Small-bore hollow waveguides for delivery of 3-μm laser radiation

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Flexible hollow glass waveguides with bore diameters as small as 250 μm have been developed for 3-μm laser delivery. All the guides exhibit straight losses between 0.10 and 1.73 dB/m, and the loss increases to between 2.4 and 5.1 dB/m upon bending 1 m of the guides into 15-cm-diameter coils. This behavior is shown to depend strongly on the launch conditions and mode quality of the input beam. The waveguides are capable of efficiently delivering up to 8 W of Er:YAG laser power with proper input coupling, and they are suitable for use in both medical and industrial applications.

Key words: Erbium YAG, erbium-YSGG, fiber optics, hollow waveguides, infrared waveguides, power delivery.

1. Introduction

Near-infrared lasers such as Er:YAG and Er:YSGG that operate at waveguides near 3 μm are gaining in popularity for various applications. Because this wavelength range matches the strongest absorption band of water in tissue, these lasers may be used for precise cutting and ablation of tissue in surgery. Industrial uses of these lasers are also being explored. As a result, much research in recent years has focused on developing a commercial fiber-optic delivery system for 3-μm lasers that meets the stringent requirements of optical efficiency, durability, and easy handling. To this end, solid-core IR transmitting fibers have been produced from both glass and crystalline materials, including heavy-metal fluorides, low-molecular-weight chalcogenides (As_2S_3), silver halides, and sapphire.[1–7] Most of these have significant drawbacks, however, such as low laser-damage thresholds, poor chemical and mechanical properties, or difficult and expensive fabrication. Reasonable success has been achieved with dielectric-coated metallic hollow waveguides,[2,8–13] but the large bore diameters of these devices (>1 mm) limit their flexibility and result in propagation of higher-order modes.

Recently we developed a new type of highly flexible small-bore hollow waveguide (bore sizes from 250 to 1000 μm), consisting of a metal and a dielectric coating deposited inside silica tubing, for delivery of 3-μm laser radiation.[8–10] This study characterizes the transmission properties of this waveguide in both straight and bent configurations for Er:YAG (2.94-μm) and Er:YSGG (2.79-μm) laser light, and it discusses its power handling capabilities. Additionally, because most Er:YAG and Er:YSGG lasers generate highly multimode beams, this study also investigates the effect of input-beam mode quality on the output distribution and attenuation behavior of this new waveguide.

2. Fabrication

The waveguides used in this study were produced by liquid phase deposition of silver on the internal surface of small-bore silica tubing, followed by reactive formation of a silver iodide layer. By adjustment of the thickness of the dielectric AgI layer, the waveguides were tailored for lowest loss in the 3-μm wavelength region. The fabrication process is relatively simple and inexpensive, and the yield is currently greater than 90%. A detailed description of this fabrication process can be found elsewhere.[9,10] For this study, hollow waveguides were fabricated with bore diameters of 250, 320, 530, 700, and 1000 μm, in lengths between 1 and 2 m.

3. Optical Characterization

A. Infrared Attenuation Spectra

Infrared attenuation spectra for each waveguide were obtained with a Fourier transform IR spectrometer (Perkin-Elmer Model 1725X). In all measure-

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ments the incoherent light was coupled into the waveguides by the use of an off-axis parabolic mirror of focal length ~2.5 cm. Figure 1 shows the spectral response of a typical 700-μm-bore hollow waveguide designed for minimum loss near 3 μm. The IR loss spectra of the other waveguides used in this study are similar in shape. The small peak at 4.25 μm and the structure between 5 and 7 μm result from absorption of the light by CO_2 and water, respectively, in the air within the waveguide; in measurements in which the waveguide bore is flushed with nitrogen, a fairly flat response beyond 3 μm is normally seen. This suggests that these hollow waveguides would be useful for broadband IR applications. The attenuation measured with a spectrometer greatly exceeds that measured with a laser, as discussed below.

B. Straight Losses

Both an Er:YAG and an Er:YSGG laser were used to measure the attenuation of the hollow waveguides and to examine the influence of the input launch conditions on the loss behavior. Although both lasers produced multimode outputs, their beam diameters and mode qualities varied as shown in Fig. 2. This figure shows the spatial profile of the beams measured with a 32 × 32 matrix pyroelectric detector array (element size: 0.8 mm × 0.8 mm). The highly apertured Er:YAG laser yielded a relatively low-order modal distribution and small beam-output diameter as depicted in Fig. 2(a). Figures 2(b) and 2(c) show the output of an Er:YSGG limited by a 2-mm aperture and a 3.75-mm aperture placed within the laser cavity. Both apertures produce Er:YSGG output beams larger than the Er:YAG output beam. The modal distribution of the Er:YSGG is also poorer for both apertures, with the 3.75-mm aperture producing the most multimode beam, as seen in Fig. 2(c).

The coupling of these input beams into the waveguides required the use of different lenses for maximum transmission. In general, longer focal length lenses excite lower-order modes within the wave-

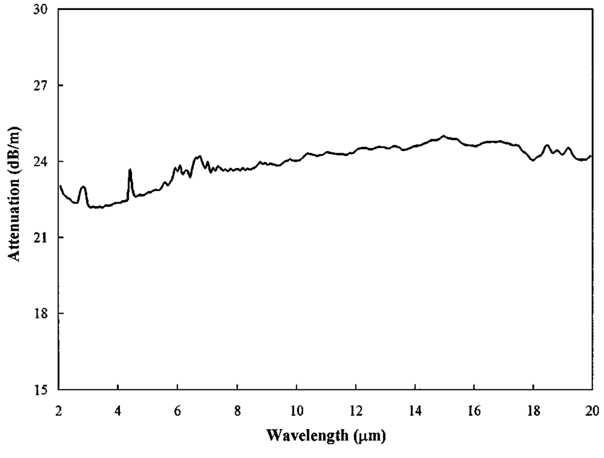

Fig. 1. Spectral loss of a typical hollow waveguide designed for use near 3 μm.

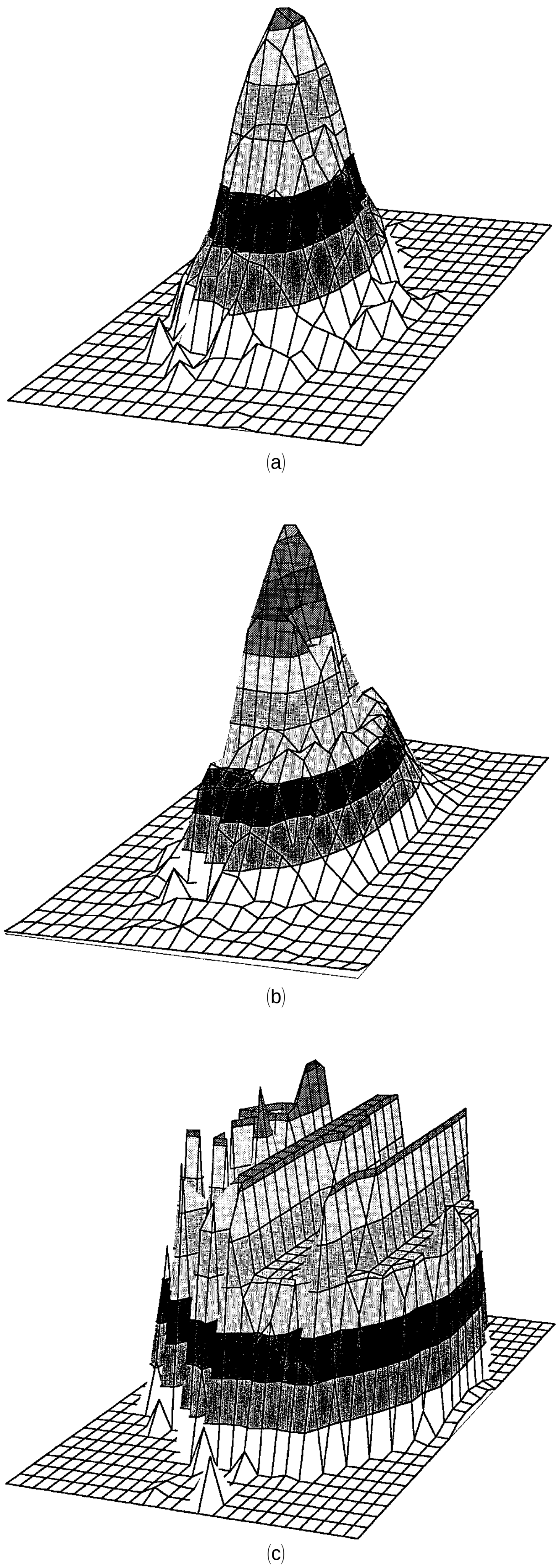

Fig. 2. Beam profile of laser outputs: (a) Er:YAG, (b) Er:YSGG with 2-mm aperture, (c) Er:YSGG with 3.75-mm aperture.

guides, decreasing the interaction of the light with the waveguide walls and minimizing the attenuation. However, shorter focal length lenses produce smaller beam diameters. Because minimal loss is achieved when the ratio of the spot size to the bore size is ~0.6, we always attempted to optimize the coupling by using appropriate focal length lenses to approximate this ratio.[14,15] As the laser mode quality became poorer and the beam diameter increased, progressively shorter focal length lenses were required to focus the input beam to a spot size smaller than the waveguide bore. In fact, we were unable to focus the light from the 3.75-mm-aperture Er:YSGG to a small enough spot to couple into the 250-µm-bore waveguide with our shortest focal length lens [$f = 0.5$ in. (~1.27 cm)].

Figure 3 shows the attenuation of five hollow waveguides measured as a function of bore diameter, using the lasers and launch conditions described above. Also included in Fig. 3 for comparison are the theoretical losses for these waveguides calculated at the Er:YAG wavelength of 2.94 µm, assuming that only the HE_{11} mode propagates. Losses calculated for Er:YSGG light at 2.79 µm are slightly lower than these and are not shown. These calculations were performed by the use of an equation derived by Miyagi and Kawakami,[16] which gives the attenuation coefficient, α_∞, for straight waveguides as

$$\alpha_\infty = \left(\frac{U_{\mathrm{nm}}}{2\pi}\right)^2 \frac{\lambda^2}{a^3} \left(\frac{n}{n^2 + k^2}\right) \frac{1}{2} \left[1 + \frac{{n_1}^2}{({n_1}^2 - 1)^{1/2}}\right]^2 . \quad (1)$$

Here, U_{nm} is a modal parameter equal to 2.405 for the lowest-order HE_{11} mode, λ is the wavelength, a is the bore radius, n and k are the optical constants of the metal film, and n_1 is the refractive index for the dielectric film (at ~3 µm the extinction coefficient of the dielectric is approximately zero). Equation (1) thus predicts that the attenuation of the straight hollow waveguide should vary as $1/a^3$ for single-mode propagation, and that higher-order modes are strongly attenuated as U_{nm} increases.

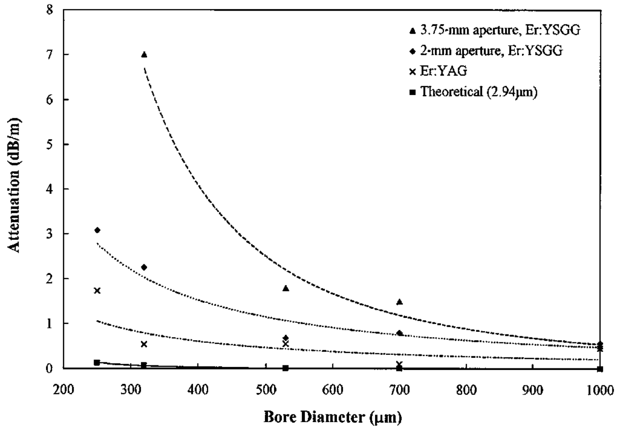

Fig. 3. Transmission loss of straight hollow waveguides as a function of bore diameter for laser inputs shown in Fig. 2. The theoretical loss assuming HE_{11} mode propagation of 2.94-µm light is included for comparison.

Figure 3 illustrates several significant results. First, the measured attenuation increasingly exceeds the theoretical loss as the quality of the beam launched into the waveguide degrades. In addition, the measured attenuation increases as the bore diameter is reduced, but the increase in loss does not follow a $1/a^3$ dependence. As the f-number of the launched beam and its mode quality improves, though, the increase in attenuation with bore diameter more closely approximates this $1/a^3$ behavior. Figure 3 also demonstrates that for reasonably good input mode and launch conditions, the attenuation of these hollow waveguides may be less than 2 dB/m, even for bore diameters as small as 250 µm.

The lack of correlation between the theoretical and the experimental attenuation in Fig. 3, as well as the high loss measured with the Fourier transform IR spectrometer in Fig. 1, is a direct result of the multimode input beam and the less than ideal coupling of the light into the waveguides. From Eq. (1), we see that as higher-order modes are excited within the guides, the attenuation increases as the square of the modal parameter. Previous research with hollow dielectric- and metallic-coated waveguides and CO_2 lasers with near-Gaussian beams has demonstrated a much better agreement between theory and experiment and provides additional evidence that if the modal quality of the input beam and the launch conditions were optimized, better transmission efficiency would be obtained.[9,17] Furthermore, it is likely that a $1/a^3$ dependence is not seen for the poorer quality beams because the modal distribution within the waveguide is changing over the length as higher-order modes are damped out. In real applications, the launch conditions are critical in maximizing the efficiency of the waveguide transmission.

C. Bending Losses

Previous theoretical and experimental research has demonstrated that hollow waveguides exhibit an additional loss caused by bending that varies inversely with the bend radius R.[8–11,18] As a way to characterize the optical behavior of the new hollow waveguides further, the increase in attenuation on bending was evaluated. For these measurements the input ends of the waveguides were held straight, and approximately 1 m of the guide was bent to a uniform bending radius. Figure 4 compares the bending loss of a 530-µm-bore waveguide for the Er:YSGG with the 2- and 3.75-mm apertures. Each data set shows a strong linear dependence on curvature, as predicted theoretically, with linear regression R^2 values greater than 0.98. Furthermore, the two lines are displaced from one another in the y direction, but they have similar slopes. As in Fig. 3, the input beam with the smaller f-number launch (3.75-mm aperture) is more highly attenuated than the input beam with the larger f-number launch.

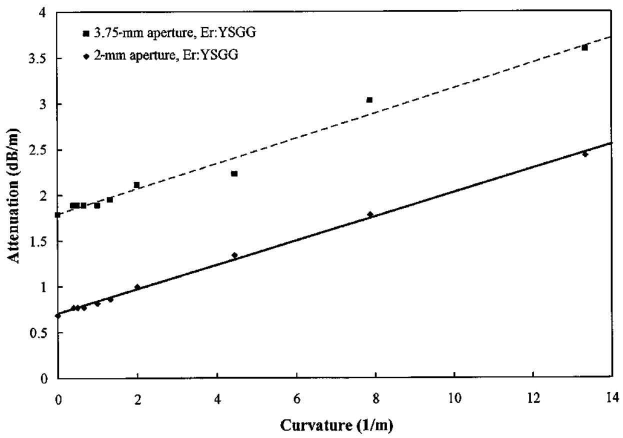

Fig. 4. Bending loss of 530-µm-bore waveguide for Er:YSGG with 2-mm and with 3.75-mm apertures.

However, the similarity in slope indicates that the additional loss caused by bending is comparable for both launch conditions.

Figure 5 illustrates the bending loss as a function of curvature $(1/R)$ for each of the different bore sizes as measured with the Er:YSGG with the 2-mm aperture. The losses shown here are quite low, generally less than 5.2 dB/m, even when the waveguides were bent into 15-cm-diameter coils. These data also show that as the waveguide bore size is reduced, the attenuation of the straight waveguides increases but the slope of the bending loss curves decreases. In other words, less additional loss is incurred on bending the smaller-bore waveguides than the larger-bore ones.

The decrease in additional loss caused by bending as the bore size decreases can be attributed to higher-order mode filtering. In general, loss results from the interaction of the light with the waveguide wall, so that from a ray optics viewpoint, higher-order modes generate higher loss because of an increased number of bounces of the light within the guide. Similarly, as the waveguide is bent, the angle of incidence of the light with the waveguide wall is increased, leading to a greater interaction of the light with the waveguide and a greater loss. Mode filtering occurs for the smaller-bore guides because with highly multimode input beams, lower *f*-number lenses must be used to produce small incident spot sizes. These lenses produce a greater beam divergence and excite higher-order modes within the waveguide, increasing the total attenuation. Equation (1) reflects this increased loss with a higher mode because α_∞ varies as $(U_{\mathrm{nm}})^2/a^3$. The smaller-bore guides are therefore able to filter out the higher-order modes more effectively within a short length. As can be seen in Fig. 5, the losses for the larger and smaller bores can eventually cross and become equal, once only the lowest order modes remain.

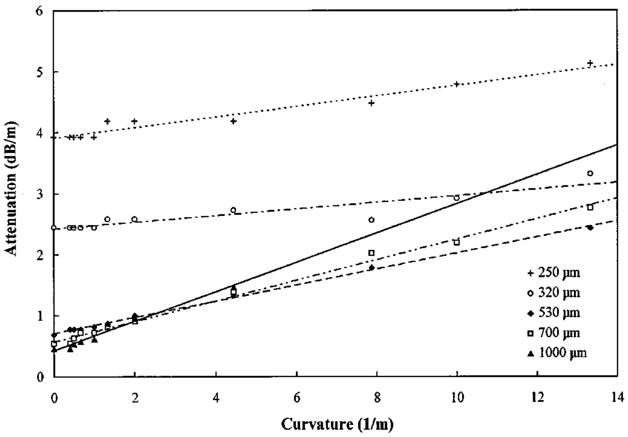

Fig. 5. Measured bending loss of 250-, 320-, 530-, 700-, and 1000-µm-bore waveguides for Er:YSGG with 2-mm aperture.

D. Output-Beam Profile

Many surgical and industrial applications require good spatial quality of the output laser beams to maintain a small spot size for well-controlled cutting and ablation. The modal output of the new hollow waveguides was examined with the same 32 × 32 matrix pyroelectric detector array used above to measure the laser outputs. Figures 6(a) and 6(b) show the output-beam profiles of a 1000- and 320-µm-bore waveguides, using the Er:YSGG laser with the 3.75-mm aperture to provide the input beam shown in Fig. 2(c). Although the input beam is of poor spatial quality with many higher-order modes, the 320-µm-bore waveguide produces a much cleaner output beam than the output beam from the 1000-µm-bore waveguide. The small-bore waveguides thus filter out many of the higher-order modes, providing further evidence for the decrease in additional loss on bending with decreasing bore diameter in Fig. 5.

E. High-Power Handling Ability

Lasers in the 3-µm wavelength region typically operate at output powers of less than 10 W. Many of the solid-core fibers that have been developed for 3-µm laser delivery are limited in their ability to transmit light at these power levels because they have low laser-damage thresholds.[1–3,6,7] Hollow waveguides have much higher laser-damage thresholds because the light is primarily confined to an air core rather than solid material, and larger-bore hollow dielectric-coated metallic guides have been shown to deliver relatively high average powers of Er:YAG light.[12] We studied the ability of the small-bore hollow waveguides to handle high-power transmission, using a high-power, highly multimode Er:YAG laser. Figure 7 shows the results of these measurements for 1000-, 700-, and 530-µm-bore waveguides. The 1000-µm-bore waveguides were consistently able to deliver nearly 8 W for maximum input powers less than 10 W. However, the smaller-bore guides were limited to less than 3 W output because we were unable to focus the multimode beam to a small enough diameter to couple into the guides with our shortest focal length [$f = 0.5$ in. (~1.27 cm)] lens without damaging the input end.

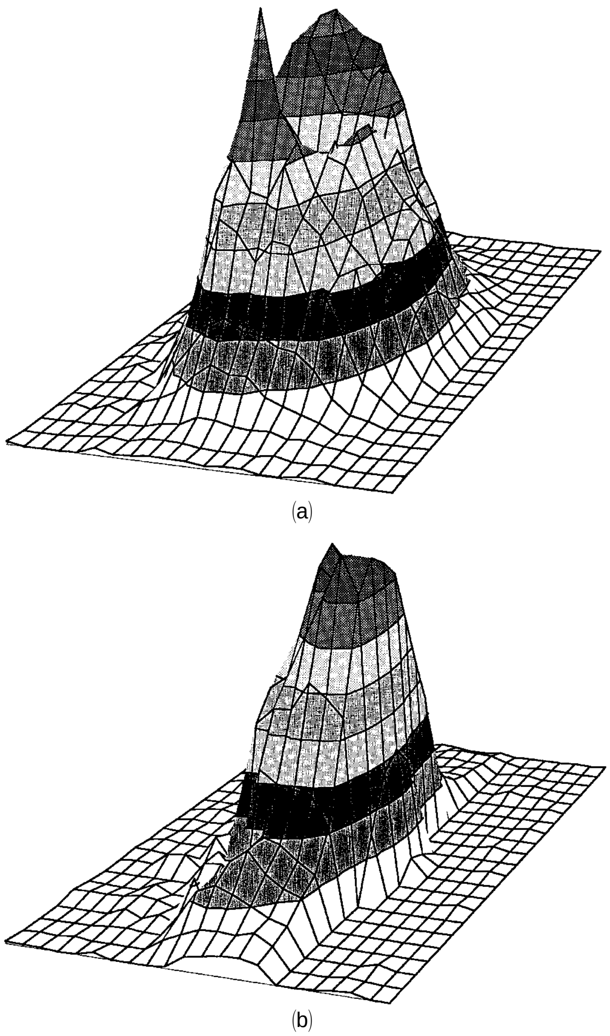

Fig. 6. Beam profiles of (a) 1000-µm and (b) 320-µm-bore straight waveguides for Er:YSGG with a 2-mm aperture.

It is likely that the new hollow waveguides would be capable of transmitting even higher average power levels of 3-µm radiation than shown here, if a better quality laser beam and launch were used.

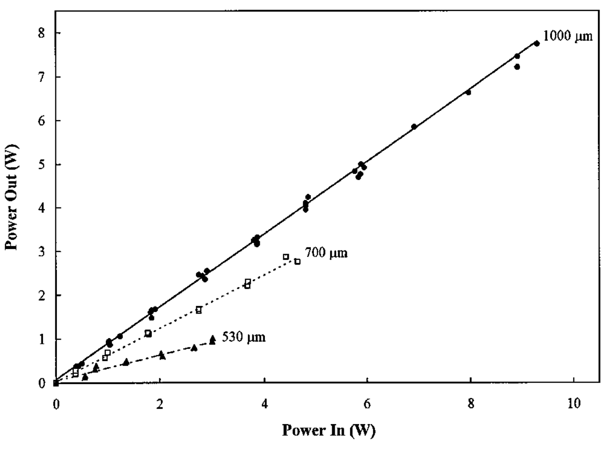

Fig. 7. Er:YAG laser power delivery for 1000-, 700-, and 530-µm-bore waveguides.

As discussed above, these improvements in the input conditions would excite lower-order modes within the waveguides, minimizing attenuation and damage. This is corroborated by the fact that similar hollow waveguides (with slightly thicker dielectric layers to provide minimal loss at 10.6 µm) have been able to deliver over 35 W of near-Gaussian CO_2 radiation without active cooling, and greater than 1.01 kW of multimode CO_2 light in a water-cooled configuration.[9]

4. Conclusion

Hollow metallic- and dielectric-coated glass waveguides with bore diameters as small as 250 µm have been developed for delivery of 3-µm radiation. These guides have been shown to provide efficient transmission not only in this spectral region, but also over a broad wavelength range extending into the mid-IR. All of the guides exhibit straight losses between 0.10 and 1.73 dB/m, and the loss increases to between 2.4 and 5.1 dB/m upon bending 1 m of the highly flexible guides into 15-cm-diameter coils. The smaller-bore guides were seen to filter out the highest order modes, resulting in less additional bending loss than the larger-bore guides. It is important to note that the optical properties of these hollow waveguides were shown to depend strongly on the launch conditions and mode quality of the input beam. With proper input coupling, however, the waveguides are capable of efficiently delivering up to 8 W of 2.94-µm light and are suitable for use in both medical and industrial applications.

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References

1. G. N. Merberg, "Current status of infrared fiber optics for medical laser power delivery," Lasers Surg. Med. **13,** 572–576 (1993).
2. U. Kubo, Y. Hashishin, H. Tanaka, and T. Mochizuki, "Development of optical fiber for medical Er:YAG laser," in *Optical Fibers in Medicine VII,* A. Katzir, ed., Proc. Soc. Photo-Opt. Instrum. Eng. **1649,** 34–40 (1992).
3. G. Merberg, M. Shahriari, J. A. Harrington, and G. H. Sigel, Jr., "Evaluation of crystalline and chemically durable glass fibers for Er:YAG laser delivery systems," in *Infrared Fiber Optics II,* J. A. Harrington and A. Katzir, eds., Proc. Soc. Photo-Opt. Instrum. Eng. **1228,** 216–233 (1990).
4. A. R. Hilton, "Chalcogenide glass optical fibers," in *Infrared Fiber Optics III,* J. A. Harrington and A. Katzir, eds., Proc. Soc. Photo-Opt. Instrum. Eng. **1591,** 34–42 (1991).
5. A. Katzir and R. Arieli, "Long wavelength infrared optical fibers," J. Non-Cryst. Solids **47,** 149–158 (1982).
6. G. N. Merberg and J. A. Harrington, "Optical and mechanical properties of single-crystal sapphire fibers," Appl. Opt. **32,** 3201–3209 (1993).
7. D. H. Jundt, M. M. Fejer, and R. L. Byer, "Characterization of single-crystal sapphire fibers for optical power delivery systems," Appl. Phys. Lett. **55,** 2170–2172 (1989).
8. J. A. Harrington and Y. Matsuura, "Review of hollow wave-

guide technology," in *Biomedical Optoelectronic Instrumentation,* A. Katzir, J. A. Harrington, and D. M. Harris, eds., Proc. Soc. Photo-Opt. Instrum. Eng. **2396,** 4–14 (1995).

9. T. Abel, J. Hirsch, and J. A. Harrington, "Hollow glass waveguides for broadband infrared transmission," Opt. Lett. **19,** 1034–1036 (1994).
10. Y. Matsuura, T. Abel, and J. A. Harrington, "Optical properties of small-bore hollow glass waveguides," Appl. Opt. **34,** 6842–6847 (1995).
11. 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,** 2213–2214 (1990).
12. 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).
13. N. Croitoru, J. Dror, and I. Gannot, "Characterization of hollow fibers for the transmission of infrared radiation," Appl. Opt. **29,** 1805–1809 (1990).
14. C. C. Gregory and J. A. Harrington, "Attenuation, modal, and polarization properties of $n < 1$, hollow dielectric waveguides," Appl. Opt. **32,** 5302–5309 (1993).
15. A. Hongo, M. Miyagi, K. Sakamoto, S. Karasawa, and S. Nishida, "Excitation dependent losses and temperature increase in various hollow waveguides at 10.6 µm," Opt. Laser Technol. **19,** 214–216 (1987).
16. M. Miyagi and S. Kawakami, "Design theory of dielectric-coated circular metallic waveguides for infrared transmission," J. Lightwave Technol. **LT-2,** 116–126 (1984).
17. 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).
18. M. Miyagi and S. Karasawa, "Waveguide losses in sharply bent circular hollow waveguides," Appl. Opt. **29,** 367–370 (1990).