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A Review of IR Transmitting, Hollow Waveguides

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IR transmitting hollow waveguides are an attractive alternative to solid-core IR fibers. Hollow guides are made from plastic, metal, or glass tubes that have highly reflective coatings deposited on the inside surface. These guides have losses as low as 0.1 dB/m at 10.6 μm and may be bent to radii less than 5 cm. For use in high-power laser delivery applications the guides have been shown to be capable of transmitting up to 3 kW of CO_2 laser power. They are also finding uses in both temperature and chemical fiber sensor applications. This paper reviews the progress in hollow waveguide technology with emphasis on the best guides available today.

Keywords IR fibers, hollow waveguides, laser power delivery, fiber sensors

Introduction

Infrared (IR) optical fibers may be defined as fiber optics transmitting wavelengths greater than approximately 2 μm. The first IR fibers were fabricated in the mid-1960'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)

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 Three main categories of IR fibers with examples of the most common type of fiber within the category of glass, crystalline, or hollow fibers.

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 paper we will review only the hollow waveguide technology with emphasis on the best and most practical hollow waveguide candidates available today. In general, both the optical and mechanical properties of IR transmitting hollow waveguides remain inferior to silica fibers and, therefore, the use of hollow guides is still limited to non-telecommunication, short-haul applications requiring only a few meters of waveguide rather than kilometer lengths common in telecommunication applications. The short-haul nature of these special IR fibers results from the fact that the guides have losses in the range of a few dB/m rather than a few dB/km. Also, hollow guides have an additional loss on bending; and they are also somewhat weaker than silica fiber. These deleterious features have slowed the acceptance of hollow guides and restricted their use today to applications in chemical sensing, thermometry, and laser power delivery.

Background

Hollow waveguides present an attractive alternative to other solid-core IR fibers. (2) Key features of hollow guides are: their ability to transmit wavelengths well beyond 20 µm; their inherent advantage of having an air core for high-power laser delivery; and their relatively simple structure and potential low cost. 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. (7),(8) In general, hollow waveguides enjoy the advantages of high laser power thresholds, low insertion loss, no end reflection, ruggedness, and small beam divergence. Potential disadvantages, however, include an additional loss on bending and a small NA. Nevertheless, they are today one of the best alternatives for both chemical and temperature sensing as well as for power delivery in IR laser surgery or in industrial laser delivery systems with losses as low as 0.1 dB/m and transmitted cw laser powers as high as 2.7 kW. (9)

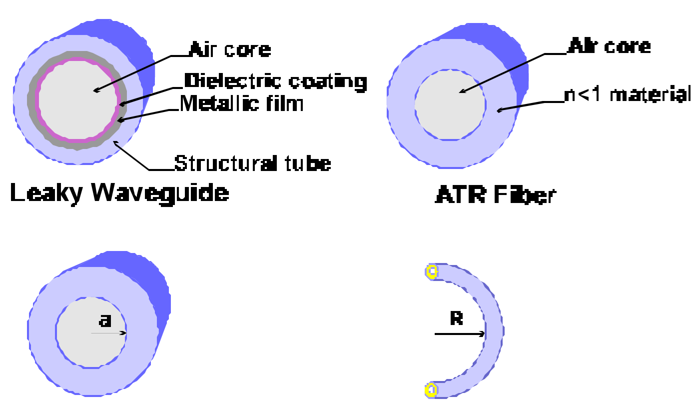

Figure 1 - Structure of two types of hollow waveguides also showing the key parameters of bore and bending radius affecting the losses in hollow guides.

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, plastic, or glass tubing. (10) ATR guides are composed of dielectric materials with refractive indices less than one in the wavelength region of interest. (11) Therefore, n<1 guides are fiberlike in that the core index (n ≈ 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. (12) The structure and key parameters for hollow guides are shown in Figure 1. In general, hollow structures with n>1 have been made from metal, plastic, and glass tubes while the n<1 or ATR guides are made of sapphire or some special n<1 oxide glass.

The theory of hollow waveguide transmission has been described from the viewpoint of both wave and ray optics. Marcatili and Schmeltzer (MS)(13) have used a wave optic approach which predicts for either metallic or dielectric waveguides that $\alpha \sim 1/a^3$, where α is the attenuation coefficient and a is the bore radius. Bending the hollow waveguides increases the total loss. Recently, Miyagi, et al. (14) have shown that the additional bending loss varies as $1/R$, where R is the bending radius. Therefore, we have, in contrast to the solid-core fibers, a loss that depends strongly on the diameter and bending radius of the fiber. For the thin film waveguide structures, Miyagi and Kawakami(15) have shown that for dielectric coatings deposited over a metallic layer, the attenuation coefficient, is given by,

$$\alpha_\infty = \left(\frac{U_o}{2\pi}\right)^2 \cdot \frac{\lambda^2}{a^3} \cdot \left(\frac{n}{n^2+k^2}\right)_{metal} \cdot F_{film} \tag{1}$$

where α_∞ is the loss for a straight guide; U_o is a mode-dependent parameter which for the lowest order HE_{11} mode equals 2.405; n and k in $(\ldots)_{metal}$ refer to the optical constants of metal film, and F_{film} is a term which accounts for the loss due to the dielectric film(s).

Metal-tube waveguides

Hollow core waveguides have been fabricated using a variety of techniques. Some of the methods include physical vapor deposition of silver and dielectric layers on metallic substrates,(16) sputtering of metallic, dielectric, and semiconductor films on a leachable mandrel followed by electroplating,(17) and liquid phase formation of coatings inside plastic tubing(18) and glass tubing. (19) Most often the cross section of the guides is circular but early work by Garmire, et al. (20) and more recently by Kubo, et al. (21) on rectangular guides continues to be of interest. The advantage of the circular cross section is the ease of bending and the small overall size compared to rectangular or square cross section guides.

Professor Miyagi and his co-workers at Tohoku University(17) have pioneered the development of metallic waveguides based on a hollow nickel substrate. Their fabrication process involves three steps. In the first step a pipe made typically of aluminum is placed in a sputtering chamber and a dielectric layer followed by a metallic film is deposited on the pipe. Next, the coated pipe is put into an electroplating tank where a thick nickel layer is deposited on top of the sputtered layers. Finally, the pipe is etched away leaving the final structure shown in Figure 2.

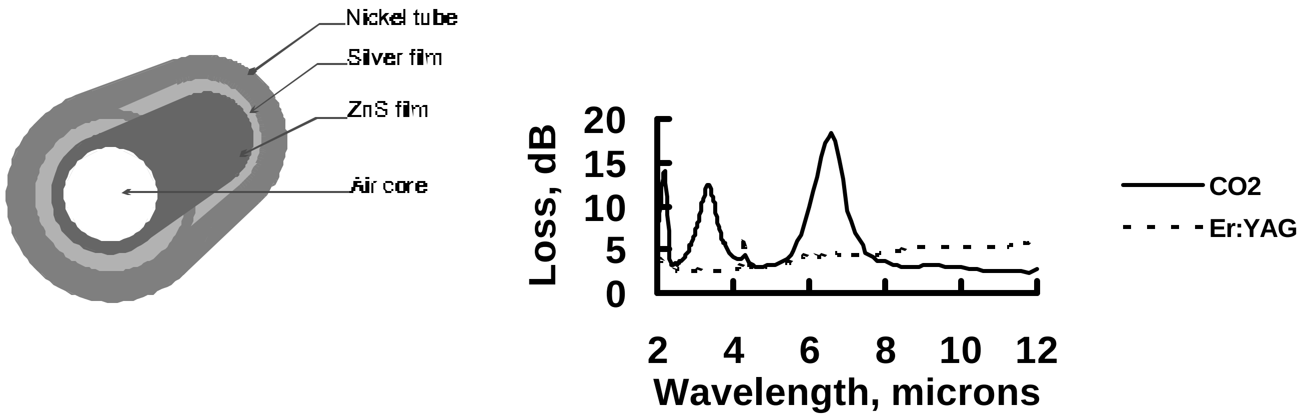

Figure 2 - Structure and spectral losses for metallic waveguide fabricated by Miyagi's group at Tohoku University. (22)

In Figure 2 we also show a typical loss curve for one of their best dielectric coatings (ZnS) over silver. The data shown are for two 1000 µm-bore guides, one optimized for the 3 µm wavelength of the Er:YAG laser and the other optimized for the 10.6 µm wavelength of the CO_2 laser. The optimization for each wavelength results from adjusting the thickness of the thin-film dielectric coating. In Figure 3, bending losses for these hollow waveguides are given for both the CO_2 and Er:YAG laser wavelengths. (22) The losses are seen to be as low as 0.25 dB/m at 10.6 µm for light polarized perpendicular to the plane of bending but slightly higher for parallel polarized light. This is as expected from waveguide theory or from simple considerations based on Fresnel reflections from metal surfaces. The highest CO_2 laser power delivered using a 2,000 µm bore metallic guide is over 3 kW. (9) Miyagi and his co-workers have also developed a hollow structure based on a square cross section. (23) To fabricate a square cross-section tube they have developed a process in which they first deposit, using evaporative techniques, thin-film coatings of ZnS, PbTe, and/or PbF_2 on phosphor bronze strips and then they solder four of these phosphor bronze metal strips together in a continuous process. The losses for these square guides are as low as 0.1 dB/m at 10.6 µm.

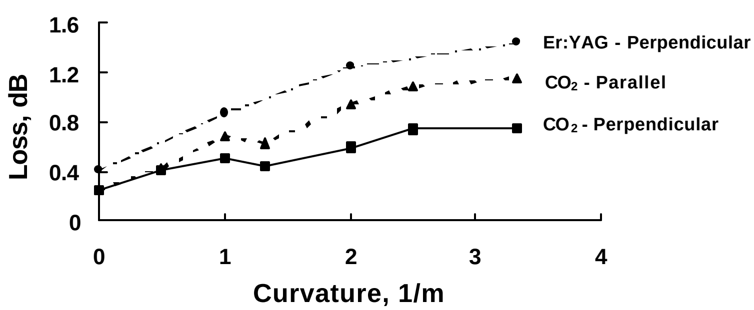

Figure 3 - Losses for bent hollow metallic guides shown in Figure 3 taken at both CO_2 and Er:YAG laser wavelengths. (22)

The waveguides developed by Morrow et al. (24) are constructed from a silver tube. Instead of depositing a metallic layer inside a hollow mandrel, they begin with an extruded silver tube and then deposit a silver halide film on the inside of the tube as shown in Figure 4. To ensure the lowest loss, Morrow et al. first etch the bore of the silver tubing to make it smooth. Then an AgBr film is applied on the inside using wet chemistry methods. The bending loss for a 1000 μm-bore tube, 1-m in length at 10.6 μm is also shown in Figure 4. We note from this data that the losses in the straight guide are quite low. Unfortunately, the guides tend to mix modes and, therefore, the beam output is rather multimode compared to the hollow glass or sapphire waveguides. This is due in large part to the rougher inner surface of the extruded tubing compared, for example, to the smooth inner surface of glass.

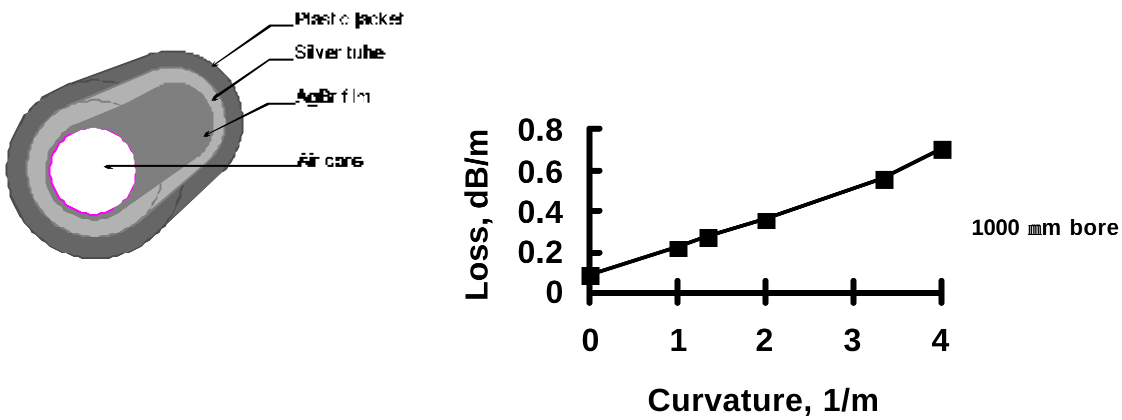

Figure 4 - Structure and bending loss for hollow guide made from silver tubing with a AgBr film deposited on the inside surface. (24)

Luxar's approach is based on technology initially developed by K. Laakmann and her colleagues. (16) Their fabrication technique involves first depositing a silver film on a metal strip and then overcoating the silver with a thin film of PbF_2. The metal strip is then rolled and inserted into stainless-steel hypodermic tubing as shown in Figure 5. The bending loss for one of their guides is also shown in Figure 5. This waveguide had a 750 μm bore, 1-m length and the losses shown are for 10.6 μm. Like the other hollow waveguides, the losses are quite low at CO_2 laser wavelengths. Furthermore, we note the 1/*R* behavior of the loss on bending. This is, of course, characteristic of all hollow guides but the magnitude of this loss depends largely on the quality of the inner surface. In general, these bending losses are tolerable for the radii normally encountered in practical applications.

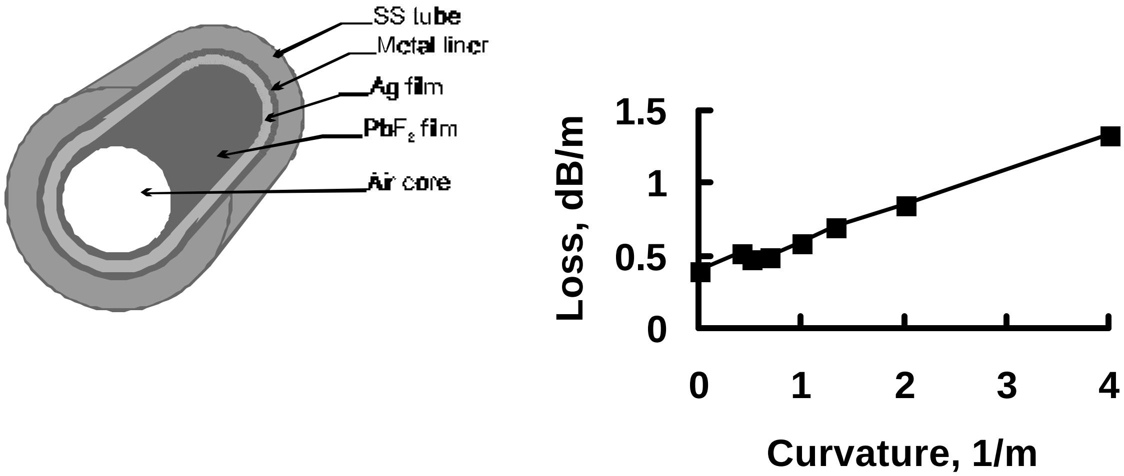

Figure 5 - Structure and bending loss for hollow guides made by Luxar. (16)

Plastic-tube waveguides

Hollow waveguides may also be formed on the inside of plastic tubing. This leads to a very flexible structure that is inexpensive to fabricate and durable enough that a reasonable laser power (safe limit < 25 W) can be transmitted through the guides. Croitoru's group at Tel Aviv University has pioneered the approach of first depositing a silver film on the inside of Teflon and polyethylene plastic tubing (see Figure 6) and then overcoating the silver film with a dielectric layer of AgI(18) using wet-chemistry techniques. (25) Initially, Croitoru used rather large bore tubing but more recently guides with bore sizes of about 1000 µm have been fabricated. In Figure 6 we show the bending loss for a 1000 µm bore tube measured at 10.6 µm. The losses are somewhat higher than those measured for the metallic tubes. This is primarily due to increased scattering losses resulting from the rougher inner surface of the plastic tubing. In an independent measurement we were able to transmit over 65 W of CO_2 laser power for several minutes through an 1850 µm bore guide.

Losses in the plastic waveguides made by Croitoru may be reduced if smoother polymer tubing is chosen. Haan and Harrington(26) have used similar wet-chemistry methods to deposit Ag/AgI films inside polycarbonate tubing. Extruded polycarbonate tubing in lengths of 2 m and bore sizes from 840 µm to 2 mm was used to make the guides. Figure 7 shows the lowest straight losses for several hollow waveguide structures; two polycarbonate waveguides, a Teflon waveguide, and hollow glass waveguides (see next section) measured using a CO_2 laser. The solid curve is calculated for the lowest order mode at 10.6 µm using Eq. 1. The attenuation values of 0.22 dB/m for an 840 µm PC guide and 0.10 dB/m for a 1500 µm PC guide show the improvement over the Teflon or polyethylene waveguides. In a simple power test using a CO_2 laser, the 1500 µm waveguide was able to withstand more than 25 W of incident laser power.

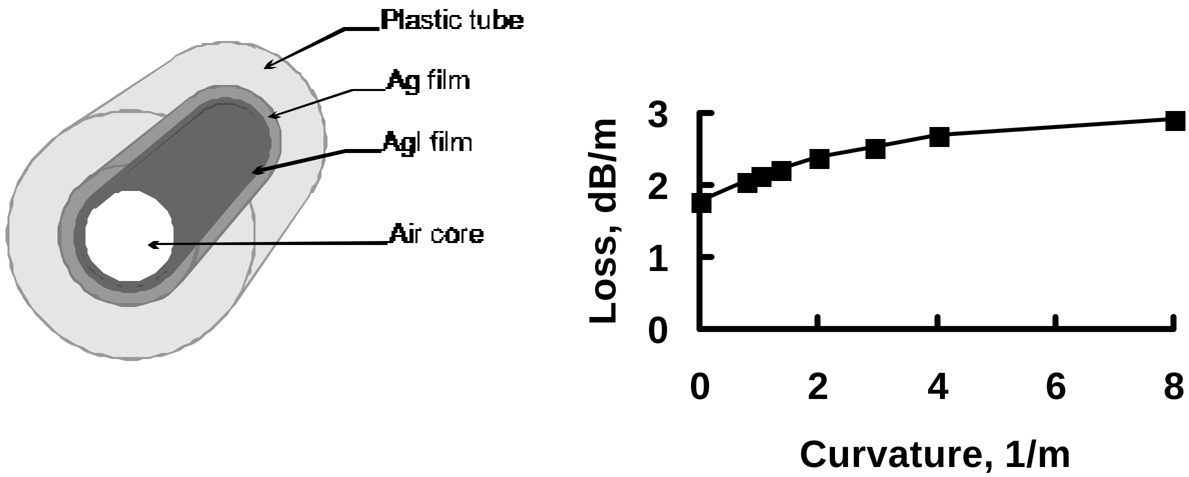

Figure 6 - Structure and bending loss for hollow plastic waveguide made by Croitoru's group at Tel Aviv University. (18)

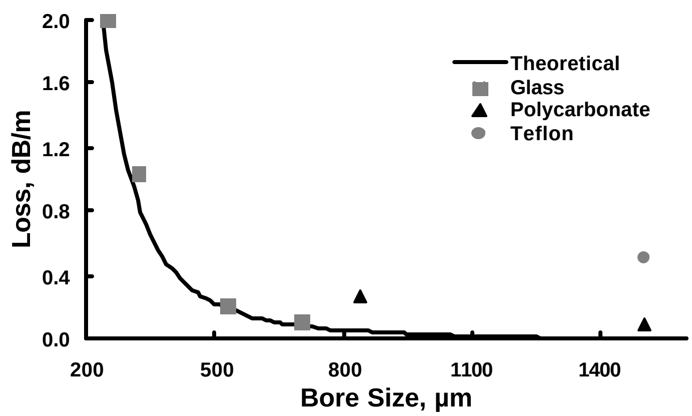

Figure 7 - Composite data for hollow glass and plastic waveguides. Note the low loss at 10.6 µm for the glass guides in comparison to the plastic guides.

Hollow glass waveguides (HGWs)

One of the most popular hollow waveguides today is the hollow glass waveguide (HGW) developed by Harrington's group at Rutgers University. This hollow glass structure has the advantage over other hollow structures because it is simple in design, extremely flexible, and, most important, has a very smooth inner surface. HGWs have a metallic layer of Ag on the inside of silica glass tubing and then a dielectric layer of AgI over the metal film identical to that used to make the hollow plastic guides. Figure 8 shows a cross-section of the structure of the

HGWs. The fabrication of HGWs begins with silica tubing which has a polymer (UV acrylate or polyimide) coating on the outside surface. A wet-chemistry technique (see Figure 9), similar to that used by Croitoru and his co-workers(27,18) to deposit metal and dielectric layers on the inside of plastic tubing, is employed to first deposit a silver film using standard Ag plating technology. (28) Next, a very uniform dielectric layer of AgI is formed through an iodization process in which some of the Ag is converted to AgI. (29) Using these methods, HGWs with bore sizes ranging from 250 to 1000 μm and lengths as long as 13 m have been made.

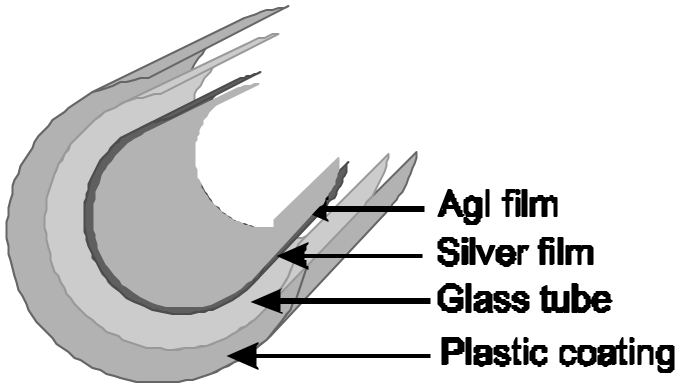

Figure 8 - Structure of the HGWs showing the metallic and dielectric films deposited inside silica glass tubing.

The spectral response for HGWs depends critically on the thickness of the dielectric film. Generally, for the AgI films, the film thickness ranges from 0.2 to 0.8 μm. In Figure 10, we show the spectral response of two waveguides which have different thickness films deposited on the inside of a 700 μm bore silica tube, 1 m in length. The thickest film gives a minimum loss at 10.6 μm while the thin film was selected for minimum loss near 3 μm. The latter guide has a fairly flat response beyond 3 μm and, therefore, this guide would be useful in broadband applications. The structure observed in the spectra is due to thin-film interference effects similar to that commonly observed in thin-film coatings on optical components. These effects have been observed and extensively discussed in the work of Matsuura, et al. (30)

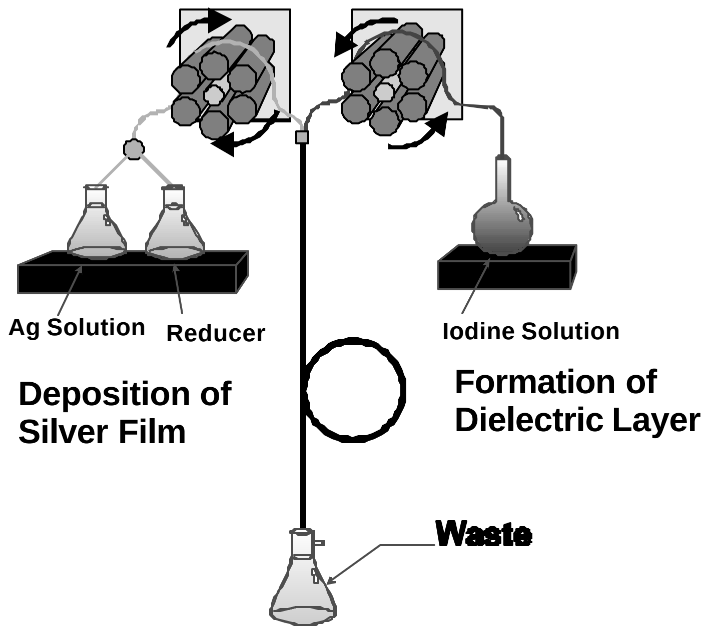

Figure 9 - Schematic of the experimental set-up for depositing the Ag metallic and AgI dielectric films inside silica tubing to form the HGWs.

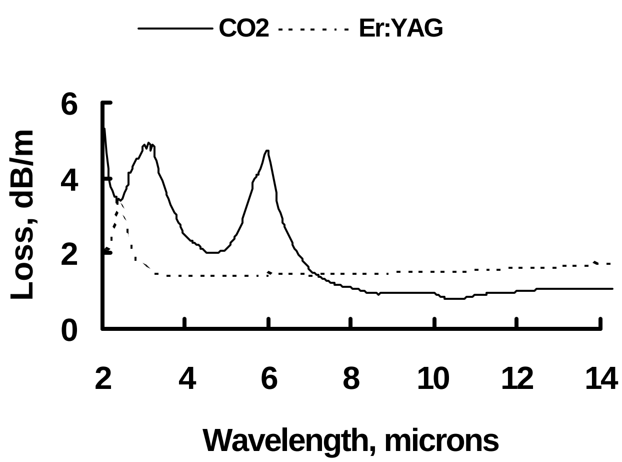

Figure 10 - Spectral response of two HGWs; one designed for low loss at the CO_2 laser wavelength of 10.6 µm and the other for low loss at the Er:YAG laser wavelength of 2.94 µm.

The strong bore-size dependent loss for straight HGWs is shown for two guides in Figure 11. (28) These data were taken using CO_2 and Er:YAG lasers and the guides were optimized for minimal loss at 10 and 3 µm, respectively. The solid curves are theoretical calculations of the losses for the lowest order HE_{11} mode. At the CO_2 laser wavelengths we see not only the strong $1/a^3$ dependence predicted by MS theory but also that there is good agreement with the experimental results. However, at 3 µm the calculated losses are much lower than the measured values. This is a result of increased scattering losses at the shorter wavelengths and the multimode character of the Er:YAG laser.

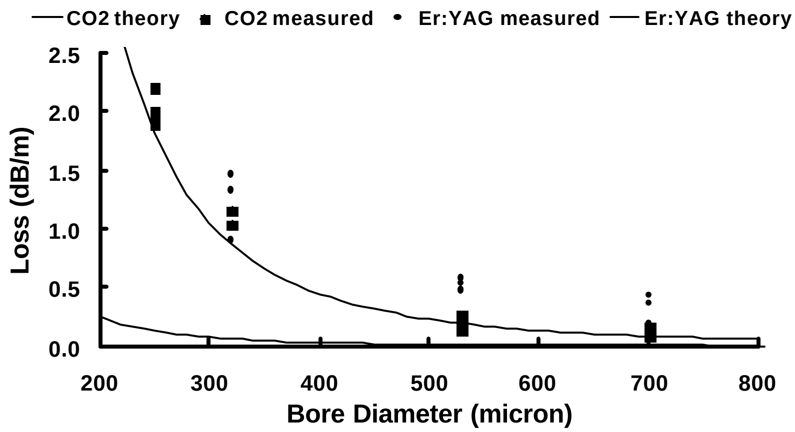

Figure 11 - Measured losses for straight HGWs using CO_2 and Er:YAG lasers. Note that the predicted losses are well below the measured ones at 2.94 μm.

Bending increases the loss in hollow waveguides beyond that shown for the straight loss seen in Figure 12. The additional bending loss varies as 1/*R* as reflected in the data for two 530 μm bore guides in Figure 12. These data show the total loss for guides with a constant length of fiber under bending. A curvature of 20 represents a bend diameter of only 10 cm. This is sufficiently small for most applications.

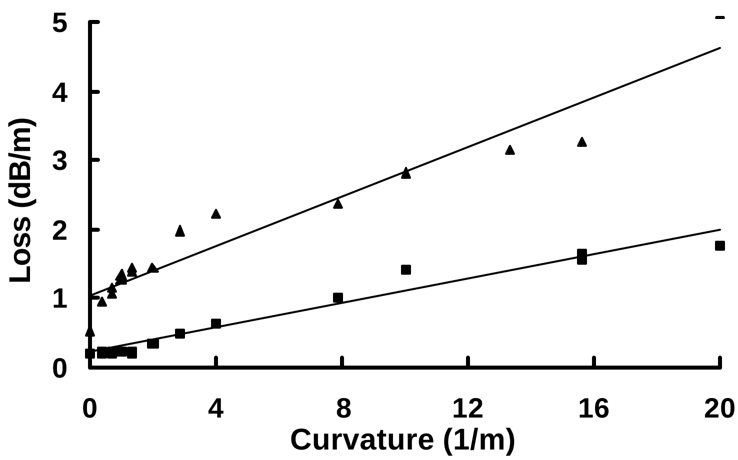

Figure 12 - Bending losses for two 530-μm-bore HGWs measured at 10.6 and 2.94 μm.

Hollow, n<1 waveguides

The idea of an n<1 structure originated with Hidaka, et al. in 1981. (31) In this structure, the air core (n=1) has a refractive index greater than the inner-wall, cladding material and, therefore, this type of waveguide is fiberlike in that $n_{clad}<n_{core}$. This is also referred to as an attenuated total reflectance (ATR) guide in contrast to the leaky structure of the n>1 guides discussed above (see Figure 1). To be useful for laser transmission, the ATR guides must have the region of anomalous dispersion, where n is less than 1, fall within some useful laser wavelength range.
The first n<1 guides studied by Hidaka, et al. (32) focused on glass tubes made from lead and

germanium doped silicates. By adding heavy ions to silica glass, he was able to shift the infrared edge to longer wavelengths so that the n<1 region of anomalous dispersion occurred within the CO_2 laser wavelength band. Worrel(33) also studied n<1 glasses, in particular the germanate glasses. The losses in the hollow-glass, n<1 fibers, however, were very high due to a high k or extinction coefficient and this technology has largely been abandoned.

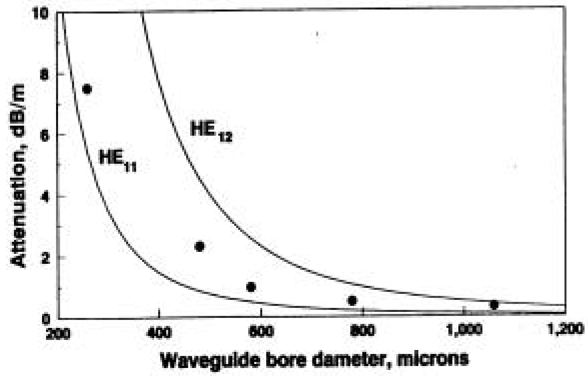

Figure 13 - Measured loss at 10.6 µm for straight, hollow sapphire waveguides. Note that the losses fall between the theoretical losses for the HE_{11} and HE_{12} modes. This is a result of surface roughness of the sapphire tubing.

A more promising n<1 structure is hollow sapphire. It was first pointed out by Harrington and Gregory(11) that sapphire or Al_2O_3 has n<1 from 10 to 16.7 µm and, in addition, it has a very small k value of 0.05 at 10.6 µm. This means that the theoretical loss predicted by MS theory is very low (less than 0.1 dB/m for a 1,000-µm-bore tube) for this material. Single-crystal sapphire tubing is fabricated by Saphikon, Inc. in Milford, NH in bore sizes ranging from 250 to 1070 µm. In Figure 13 we show the measured straight losses for five different bore sizes. Also in Figure 13 the theoretical losses for both the lowest order HE_{11} and next higher-order HE_{12} modes are plotted. The measured losses are somewhat higher than that predicted by MS theory as a result of the roughness of sapphire's inner wall. Gregory and Harrington(11) showed that the surface roughness of hollow sapphire accounted for the increased attenuation over that predicted by theory for the HE_{11} mode. Figure 14 shows the bending loss for the 530 µm bore tube. The curvature is not as great as it is for the HGWs because sapphire has a high modulus and, therefore, cannot be bent to small diameters. Hollow sapphire delivery systems have been coupled to CO_2 lasers for use in gynecology and orthopedic surgery and they have been packaged in a water-cooled jacket for the delivery of over 1,900 W of CO_2 laser power.(34)

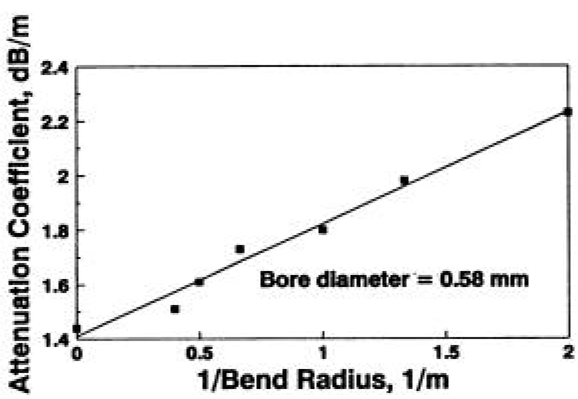

Figure 14 - Bending loss for 560 µm bore, hollow sapphire tubing at 10.6 µm.

Laser power delivery in hollow glass waveguides

Hollow waveguides are ideal for high power laser delivery because of the inherently high damage threshold of an air-core structure. For most medical and some low-power industrial applications, it is sufficient to be able to deliver up to 100 W of laser power. For these purposes, the HGWs can be used without cooling although it is often helpful if an inert gas is used to purge the bore of the guide. In Figure 15, we show the results of low-power, CO_2 laser power delivery through 700 and 530 µm bore HGWs. It is also possible to delivery higher CO_2 laser powers through the guides if active cooling is incorporated. In Figure 16, we show the results of high-power CO_2 laser transmission through a 700-µm-bore HGW that has a water jacket surrounding the guide. The maximum laser power delivered through the guide was just over 1,000 W! (34)

The 2.94-µm, pulsed Er:YAG laser is becoming an important medical laser because the depth of ablation is very shallow and, therefore, this laser has great potential in surgical applications involving precise cutting and ablation. In Figure 17 we show the average 3 µm laser power delivered by the 1000 µm-bore HGW. These data were obtained using a multimode Er:YAG laser made by Continuum. The maximum average output power of about 8 W represents a substantial average power for this wavelength. This power is sufficient for most surgical and dental applications.

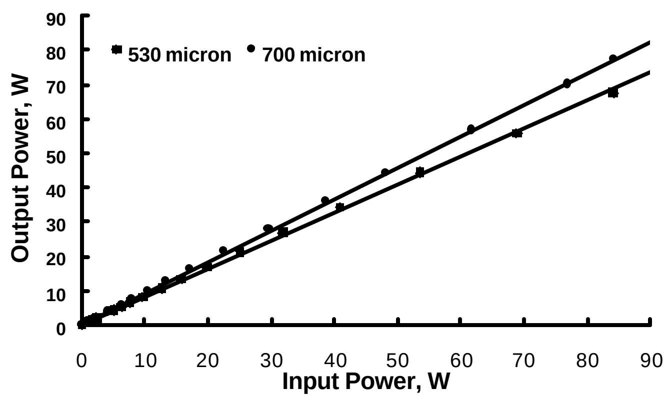

Figure 15 - Low CO_2 laser power delivery for two bore size HGWs with no cooling. This is the typical laser power used in medical lasers and for low power cutting and marking.

The output beam profile of the HGW is important for many applications. In principle the HGWs are nearly single mode because the higher order modes are attenuated by the factor $(U_0)^2$ (see Eqn. 1). In practice, however, mode distortion can occur even with a TEM_{00} input beam. The spatial profile can worsen on bending due to increased coupling into higher order modes. The amount of coupling into higher order modes is a function of the diameter of the waveguide, the roughness of the surface, and the refractive indices of the material. The spatial profile of a 530-µm-bore HGW is shown in Figure 18 A and B. From the data we see that it is possible to generate a single-mode HE_{11} output when the guide is straight or bent (Figure 18A), but, at other times when the guide is bent, low-order modes can be generated resulting in the modal pattern in Figure 18B. An important point is that the smaller the bore size the better the modal purity even on bending. A 250-µm-bore, straight or bent guide, for example, retains a nearly perfect single mode output. (35) The near single-mode output from the glass waveguides is very important when small spot sizes are needed for precise cutting or marking.

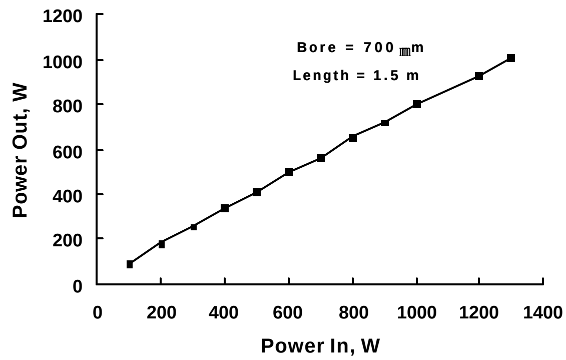

Figure 16 - High CO_2 laser power delivery for a 700 μm bore HGW with a water cooling jacket. Note that the maximum power is just over 1,000 W!

Applications of hollow waveguides

Applications of hollow waveguides fall into two broad categories: laser power delivery and fiber sensors. As fiber sensors, hollow waveguides are generally used either to transmit blackbody radiation for temperature measurements or as an active or passive link for chemical sensing. Saito and Kikuchi(36) give a good review of the use of hollow guides as IR fiber sensors. The use of hollow glass or metallic waveguides to deliver laser power has largely been relegated to laser surgery where the required power is less than 100 W. Furthermore, most of the surgical applications to date involve the CO_2 laser, as this laser is one of the most commonly used medical lasers. As mentioned above, the HGWs are capable of delivering over a kilowatt of CO_2 laser power yet they have not been accepted as flexible delivery systems for industrial lasers. There are two most likely explanations for this: 1. hollow guides have a somewhat higher loss when compared to current articulated arm technology; and 2. industrial applications generally require a high quality (low M^2) laser output mode whereas hollow waveguides can distort the TEM_{00} input beam of the CO_2 laser and this can lead to unacceptable kerfs and welds in cutting and welding applications.

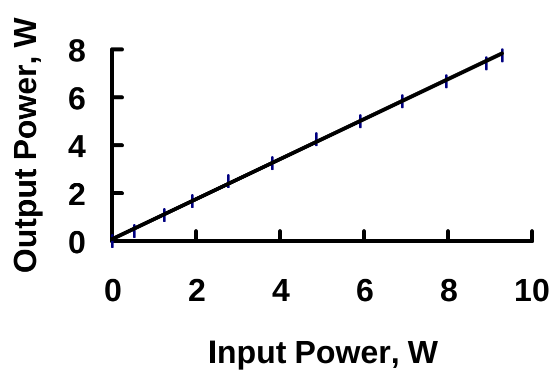

Figure 17 - Power delivery though a HGW using an Er:YAG laser.

Hollow waveguides are an ideal means of transmitting blackbody radiation for thermometric measurements. In particular, the peak of blackbody radiation near room temperature is around 10 μm where these guides transmit very well. They have also been used to transmit radiation above 1,000 ^{o}C for the measurement of jet engine blade temperatures. As a delivery system in chemical sensing applications, hollow guides may be used merely as a passive fiber link from the chemical processing area to a remote detector, or they may play a more active role in which the guide is filled with the gas to be sensed. The latter application involves using the hollow guide itself as both the container for the gas sample and as a waveguide. (26) That is, a coiled hollow guide can replace a standard White cell to give a long pathlength and a small volume cell. Several researchers have used this method to measure small quantities of benign gases. (26)

Conclusions

Hollow, IR transmitting waveguides are becoming an attractive fiber optic for the delivery of high power laser radiation as well as for important temperature and chemical fiber sensor applications. In general, these guides enjoy losses of a few tenths of a dB/m and are quite flexible. Because the energy is carried in the hollow core, there is no core material that might be easily damaged by high peak or average laser powers as there would be in a comparable solid-core IR fiber. In addition, there is no Fresnel loss; this is especially important in comparison to the chalcogenide glass fibers where Fresnel losses can be as high as 25%/surface. When selecting a hollow guide, it is important to remember that the optical principles are different between a hollow core-guide and a solid-core fiber. The most important distinctions are that the hollow guides have a loss that varies as the reciprocal of the bore radius cubed and that there is an additional loss on bending which varies as $1/R$. These properties are not shared by conventional solid-core fibers. It is our experience, however, that most applications of IR fibers do not require tight bending radii so that the additional loss on bending is not prohibitive. Two other advantages of hollow guides are important: these guides are nearly single mode and there seems to be no loss due to aging as we have observed no change in transmission after storage of the guides for over two years.

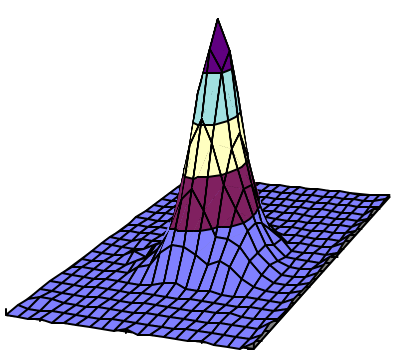

Figure 18 A - High quality output beam profile from a bent 530 μm bore HGW.

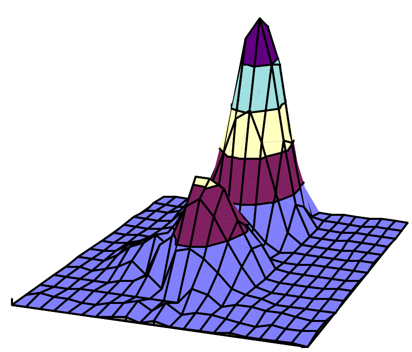

Figure 18 B - A similar HGW but with the output beam profile distorted somewhat by pushing against the side of the guide.

References

1. N.S. Kapany and R.J. Simms, "Recent developments of infrared fiber optics," *Infrared Phys.* **5**, 69-75, 1965.
2. J.A. Harrington, *Selected Papers on Infrared Fiber Optics,* Milestone Series, Volume ***MS-9***, SPIE, Bellingham, WA, 1990,
3. J. Sanghera and I. Aggarwal, *Infrared Fiber Optics*, CRC Press, Boca Raton, FL, 1998,
4. P. France, M.G. Drexhage, J.M. Parker, M.W. Moore, S.F. Carter, and J.V. Wright, *Fluoride Glass Optical Fibres*, Blackie, London, 1990,
5. I. Aggarwal and G. Lu, *Fluoride Glass Optical Fiber*, Academic Press, New York, 1991,
6. T. Katsuyama and H. Matsumura, *Infrared Optical Fibers*, Adam Hilger, Bristol, 1989,
7. S.J. Saggese, J.A. Harrington, and G.H. Sigel, Jr., "Attenuation of incoherent infrared radiation in hollow sapphire and silica waveguides," *Opt. Lett.* **16**, 27-29, 1991.
8. M. Saito, Y. Matsuura, M. Kawamura, and M. Miyagi, "Bending losses of incoherent light in circular hollow waveguides," *J. Opt. Soc. Am. A* **7**, 2063-2068, 1990.
9. A. Hongo, K. Morosawa, K. Matsumoto, T. Shiota, and T. Hashimoto, "Transmission of kilowatt-class CO_2 laser light through dielectric-coated metallic hollow waveguides for material processing," *Appl. Opt.* **31**, 5114-5120, 1992.
10. Y. Matsuura and M. Miyagi, "Bending losses and beam profiles of zinc selenide-coated silver waveguides for carbon dioxide laser light," *Appl. Opt.* **31**, 6441-6445, 1992.
11. C.C. Gregory and J.A. Harrington, "Attenuation, modal, polarization properties of n<1, hollow dielectric waveguides," *Appl. Opt.* **32**, 5302-5309, 1993.
12. J.A. Harrington and C.C. Gregory, "Hollow sapphire fibers for the delivery of CO_2 laser energy," *Opt. Lett.* **15**, 541-543, 1990.
13. E.A.J. Marcatili and R.A. Schmeltzer, "Hollow metallic and dielectric waveguides for long distance optical transmission and lasers," *Bell Syst. Tech. J.* **43**, 1783-1809, 1964.
14. M. Miyagi, K. Harada, and S. Kawakami, "Wave propagation and attenuation in the general class of circular hollow waveguides with uniform curvature," *IEEE Trans. Microwave Theory and Techniques* **MTT-32**, 513-521, 1984.
15. M. Miyagi and S. Kawakami, "Design theory of dielectric-coated circular metallic waveguides for infrared transmission," *J. Lightwave Technology* **LT-2**, 116-126, 1984.
16. K.D. Laakmann and M.B. Levy, U.S. Patent No. 5,005,944, (1991).
17. M. Miyagi, A. Hongo, Y. Aizawa, and S. Kawakami, "Fabrication of germanium-coated nickel hollow waveguides for infrared transmission," *Appl. Phys. Lett.* **43**, 430-432, 1983.
18. N. Croitoru, J. Dror, and I. Gannot, "Characterization of hollow fibers for the transmission of infrared radiation," *Appl. Opt.* **29**, 1805-1809, 1990.
19. T. Abel, J. Hirsch, and J.A. Harrington, "Hollow glass waveguides for broadband infrared transmission," *Opt. Lett.* **19**, 1034-1036, 1994.

20. E. Garmire, T. McMahon, and M. Bass, "Flexible infrared waveguides for high-power transmission," *IEEE J. Quantum Electron.* **QE-16**, 23-32, 1980.

21. U. Kubo, "Medical applications of optical fibers," *Review of Laser Engineering* **2,** 329-337, 1994.

22. Y. Matsuura and M. Miyagi, "Er:YAG, CO, and CO_2 laser delivery by ZnS-coated Ag hollow waveguides," *Appl. Opt.* **32**, 6598-6601, 1993.

23. H. Machida, Y. Matsuura, H. Ishikawa, and M. Miyagi, "Transmission properties of rectangular hollow waveguides for CO_2 laser light," *Appl. Opt.* **31**, 7617-7622, 1992.

24. P. Bhardwaj, O.J. Gregory, C. Morrow, G. Gu, and K. Burbank, "Performance of a dielectric-coated monolithic hollow metallic waveguide," *Mater. Lett.* **16**, 150-156, 1993.

25. R. Dahan, J. Dror, and N. Croitoru, "Characterization of chemically formed silver iodide layers for hollow infrared guides," *Mater. Res. Bull.* **27**, 761-766, 1992.

26. D.J. Haan and J.A. Harrington, "Hollow waveguides for gas sensing and near-IR applications," in *Specialty Fiber Optics for Medical Applications,* A. Katzir and J.A. Harrington, editors, Proc. SPIE Vol. 3596, 43-49, (1999).

27. M. Alaluf, J. Dror, R. Dahan, and N. Croitoru, "Plastic hollow fibers as a selective infrared radiation transmitting medium," *J. Appl. Phys.* **72**, 3878-3883, 1992.

28. Y. Matsuura, T. Abel, and J.A. Harrington, "Optical properties of small-bore hollow glass waveguides," *Appl. Opt.* **34**, 6842-6847, 1995.

29. K. Matsuura, Y. Matsuura, and J.A. Harrington, "Evaluation of gold, silver, and dielectric-coated hollow glass waveguides," *Opt. Eng.* **35**, 3418-3421, 1996.

30. Y. Matsuura, A. Hongo, and M. Miyagi, "Dielectric-coated metallic hollow waveguide for 3-μm Er:YAG, 5-μm CO, and 10.6-μm CO_2 laser light transmission," *Appl. Opt.* **29**, 2213-2217, 1990.

31. T. Hidaka, T. Morikawa, and J. Shimada, "Hollow-core oxide-glass cladding optical fibers for middle-infrared region," *J. Appl. Phys.* **52**, 4467-4471, 1981.

32. T. Hidaka, J. Kumada, J. Shimada, and T. Morikawa, "GeO_2-ZnO-K_2O glass as the cladding material of 940-cm^{-1} CO_2 laser-light transmitting hollow-core waveguide," *J. Appl. Phys.* **53**, 5484-5490, 1982.

33. C.A. Worrell, "Transmission properties of some hollow glass waveguides at 10.6 μm wavelength," *Elect. Lett.* **25**, 570-571, 1989.

34. R. Nubling and J.A. Harrington, "Hollow-waveguide delivery systems for high-power, industrial CO_2 lasers," *Appl. Opt.* **34**, 372-380, 1996.

35. Y. Matsuura, T. Abel, J. Hirsch, and J.A. Harrington, "Small-bore hollow waveguide for delivery of near single-mode IR laser radiation," *Electron. Lett.* **30**, 1688-1690, 1995.

36. M. Saito and K. Kikuchi, "Infrared optical fiber sensors," *Optical Review* **4**, 527-538, 1997.