

Optical properties of small-bore hollow glass waveguides

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Hollow glass waveguides with a 250- μm i.d. have been fabricated with a liquid-phase deposition technique that uses silica tubing as a base material. The losses of the 250- μm -bore guide measured at CO₂ laser wavelengths are as low as 2.0 dB/m. The straight losses for the hollow guides are in good agreement with theoretically predicted losses as a result of the nearly ideal structure of the guides. It is also shown that the guides have low bending losses, a nearly pure-mode delivery, and good high-power laser transmission. By proper design of the dielectric thickness, the guide is also able to deliver Er:YAG laser energy with a low loss of 1.2 dB/m for the 320- μm -bore waveguide. Because the hollow glass waveguide is very flexible and robust, it is quite suitable for medical applications.

Key words: Hollow waveguides, infrared fibers, biomedical optics.

1. Introduction

A flexible hollow waveguide is an excellent substitute for an articulated-arm delivery system, which is generally used for the transmission of high-power IR laser radiation. Some hollow waveguides have already been used in medical applications, such as laser surgery and dental treatment.¹ In these applications, good flexibility for easy handling and a small spot size for precise treatment are often necessary. A small-bore hollow waveguide is the best solution for these uses; therefore, attempts have been made to fabricate small bore (i.d. ≤ 1 mm) waveguides.²⁻⁵ Our results for hollow glass waveguides have been reasonably successful,⁶ but it has been difficult to fabricate the smallest bore in lengths greater than 1 m.

To make a small-bore hollow waveguide with a low transmission loss, we applied a simple liquid-phase deposition technique to form a metal and a dielectric coating inside silica tubing. Silica tubing has an ideal surface smoothness and a highly uniform cross section, and thus it is an ideal substrate for a hollow waveguide. Using this fabrication method, we have succeeded in making a hollow waveguide with a bore size of as small as 250 μm and a guide with a length of

as long as 6 m. The 250- μm bore size is, as far as we know, the smallest bore size hollow waveguide ever made. Here we describe the methods for fabricating the guides and give experimental results for CO₂ laser transmission in comparison with theoretical losses. We also show transmission characteristics for an Er:YAG laser operating in the 3- μm region.

2. Fabrication of Small-Bore Waveguides

The waveguide that we developed has a metal and a dielectric layer deposited on the inside of silica tubing. The first results and structure of the hollow glass waveguides are given in Ref. 6. For IR light, this guide acts as a dielectric-coated, metallic, hollow waveguide (leaky guide)⁷ because the metal layer is designed to be thick enough so that the outer glass tube does not affect the transmission properties.

To fabricate a waveguide, we begin with thin-wall silica tubing coated on the outside with a polyimide film to give strength to the glass. First we deposit a silver layer on the inside of the silica tube by using a conventional electroless plating technique, which involves mixing a silver solution and a reducer.⁸ Next we form a dielectric film of silver iodide by flowing iodine inside the tube. Figure 1 shows a schematic view of the coating setup. Croitoru and co-workers⁹⁻¹¹ used a similar method with plastic tubing as a base material, and Kato *et al.*³ used a similar setup to deposit a silver layer inside a glass tube. The thickness of the silver iodide film can be controlled by the amount of iodine and the flow speed. In our setup, the glass tube need not be kept straight; instead it can

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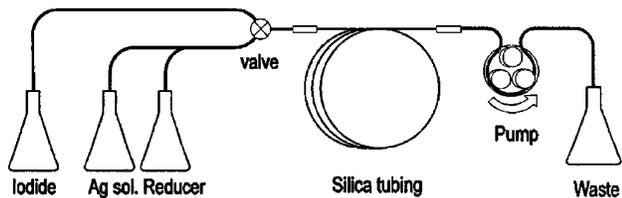


Fig. 1. Schematic view of the fabrication setup for the production of coatings inside glass tubing; sol, solution.

be spooled. This makes it possible to fabricate a considerably longer waveguide.

Using this technique, we succeeded in fabricating waveguides with bore diameters of 250, 320, 530, and 700 μm and with lengths as long as 6 m. This fabrication process is simple and inexpensive, and we can now fabricate waveguides with yields greater than 90%. Therefore, we believe that this process is suitable for mass production.

3. Transmission Properties for CO_2 Laser Light

A. Infrared Loss Spectra

The spectral loss measurements were measured with a Fourier transform infrared spectrometer. Figure 2 shows the measured loss spectrum of a waveguide designed for CO_2 laser transmission. The guide is 20 cm long, and the inside diameter is 530 μm and excited by a Gaussian beam whose divergence angle is 8° at FWHM. Although the measured spectrum shows minimal loss at the CO_2 laser wavelength (10.6 μm) as designed, this loss is much larger than the minimum loss measured by the use of CO_2 laser light (cf. Fig. 3 below). The reason for this is that the divergence angle of the Fourier transform infrared incident beam is much larger than that of the laser beam. This divergent beam excites many higher modes with higher propagation loss. The theoretical spectrum calculated by a ray-optics method¹² is also shown in Fig. 2. We obtain this theoretical spectrum by fitting the ray-optic theory to the data of the measured spectrum. This fit allows us to estimate

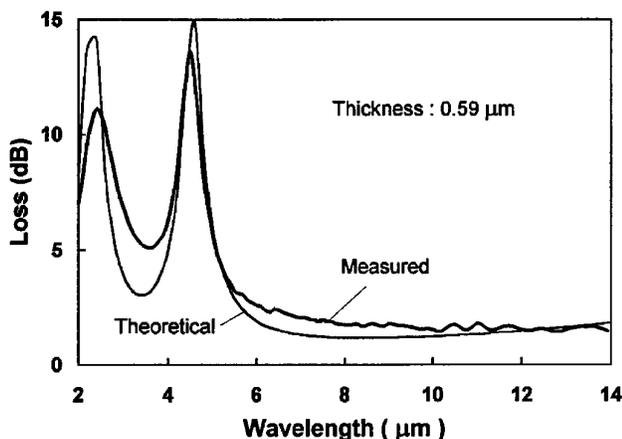


Fig. 2. Spectral loss of the hollow glass waveguide designed for use at 10.6 μm . The waveguide is excited by a Gaussian beam with a FWHM of 8° .

the thickness of the silver iodide layer at 0.59 μm , assuming that the refractive index of silver iodide is 2.10. The theoretical result also shows that the inner surface of the guide is very smooth and that the rms surface roughness is estimated as 0.04 μm .¹²

To examine the uniformity of dielectric layer, we measured the loss spectra of 10-cm-long pieces at both ends of all the guides that we fabricated. The result shows that the difference of the dielectric thickness between both ends is within 0.02 μm , even in the longest (6-m) waveguide. Because this slight difference of the thickness does not cause a change of the loss at 10.6 μm , we confirmed that the guides have uniform transmission characteristics in the longitudinal direction.

B. Straight Losses

We measured the losses in the hollow waveguides by using a tunable CO_2 laser with TEM_{00} output at a 10.6- μm wavelength. In this measurement, spot sizes of the input laser beam are optimized for each bore size to produce minimum coupling loss.^{5,13} Because the beam profile of the input beam has a nearly perfect Gaussian power distribution, a coupling waveguide is not used in our measurement.¹⁴

Figure 3 shows the measured straight losses of 250, 320, 530, and 700- μm -bore waveguides. Theoretical losses are also shown in Fig. 3. For this calculation we used an attenuation coefficient for the HE_{11} mode derived by Miyagi and Kawakami.⁷ The attenuation coefficient of the power, $2\alpha_\infty$, is expressed in terms of the normalized surface impedance, z_{TE} , and admittance, y_{TM} , as

$$2\alpha_\infty = n_0 k_0 \frac{8U_0^2}{(n_0 k_0 a)^3} \text{Re}(z_{\text{TE}} + y_{\text{TM}}), \quad (1)$$

where n_0 ($\cong 1$) is the refractive index of air, k_0 is the wave number of the transmitted light in vacuum, a is the bore diameter of the guides, and U_0 is the first zero point ($= 2.4048$) of Bessel function $J_0(U_0)$. In sapphire hollow fibers that we previously developed⁵

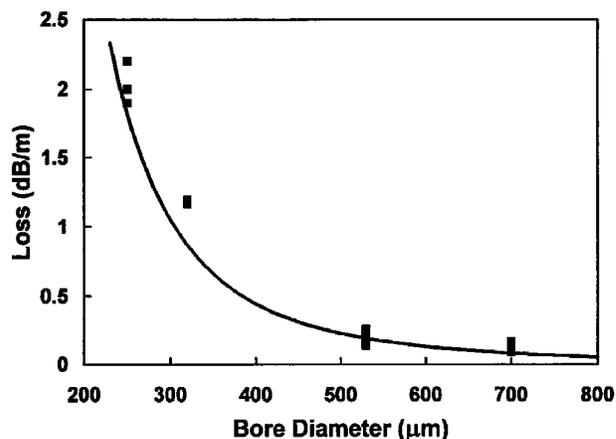


Fig. 3. Transmission losses of the straight, hollow glass waveguides at 10.6 μm . The squares are measured results, and the solid curve is the theoretical loss calculated from Eq. (1).

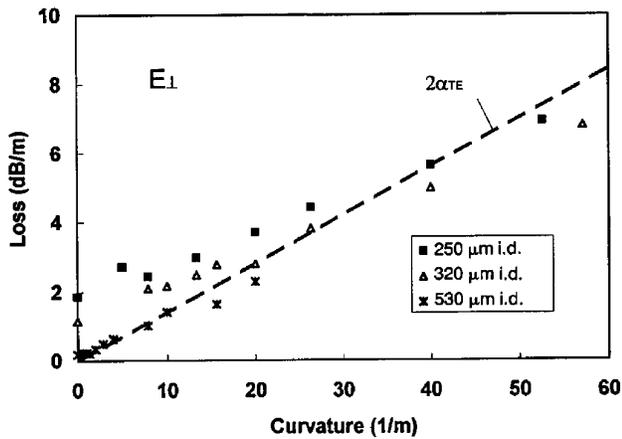


Fig. 4. Measured bending losses for CO₂ laser light whose polarization is perpendicular to the bending plane. The dashed line is the theoretical bending loss of a corresponding slab waveguide for a TE wave.

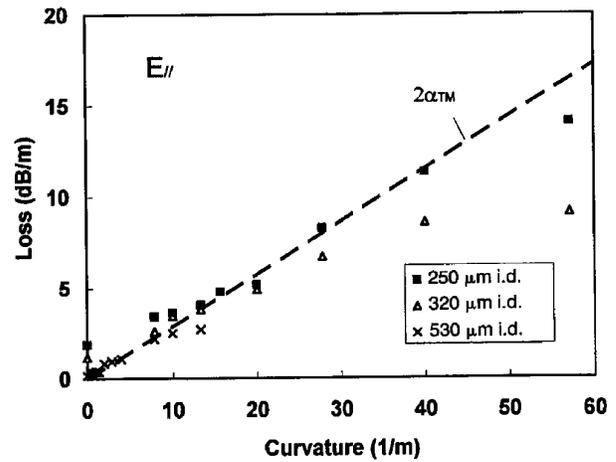


Fig. 5. Bending losses for parallel polarized light. The dashed line is the theoretical loss of a corresponding slab guide for a TM wave.

or in plastic hollow guides developed by Gannot *et al.*,² the measured losses are much larger than the theoretical losses. As a reason for this, it was shown theoretically and experimentally that the structural imperfections, mainly inner surface roughness of the guides, affect the transmission losses.^{14,15} In contrast to those guides, the measured losses of the hollow glass guides in Fig. 3 show good agreement with theoretical losses. This is because of the nearly ideal structure of glass, i.e., the excellent optical quality of the inner dielectric layer and the perfect circular uniformity of the guides' cross section. In addition, it is apparent from the data in Fig. 3 that the inner surface roughness does not affect the loss at 10.6 μm because it is very small and negligible even in the smallest bore, 250-μm i.d. guides.

C. Bending Losses

The lengths of the waveguides used in the measurement of the bending losses are approximately 120 cm. Input and output ends of the guides are kept straight, and a center part with a fixed length of 80 cm is bent to a uniform bending radius. As a way to keep the length of the bent region at 80 cm for all bending radii, the waveguides are bent with multiple loops.

Figures 4 and 5 show bending losses as a function of curvature for three different bore sizes. The polarization of light is either perpendicular (E_{\perp}), Fig. 4, or parallel (E_{\parallel}), Fig. 5, to the bending plane. We derive these bent losses from the measured total losses by subtracting losses of the straight sections.

Theoretical bending losses of hollow waveguides have been thoroughly studied.¹⁶⁻¹⁹ In relatively large curvature, i.e., small radius, the guide supports the edge-guided mode. In this region the loss of the hollow guide is expressed as a combination of the attenuation constants of the slab waveguide, α_{TE} and α_{TM} , which is corresponded to the TE and TM wave,

$$\alpha_{TE} = \frac{\text{Re}(z_{TE})}{R}, \quad \alpha_{TM} = \frac{\text{Re}(y_{TM})}{R}, \quad (2)$$

where R is the bending radius and z_{TE} and y_{TM} are normalized surface impedance and admittance defined at the core-clad interface.⁷ One should note that the attenuation constants are independent of bore size. This is because the transmitted light reflects only at the outer wall and not at the inner wall of the guide. The total attenuation constant of bent, circular, hollow guides is expressed as^{18,19}

$$\alpha = \frac{c_1 \alpha_{TE} + c_2 \alpha_{TM}}{c_1 + c_2}, \quad (3)$$

where c_1 and c_2 are weighting parameters. In the measured results in Figs. 4 and 5, most of the larger curvature region ($1/R \geq 5$) should satisfy the edge-guided mode condition for all bore sizes. Therefore, in the large curvature region, losses are predicted to be very close to the power attenuation coefficient, $2\alpha_{TE}$ (dashed curve in Fig. 4) for E_{\perp} and to $2\alpha_{TM}$ (Fig. 5) for E_{\parallel} ; because our calculation that uses Eqs. (52) and (53) in Ref. 19 showed $c_1 \gg c_2$ for E_{\perp} and $c_1 \ll c_2$ for E_{\parallel} for all sizes of waveguides. As theoretically predicted, the measured losses for E_{\perp} polarization shown in Fig. 4 are very close to the calculated $2\alpha_{TE}$ in the large curvatures. These coincidences are due to the nearly ideal structure of the glass waveguides. In contrast, for E_{\parallel} polarization in Fig. 5, the measured losses are much smaller than $2\alpha_{TM}$ in the large curvatures. The difference between the measured and the theoretical bending losses appears to be caused by a change of the polarization of the transmitted light. We found that the polarization is not well maintained for the E_{\parallel} polarization, although it is well maintained for the E_{\perp} . This polarization shift may be due to deformation of the bore of fibers by the sharp bending. Further theoretical and experimental investigations, including mode conversion and the polarization shift, are underway; the results will be reported elsewhere.

D. Output Beam Profile

When the waveguides are used in medical or industrial applications, it is often desirable to maintain the spatial purity of the input laser beam because it is necessary to cut or ablate with as small a spot size as possible. To evaluate the mode purity of the output beam, we measured the output beam profiles by using a 32×32 matrix pyroelectric detector array. The size of each element is $0.8 \times 0.8 \text{ mm}^2$. Figure 6 shows the measured beam profile of the 250- μm -bore straight waveguide. The lowest-order mode of the waveguide (HE_{11} mode) is maintained nearly perfectly because of the smooth inner surface and the high uniformity in the cross section of the waveguide. Other hollow guides that are made from plastic and metal tubes result in greater mode mixing.¹⁴

Figures 7 and 8 show the measured profiles of a 250- μm -bore guide bent to a 25-mm radius and a 530- μm -bore guide bent to a 69-mm radius, respectively. As we can see, a small-bore waveguide has an advantage in that it maintains a nearly pure HE_{11} mode, even when it is bent to small radii. From our numerical evaluation of mode purity in Ref. 20, we found that the HE_{11} modal purity of the profile for the 250- μm -bore guide shown in Fig. 7 is as high as 90%, in contrast with 82% for the 530- μm -bore guide in Fig. 8. This result may be explained in terms of the higher-order modes that are excited on bending. These are eliminated in the smaller bore guide as a result of a larger loss difference between the lowest and the higher-order modes.

E. High-Power Laser Handling Ability

Because of its intrinsic higher loss and higher energy density, a small-bore hollow guide has a lower laser power threshold compared with that of larger bore sizes. In medical applications in which small-bore guides are highly desired, however, relatively low output powers ($<20 \text{ W}$) are required.

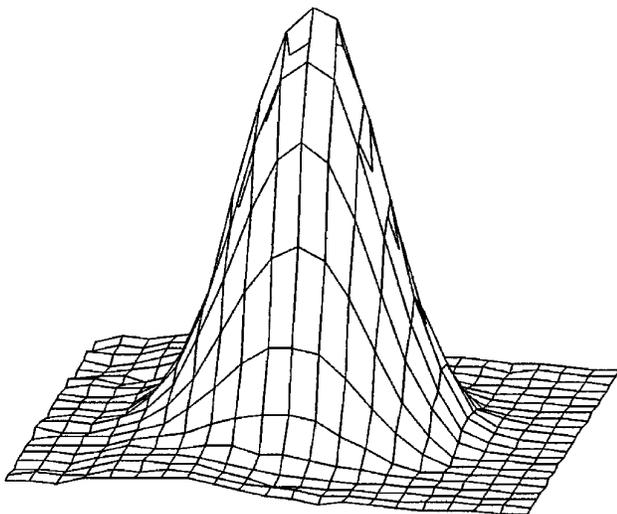


Fig. 6. Measured beam profile of the 250- μm -bore straight waveguide at a distance of 86 mm from the output end.

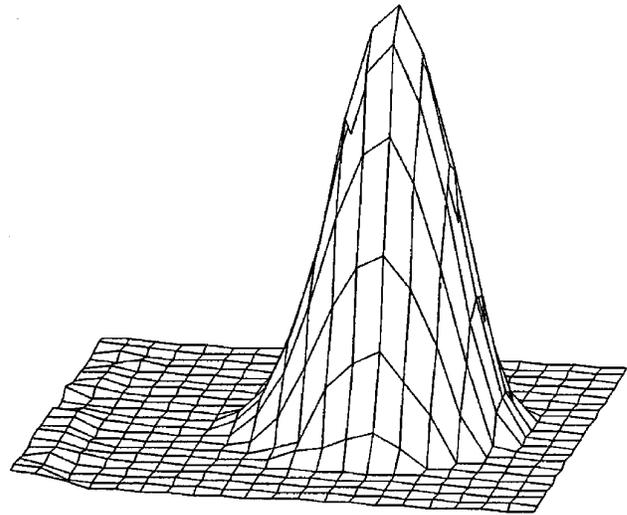


Fig. 7. Measured beam profile of the 250- μm -bore bent waveguide. The bending radius is 25 mm.

Figure 9 shows the input-output power relations for three different bore sizes. All the guides are 1 m long. Because the input beam profile of the CO_2 laser used in this experiment is not Gaussian, it gives high coupling loss and the measured losses are much higher than those in Fig. 2. However, approximately 25 W of maximum input power with the 250- μm -bore guide and 50 W of power with the 320- μm -bore guide will still be useful. In this experiment the high coupling loss caused the input end to melt, so we feel that a much higher power can be delivered by using a laser with a better beam quality. In some other recent experiments, we have succeeded in delivering a 1-kW output power by using the 700- μm -bore guide with a water-cooled jacket. Results of this study will be published elsewhere.

4. Transmission Properties for Er:YAG Laser Light

The hollow waveguide is able to deliver Er:YAG laser energy by altering the design of the dielectric thick-

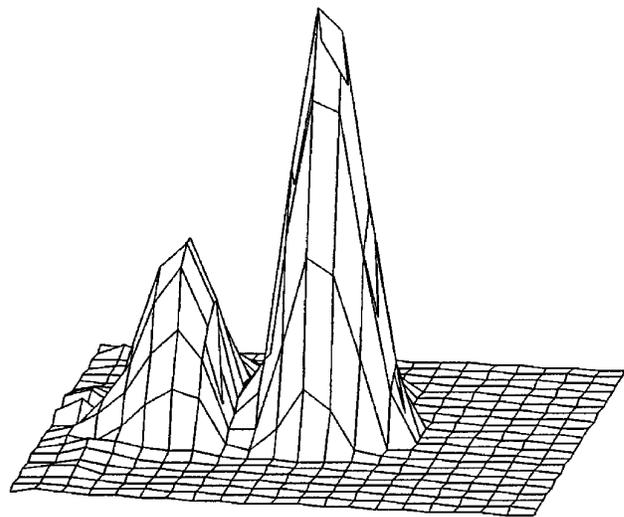


Fig. 8. Beam profile of the 530- μm -bore waveguide bent to a 69-mm radius.

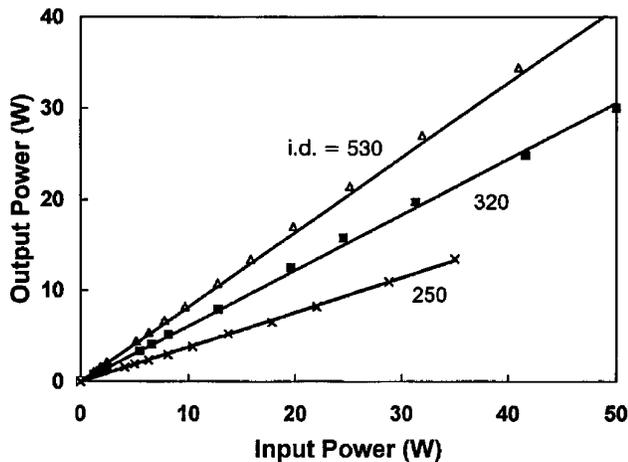


Fig. 9. CO₂ laser power delivery in different bore sizes of a hollow glass waveguide with a length of 1 m.

ness.⁴ Figure 10 shows the measured and the theoretical loss spectra of the waveguide designed for Er:YAG laser delivery. The guide is 20 cm long, the inside diameter is 530 μm, and the excitation condition is same as in Fig. 2. The thickness of the silver iodide layer is estimated as 0.23 μm and the inner surface roughness of the guide is estimated as 0.03 μm from the theoretical spectrum in Fig. 10. By choosing such a small thickness, we can obtain low attenuation at the Er:YAG laser wavelength of 2.94 μm. Figure 11 gives the measured straight losses for an Er:YAG laser source. The dashed curve is a fit to the measured losses calculated by a least-squares method. The solid curve gives theoretical losses calculated with Eq. (1) for the HE₁₁ mode only. In contrast to the results for CO₂ laser light, the measured losses are much higher than the theoretical ones. There are two reasons for this extra loss. One is that the input beam quality of our multimode Er:YAG laser source excites many higher modes in the waveguide. Another is that the decrease in reflectivity of light caused by surface roughness is proportional to $1/\exp(\lambda^{-2})$.¹² Therefore, a slight inner roughness can drastically affect transmission

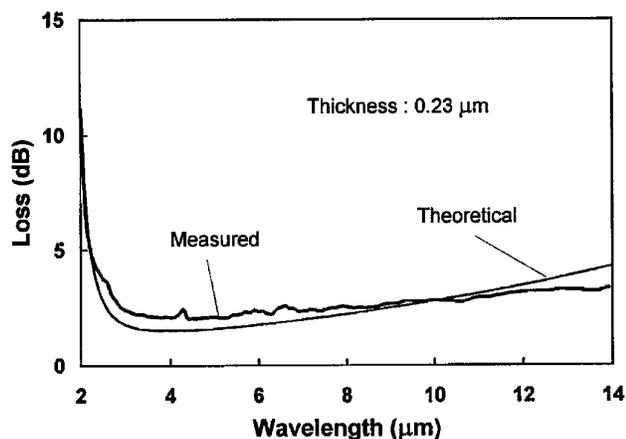


Fig. 10. Loss spectra of a hollow glass waveguide designed for Er:YAG laser light transmission.

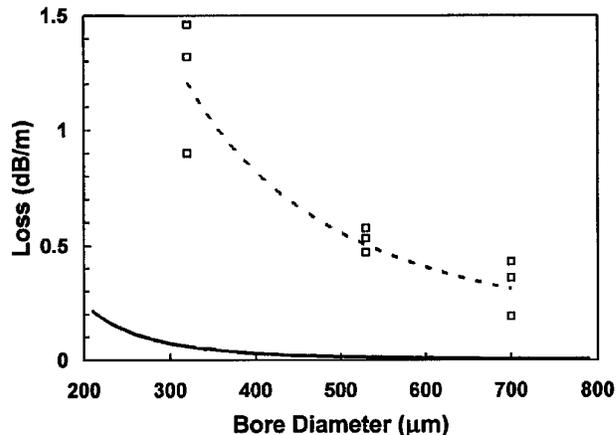


Fig. 11. Transmission losses of straight, hollow glass waveguides, using a 2.94-μm Er:YAG laser source. The solid curve is the theoretically calculated loss from Eq. (1). The dashed curve is a fit to the measured losses calculated by the use of a least-squares method.

losses in the shorter wavelength region. However, the losses are still low, i.e., ≈ 1.2 dB/m for a straight 320-μm-bore guide and 6 dB/m with 320-μm-bore guides bent to the radius of 10 cm.⁶ Therefore, the guide is quite useful in medical applications of the Er:YAG laser.

5. Conclusion

We have fabricated hollow glass waveguides with bore sizes as small as 250 μm by forming a metal and a dielectric layer on the inside of silica capillary tubing, using a liquid-phase deposition technique. The measured results show that excellent transmission properties are obtained in small-bore hollow waveguides. These hollow guides are so flexible and robust that they are readily applied to many fields of laser surgery. Furthermore, because our fabrication process is very simple and stable, the guides are relatively inexpensive to fabricate and are therefore appropriate for mass production.

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