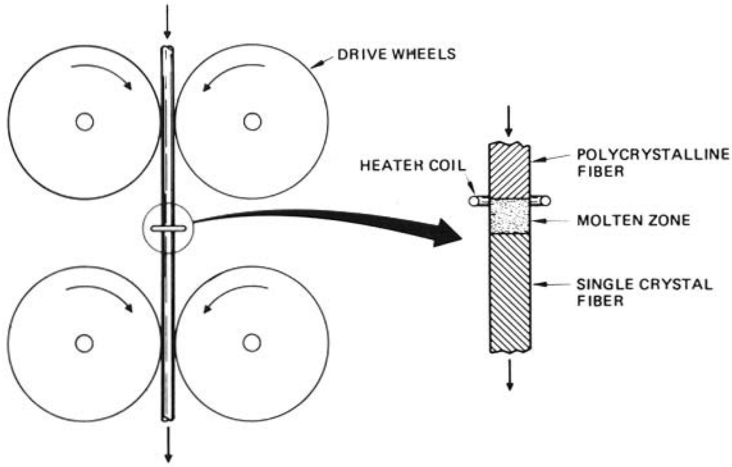


Figure 6 Traveling-zone growth of SC fibers in which PC fiber is converted into SC fiber.

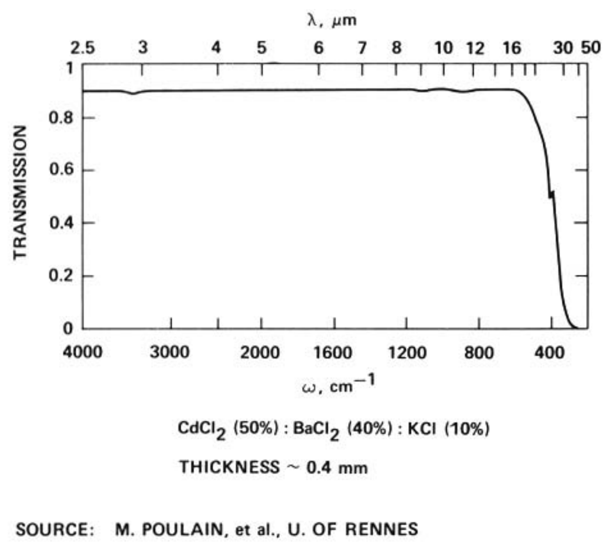


Figure 7 New chloride glass with transmission beyond 10 μm.

TABLE 2
Loss at 10.6 μm

PC FIBER		SC FIBER	
LENGTH (cm)	LOSS (dB/m)	LENGTH (cm)	LOSS (dB/m)
94	2.6	80	6.6
49	8.5	28	8.3

melt zone it freezes into a single crystal. The melt zone is held together by surface tension, and we find no sagging even if growth is horizontal. The growth rates are approximately 1 cm/min and all fibers grown to date have preserved the original PC fiber diameter.

We had the best success growing SC fibers of the silver salts. This is because of their low vapor pressure. The optical absorption of several samples of 620 μm diameter AgBr fiber is given in Table 2. From the table, we note that the longer SC fiber had a higher attenuation than the starting PC fiber. This, plus the fact that the lowest loss of 6.6 dB/m is still rather high, is because of some irregularities in the fiber surface quality and a few bubbles included in the fiber core.

We have begun to apply these same techniques to the fabrication of SC fibers from nonlinear and electro-optic materials. Nonlinear fibers[12] only tens of centimeters in length would be useful in frequency conversion applications, while EO fibers would be potentially useful modulators. Based on our work to date, it would seem that near-term applications for SC fibers would involve nonlinear and EO materials.

Future directions

The lowest-loss IR fibers are the fluoride glass fibers, and it would seem that the losses in these waveguides would continue to decrease as new glass fabrication and purification methods are developed. Of particular importance will be the development of a chemical vapor deposition method of making glass preforms analogous to that used so successfully for silica-based glasses. The use of CVD methods should allow losses lower than 1 dB/km to be achieved.

A new glass technology that shows promise is the development of fluorochloride and chloride glasses for transmission beyond 10 μm. A recent example of an all-chloride glass is shown in Figure 7. While this sample of CdF_2 :BaF_2 :KC1 is only 0.4 mm thick, the transmission range out to 15 μm is impressive. Unfortunatly, these chloride glasses suffer from very low glass transition temperatures—some are as low as room temperature—and poor stability. In particular, they are very sensitive to moisture and, for some glasses like $ZnCl_2$, they deliquese and devitrify within minutes after exposure to the atmosphere.

PC fibers made by the extrusion process may be very near their practical lower limit. With some further improvements in extrusion, the losses in fibers like KRS-5 may be reduced even further to about 100 dB/km. However, the induced strain and poor surface quality of extruded fibers preclude achieving the low loss of glass fibers. While SC fibers may solve some of the problems that extrusion presents, the usefulness of SC fibers will be in short length nonlinear and EO applications.

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