Chapter 1

Introduction to Infrared Fiber Optics

1.0 Historical overview

Infrared (IR) optical fibers may be defined as fiber optics that transmit radiation with wavelengths greater than approximately 2 μm. The first IR fibers were fabricated in the mid-1960s from a rather special class of IR transparent glasses called chalcogenide glasses.[1] It had been known for some time that blending chalcogen elements such as arsenic and sulfur can form a dark red-colored glass that is transparent well beyond 2 μm. Being an excellent glass former, arsenic trisulfide (As_2S_3) was a logical choice to be drawn into crude fiber using a simple fiber drawing apparatus. Kapany et al.[2] reported on these first IR fibers in 1965, but the losses were very high. In fact, the losses were an untenable 10 dB/m over the IR spectrum from 2 to 8 μm. A loss of 10 dB/m means that a mere 1-m length of As_2S_3 fiber would transmit only 10% of the incident light apart from reflection losses from the fiber end faces. The reflection losses would amount to an additional 31%, as this glass has a high refractive index of about 2.3. On top of these problems, their As_2S_3 fiber was quite brittle. During the mid-1970s, 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 1975, Hughes Research Laboratories (HRL) researchers in Malibu, CA, began to search for an IR fiber that could be used in a satellite application to link IR radiation in the 3- to 5-μm, 8- to 12-μm, and longer wavelength bands, which was incident on a surveillance satellite, to an interior IR detector array. The basic fiber/detector system as envisioned by HRL is shown schematically in Fig. 1.1. The idea was simple: Take an array of IR fibers and position them so that they would each intercept a large field of view, and then transmit that signal through an IR fiber for a distance of no more than about 50 cm to a mosaic IR detector array. This particular U.S. Army-funded program, called Mosaic Infrared Sensor Technology (MIST), would ultimately require a fiber array consisting of several hundred fibers, each interfaced with one detector element in the detector array. Initially the investigators at HRL experimented with the chalcogenide fibers, but they found the loss too high and the fibers too brittle for their application. Another unfortunate feature of chalcogenide fibers is that they are made from toxic materials. Some people working with them

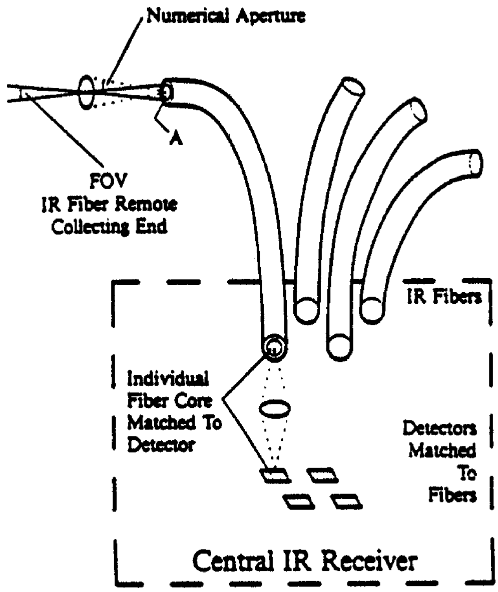

Figure 1.1 Early concept of IR fibers used in a laser threat warning system. A small number of IR fibers access a wide field-of-view (FOV) and transmit the signal to a remote photodetector array.

accidentally poked their fingers with the sharp fiber ends, and this led to some tissue darkening in the areas of broken skin, which they attributed to the death of tissue (necrosis). Needless to say, this aspect contributed to the search for another IR fiber better suited to the satellite application. The IR fiber that grew out of this program was the first polycrystalline fiber made from thallium halides, or KRS-5, as it was known.[3] Oddly enough, KRS-5 fibers were also toxic due to the presence of thallium compounds. Nevertheless, KRS-5 fibers had the advantage of being very flexible and transmitting wavelengths even beyond 20 μm.[4]

At this same time another application emerged that was to help drive IR fiber technology for many years. This application involved the ever-increasing need for a flexible fiber delivery system for transmitting CO_2 laser radiation in surgical applications. Surgical lasers began to be developed only a few years after the invention of the laser in 1960. There were basically two surgical lasers in the early years of their development: the Nd:YAG laser operating at 1.06 μm, and the CO_2 laser operating at 10.6 μm. While each laser could be used for cutting, ablating, and coagulating tissue, the Nd:YAG laser had a distinct advantage over the CO_2 laser in that the 1.06-μm radiation could be delivered by a conventional albeit large-core silica fiber optic. Surgeons quickly became accustomed to the tactile feel and flexibility of a silica fiber; this is especially important when the fiber optic is introduced into the body least invasively through an endoscope into the body. The problem was that there was no counterpart to the silica fiber for the CO_2 laser medical lasers. Instead of a fiber delivery system for 10.6 μm, these lasers employed cumbersome articulated arms. Articulated arms, like the one shown attached to a CO_2 laser in

Fig. 1.2, are made of tubes and mirrors that can move in any direction. It is obvious from Fig. 1.2, however, that these arms are meant only for the delivery of laser power outside the body, as they are too big to be used otherwise. This fact coupled with the easy misalignment of the early arms and their high cost argued strongly for a better, i.e., fiber optic, solution to the problem of delivering of IR surgical laser power. When HRL workers announced the invention of the first polycrystalline KRS-5 fibers in 1976, it was immediately realized that they could also deliver CO_2 laser power. In fact, some quite optimistic scientists at HRL said that KRS-5 fibers could deliver up to 100 W of CO_2 laser power, well before this had ever been tried. It would be some years later before this goal was reached, but the mere ability to deliver this important surgical laser wavelength set many laboratories around the world on the quest for a good 10.6-μm transmitting fiber. After almost 30 years of research on IR fibers, the need for a CO_2 laser fiber similar to silica fiber still remains a goal today. The difference today is that there are many more IR fiber candidates for this wavelength including the popular hollow waveguides. In point of fact, a close analog to silica fiber operating at 10 μm will never be attained because there is no IR material at this wavelength that has optical and mechanical properties equal to that of silica.

There was yet one other motivation for developing IR fibers beside their use in sensor and laser power delivery applications. As will be elucidated in some detail in Chapter 2, many if not most of the IR materials transmitting beyond 2 μm have a theoretical loss that is much less than silica. In fact, when the KRS-5 fiber was developed by HRL it was realized that the intrinsic or fundamental losses for this crystalline material could be as low as 10^{-3} dB/km at approximately 6 μm. This is the minimum theoretical loss for this material, but there are hundreds of other IR optical materials including glasses that have similar low losses. The key issue here

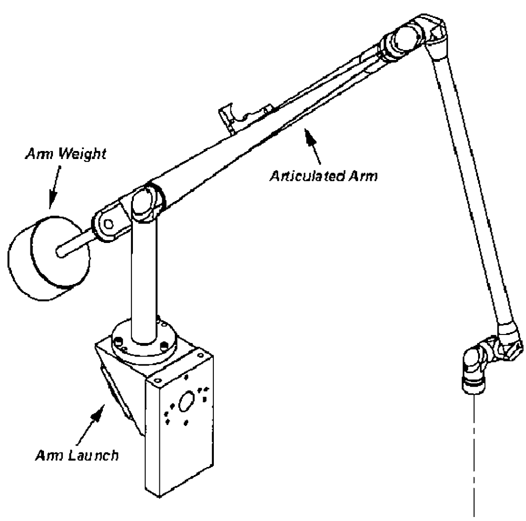

Figure 1.2 Articulated arm composed of tubes, mirrors, and movable joints for the delivery of CO_2 laser radiation. [From Haser Mechanisms, Inc.]

is that silica fibers have a theoretical minimum attenuation of about 0.14 dB/km at 1.55 μm, or about 100 times higher than KRS-5 or many other IR materials. Therefore, if a fiber could be made with a loss this low, then it would be possible to construct telecommunications links thousands of kilometers in length without repeaters. In particular, the U.S. government funding agency DARPA started a program in the late 1970s called the Clear Day Program to fund development of ultralow-loss fibers for undersea applications. The idea was that a submarine could be in constant contact with its base station by paying out an ultralow-loss fiber as it traveled under water. Because the fiber had such a low loss, "On a clear day you can see forever." Unfortunately, no IR fiber was ever developed with a loss lower than silica, much less near its intrinsic loss. This is still a long-term goal, but at least it remains a theoretical possibility even though there are enormous challenges to overcome before it becomes a reality.

Interestingly enough, other types of IR fibers began appearing at about the same time as KRS-5 fiber. These other fibers included the heavy metal fluoride glass (HMFG), other polycrystalline fibers like the silver halides, and hollow rectangular waveguides. While none of these fibers had physical properties even approaching that of conventional silica fibers, they were, nevertheless, useful in lengths of less than 2 to 3 m for a variety of IR sensor and power delivery applications.[1]

1.1 Types of IR fibers

Infrared fiber optics may logically be divided into three broad categories: glass, crystalline, and hollow waveguides. These categories may be further subdivided based on the fiber material or structure or both, as shown in Fig. 1.3. An example of a typical fiber for each subdivision is given in the last row of Fig. 1.3. Another way of viewing IR fibers that is more convenient from the viewpoint of laser power delivery applications, is to ask for the best IR fibers for use at the two most popular IR laser wavelengths: the 10-μm CO_2 laser and the 3-μm Er:YAG laser. The chart in Fig. 1.4 is a guide to the most useful fibers available today for delivering these two laser energies.

Over the past 30 years many 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 few other books on IR fibers and in review

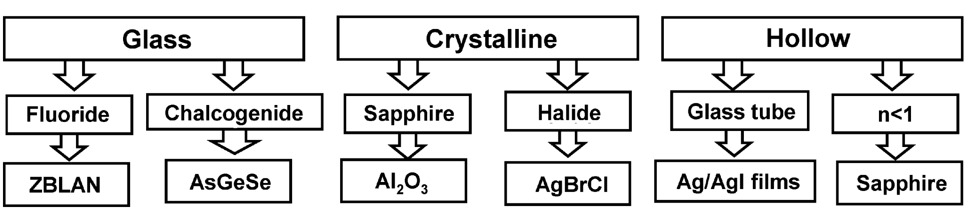

Figure 1.3 Major categories of IR fiber optics and an example of each fiber type.

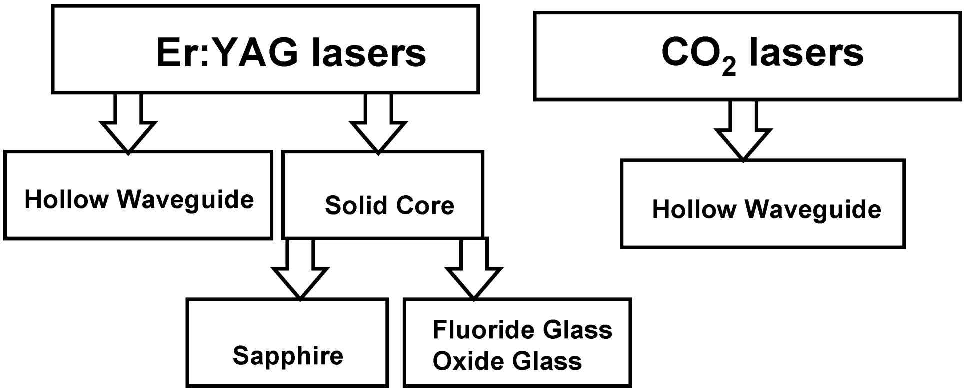

Figure 1.4 IR fibers most commonly used for the delivery of two popular IR lasers: the CO_2 and Er:YAG laser.

articles.[5–8] In this treatise only the best, most viable and, in most cases, commercially available IR fibers are treated in detail, although mention is made of a few other attempts to make a viable IR fiber. One of the most important points to glean from a study of IR fiber optics is that because their physical properties are inferior to silica fibers, they are primarily limited to non-telecommunication, short-haul applications that require only a few meters of fiber rather than the kilometer lengths common to telecommunication applications. The primary reason that their use is limited to short lengths is that the losses for most of the fibers are a few decibels per meter (dB/m) rather than less than 1 dB/km, which is common for silica fibers. An exception is fluoride glass fiber, 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 to applications in chemical sensing, thermometry, and laser power delivery.

1.2 General properties of IR fibers

The obvious key property of 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 there are few applications requiring the transmission of IR radiation longer than about 12 μm. A summary of the spectral loss for five of the six subcategories of fibers listed in Fig. 1.3 is shown in the composite data[1] in Fig. 1.5. From the data it is clear that there is a wide variation in range of transmission for the different IR fibers, and that the loss of most of the IR fibers is quite high compared with silica fibers. Remembering that 1 dB/m is a bulk loss of about 20% per meter, it is again evident that this high loss will restrict applications to meter-long lengths. In fact, the losses for all of these fibers except the hollow waveguide should be much lower. The reason that they are not is that the fibers contain impurities and imperfections, which give rise to a large extrinsic absorption and scattering. Some of these extrinsic absorption bands are evident in

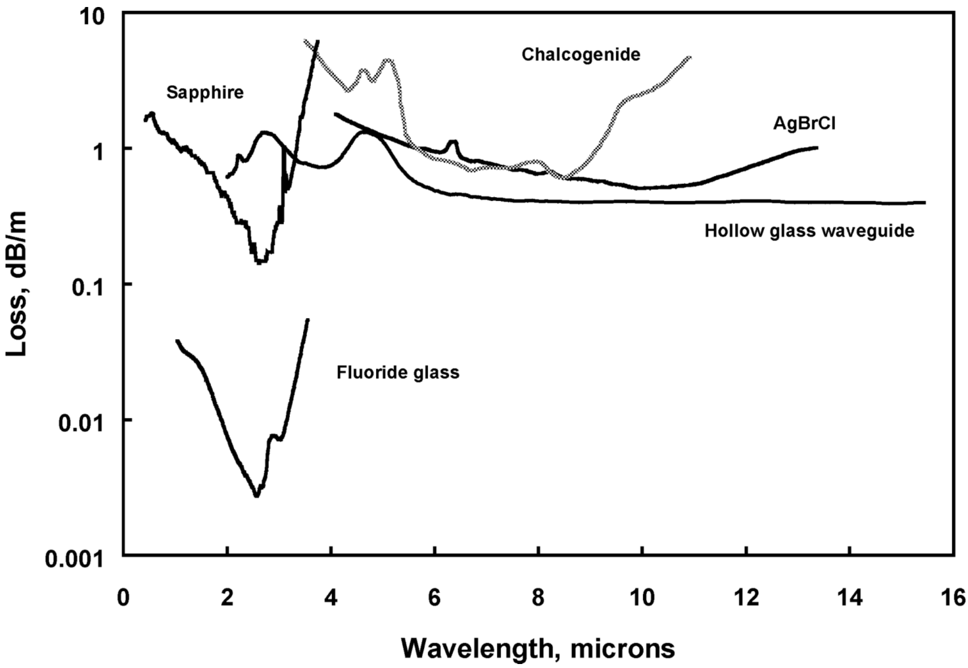

Figure 1.5 Composite loss spectra for some common IR fiber optics: ZBLAN fluoride glass, SC sapphire, chalcogenide glass, PC AgBrCl, and hollow glass waveguide.[1] [Reprinted with permission from The McGraw-Hill companies.]

Fig. 1.5. The absorptions shown for the hollow waveguide are not due to impurities; rather they are due to interference effects resulting from the thin-film coatings used to make the guides. One of the most important research areas of IR fibers is the study of the sources for these extrinsic absorptions and methods to eliminate them. Details of a myriad of extrinsic absorption mechanisms in IR fibers are a major part of each chapter on glass, crystalline, and hollow IR waveguides.

Some of the important optical and mechanical properties of IR fibers are listed in Table 1.1. For comparison, the properties of silica fibers are also listed. The data in the Table 1.1 and in Fig. 1.5 reveal that, compared with 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 reflection or Fresnel loss exceeds 20% for two fiber ends. The higher dn/dT and low melting or softening point leads to thermal lensing and, as a result, low laser-induced damage thresholds for the solid-core IR fibers. Finally, many IR fibers do not have a proper cladding analogous to conventionally clad oxide glass fibers. Nevertheless, core-only IR fibers such as sapphire and chalcogenide fibers can still be useful. This is because their refractive indices are sufficiently high so that there is less evanescent wave energy outside the core. As long as the unclad fiber does not come in contact with an absorbing medium, the fiber can operate reasonably well, as there will be very little leakage of light from the core to the surrounding air.

Table 1.1 Selected physical properties of key IR fibers compared to conventional silica fiber.

	Glass			Crystal		Hollow
		HMFG	Chalcogenide	PC	SC	Hollow Silica
Property	**Silica**	**ZBLAN**	**AsGeSeTe**	**AgBrCl**	**Sapphire**	**Waveguide**
Glass transition or melting point, °C	1175	265	245	412	2030	150 (useable T)
Thermal conductivity, W/m °C	1.38	0.628	0.2	1.1	36	1.38
Thermal expansion coefficient, 10^{-6} °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} °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

*Typical measured loss, NA = not applicable.

1.3 General applications of IR fibers

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 1.2. There are several noteworthy trends seen in 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 because IR materials used in solid-core fibers have laser damage thresholds that are frequently very low. The air-core waveguides are capable of delivering close to 3000 W of cw CO_2 laser power, far in excess of any IR solid-core fiber. However, solid-core IR fibers are ideal evanescent-wave sensors for monitoring chemical processes in the sensitive fingerprint region of the infrared spectrum. In these applications the fiber core is surrounded by the chemical or biological agent, and some portion of the light is coupled out of the core into the surrounding medium. This type of chemical sensor is potentially very sensitive and selective. Chalcogenide and silver halide fibers are particularly good for this application, as they are quite inert and their high refractive index means that only a small portion of the light is out-coupled from the core into the absorbing medium. A good fiber for gas sensing is the hollow waveguide, as the core of this fiber can

Table 1.2 Examples of IR fiber candidates for various sensor and power delivery applications.

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

be filled with gas so that light propagating through the waveguide is partially absorbed by the gas. Temperature measurements using long-wavelength transmissive fibers like the silver halides or hollow waveguides are possible over a large temperature range. Normally, blackbody radiation from a source is transmitted through the fiber and the temperature determined by calibration to a blackbody of known temperature. Since blackbody radiation from room temperature objects peaks near 10 μm IR, fibers are excellent candidates for use in measuring temperatures below 50°C. A host of different IR fiber applications with many examples are given in Chapters 8, 9, and 10.

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