Hollow-waveguide delivery systems for high-power, industrial CO_2 lasers

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Hollow-sapphire and metal–dielectric-coated hollow-glass waveguides have been used to deliver CO_2 laser power for industrial laser applications. The transmission, bending loss, and output-beam properties of these waveguides are described. The bore sizes of the hollow-sapphire waveguides were 1070 and 790 μm, and the hollow-glass waveguide had a bore of 700 μm. The waveguides ranged in length from 1.1 to 1.5 m. The sapphire waveguides were bent to 90°, and the hollow-glass waveguides were bent into a full 360° loop. We delivered a maximum of 1.8 kW through the 1070-μm-bore sapphire waveguide and 1.0 kW through the hollow-glass waveguide. All the hollow waveguides incorporated a water jacket to prevent overheating.

Key words: Fiber optics, hollow waveguides, hollow-sapphire waveguides, hollow-glass waveguides, beam delivery, industrial lasers, power delivery, CO_2 lasers.

1. Introduction

There has been an increasing interest in developing flexible fiber optics for use as beam-delivery systems for high-power, industrial CO_2 lasers. Today's industrial Nd:YAG lasers successfully incorporate the use of silica fiber-optic beam-delivery systems that transmit up to 2 kW of laser power through 600-μm-core fibers. Unfortunately, industrial CO_2 laser beam-delivery systems must rely on the articulated motion of mirrored or lensed arm segments. These systems are intrinsically larger than their fiber-optic counterparts, and they require frequent maintenance to preserve alignment and beam quality. In addition, these expensive systems are cumbersome in terms of their ability to gain access to remote locations. In contrast, fiber-optic-based systems offer the advantage of small size, good maneuverability, and lower cost. Additionally, it may be possible to use multiple fiber arrays to distribute laser power for multitasking applications.

Currently there are no fibers in practical use with industrial CO_2 lasers. The technology that is pursued for the high-power system is an offshoot of fiber technology initially developed for the delivery of infrared laser energy in laser surgery. Two types of infrared fibers have been developed for CO_2 laser surgery: one is the solid-core, silver halide fiber, and the other is the hollow-core fiber.[1] Today, hollow-core fibers are the best choice for the delivery of laser power. This is because the energy is carried in the air core, thus eliminating the possibility of damage to the bulk fiber as well as to the ends of the fiber. Furthermore, there are no Fresnel reflection losses at the ends of a hollow fiber.

Hollow metallic[2,3] and dielectric waveguides[4] with air cooling have been used to deliver up to 100 W of CO_2 laser power in laser surgical applications. Industrial laser power requirements, however, are considerably higher, and therefore hollow fibers need to be upgraded with special cooling jackets to withstand the rigors of higher industrial laser powers. Extreme care must also be taken to ensure that none of the laser power is focused onto the wall of the waveguide, as immediate and disastrous failure will result.

Dielectric-enhanced, metallic waveguides developed by Miyagi and his co-workers[5,6] and Hongo *et al.*[7,8] have been investigated for possible use in industrial CO_2 laser power delivery. Hongo *et al.*[8] were able to deliver 2.6 kW of CO_2 laser power through 1.7-mm-i.d., Ge-coated Ag waveguides, and they used these waveguides to weld two 1-mm-thick steel plates at a rate of 2 m/min. Matsumoto *et al.*,[9] at Kawasaki Heavy Industries, Ltd., have demonstrated greater than 3-kW power delivery through a 2-mm-i.d. Ge–Ni structured waveguide.

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Two types of waveguide structures are investigated in this study. The first is hollow sapphire, which has been shown to be an excellent waveguide for the delivery of CO_2 laser light.[4] Hollow sapphire is currently used in the medical industry for transmitting up to 100 W of CO_2 laser power, with losses as low as 0.4 dB/m. We were recently successful in delivering up to 1500 W through a 1070-µm-bore hollow-sapphire waveguide.[10] The single-crystal, sapphire waveguides used in this study were fabricated by Saphikon, Inc., Milford, New Hampshire. Details of the optical properties of these guides may be found in a recent publication.[11] The second type of waveguide used in this study has a hollow-glass structure and was recently developed at Rutgers University. The hollow-glass waveguides have some of the lowest measured losses to date of any infrared fiber optic.[12,13] The high-power tests were performed at PRC Corp. in Landing, New Jersey, on three different high-power lasers from 1500 to 3000 W.

2. Hollow Waveguides

The theory that describes losses in hollow waveguides was originally due to Marcatilli and Schmeltzer.[14] Their work was followed by that of Miyagi and Karasawa, who calculated bending losses in these structures.[15] The results of these works give two important relationships for the attenuation coefficient, α, which govern the losses in hollow guides, that is,

$$\alpha \propto \frac{1}{a^3}, \qquad \alpha \propto \frac{1}{R}, \tag{1}$$

where a is the bore diameter and R is the bending radius. These relationships show that the waveguide losses will increase dramatically as the bore size is reduced and that there is an additional loss on bending that increases as the inverse of the bend radius. In addition, hollow waveguides have the lowest loss for the lowest-order waveguide modes. Higher-order modes are much more lossy, and therefore, even though the core diameter is often more than 100 times greater than the wavelength, hollow waveguides tend to propagate near single-mode energy because the higher-order modes are rapidly attenuated.[14] Therefore hollow waveguides will have a higher loss when transmitting the multimode energy of kilowatt-class CO_2 lasers than when they transmit low CO_2 laser power with a TEM_{00} beam. In contrast, solid fibers will not experience the loss on bending like hollow waveguides; however, because of the large core diameters necessary to carry such high powers, they are extremely multimode. These facts illustrate the unique and fundamental difference between a hollow and a solid fiber.

The two types of waveguides used in this study operate by fundamentally different principles. Hollow-sapphire waveguides for CO_2 laser delivery can be thought of as attenuated total reflectance guides. This is because the air–core refractive index ($n = 1$) is greater than that of sapphire at 10.6 µm ($n = 0.67$ for sapphire at 10.6 µm). This fact was first discussed by Harrington and Gregory[4] who noted that sapphire also has a very small extinction coefficient k of 0.05 at 10.6 µm. From Marcatilli and Schmeltzers' theory[14] we calculate the theoretical loss for hollow-sapphire waveguides at 10.6 µm to be less than 0.1 dB/m for a 1000-µm-bore tube. In practice, however, surface roughness of the inner sapphire wall leads to an additional loss, even with optimal launch conditions (input spot size 0.64 times the waveguide bore).[11] The measured loss for a 1070-µm tube is measured to be ~0.4 dB/m at 10.6 µm. In contrast, the dielectric-enhanced metal film deposited on the inner wall of hollow-glass waveguides has an index of refraction of greater than 1. These films create a highly reflective surface to guide the energy. Because of the extremely smooth surface of the hollow-glass tubes, actual losses approach the theoretical limits calculated with the above theories.[12] Losses of less than 0.1 dB/m have been achieved. The 700-µm-bore, hollow-glass waveguides used in this study had a measured loss (with optimum coupling) of approximately 0.24 dB/m.

The single-crystal sapphire tubing fabricated by Saphikon, Inc., has bore sizes ranging from 250 to 1070 µm and lengths as long as 1.5 m. The two largest bore sizes, 790 and 1070 µm, were used for this study. Hollow-glass waveguides have been fabricated with bore sizes ranging from 250 to 1000 µm and in lengths as long as 6 m. In Fig. 1 we show the measured and the theoretical losses at 10.6 µm for different bore size hollow-sapphire and hollow-glass waveguides. The losses shown in Fig. 1 were obtained with a low-power CO_2 laser that delivered a TEM_{00} beam. Thus these losses represent the best possible transmission in contrast to the higher loss that we measure by using some high-power, multimode industrial CO_2 lasers. The measured low-power loss was 0.79 dB/m (80% transmission) for the 790-µm-diameter bore, 0.41 dB/m (89%) for the 1070-µm-diameter bore, 1.22-m-long hollow-sapphire waveguides, and 0.24 dB/m for the 700-µm-diameter bore, 1.32-m (93%) and 1.54-m (92%) hollow-

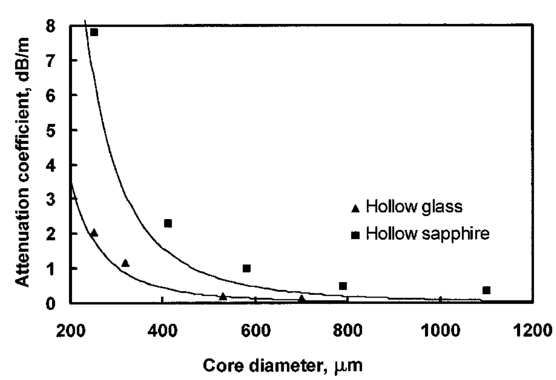

Fig. 1. Theoretical (solid curves) and measured attenuation in straight hollow-glass and hollow-sapphire waveguides at 10.6 µm.

glass waveguides. This is in good agreement with the results shown in Fig. 1 for our best fibers.

3. Waveguide Cooling

A waveguide's maximum power handling capability for cw CO_2 laser use is limited by the heat generated because of the losses and by the ability to remove the heat to keep the waveguide sufficiently cool. Sapphire has a distinct advantage over hollow-metallic or hollow-glass waveguides because of its extremely high melting point, 2050 °C. In comparison, the melting point of the metal halides used in coating the hollow-glass waveguides is as low as a few hundred degrees Celsius. However, we have calculated that with water cooling, the temperature of the waveguides can be kept low enough to eliminate the risk of thermal damage, even in the case of the hollow-glass waveguides.

Hiratani *et al.*[16] predicted the maximum power-handling capability of Ge-coated hollow Ag waveguides to be ~1.6 kW under a state of natural convection. Detailed analyses by Karasawa *et al.*[17] and Hongo *et al.*[18] showed that the temperature distribution along a hollow waveguide decreases in an oscillatory manner because of modal interefer-ence effects. In our calculations, we have ignored the modal interference. We are interested primarily in the maximum temperature of the waveguides, which will invariably be at the input end, assuming a uniform attenuation coefficient along the length of the guide. To simplify the calculations further, we assume that the heat conduction along the length of the guides is negligible compared with the radial heat flow. This is a good approximation for dielectric materials with low thermal conductivity.

The removal of heat from the waveguide can be accomplished by conduction or convection cooling. Conduction cooling would require a tight outer covering with sufficient heat capacity for the duration of the task. This is certainly impractical as it is task specific and would certainly reduce the flexibility of the waveguide. Convective cooling can be accomplished by gases or liquids and can be forced or natural. To achieve the maximum convective cooling, forced liquids should be used.

Gregory applied a tube-in-tube heat-exchanger model to analyze the heat flow out of a hollow waveguide by using forced convective cooling.[19] From his calculations he determined the temperature at the input end of a waveguide. We have modified these calculations slightly to show the temperature distribution along the length of a waveguide. Consider the portion of a hollow waveguide, as shown in Fig. 2. At steady-state conditions, the power lost in the cylindrical section between z and $z + \Delta z$, $P_L(\Delta z)$, equals the heat flow from that section, $Q_1(\Delta z) + Q_2(\Delta z)$. Q_1 represents the convective heat transfer to the gas (air) in the bore of the waveguide, and Q_2 represents both the radial conduction in the waveguide wall as well as the heat transfer to the cooling water. Using well-known heat-flow analyses for a cylindrical tube, we obtain the radial heat-flow equations:

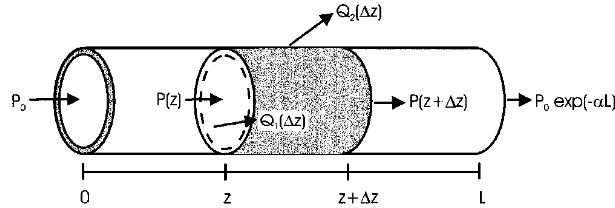

Fig. 2. Diagram showing power lost, $P(z) - P(z + \Delta z)$, and heat flow from the outer surface, $Q_2(\Delta z)$, and inner surface, $Q_1(\Delta z)$, in a waveguide section of length Δz.

$$Q_1 = \frac{T_i - T_1}{\left(\dfrac{1}{2\pi h_1 r_i \Delta z}\right)}, \qquad (2)$$

$$Q_2 = \frac{T_i - T_2}{\dfrac{\ln(r_o/r_i)}{2\pi k \Delta z} + \dfrac{1}{2\pi h_2 r_o \Delta z}}, \qquad (3)$$

where T_i, T_1, and T_2 are the temperatures of the inner bore of the waveguide, the gas inside the tube, and the outer cooling water, respectively; h_1 and h_2 are the heat-transfer coefficients of air and water per unit surface area, respectively; k is the thermal conductivity of the waveguide; and r_i and r_o are the inner and the outer diameters of the waveguide, respectively.

Assuming that the absorbed power is distributed uniformly along the length of the waveguide, the power in the core at a distance z from the input is given by

$$P_z = P_0 \exp(-\alpha z), \qquad (4)$$

where P_0 is the input power and α is the attenuation coefficient. The power lost at point z in a length Δz is therefore given by

$$P_L(\Delta z) = P_0 \exp(-\alpha z) - P_0 \exp[-\alpha(z + \Delta z)], \qquad (5)$$

or, on simplification,

$$P_L(\Delta z) = P_0 \exp(-\alpha z)[1 - \exp(-\alpha \Delta z)]. \qquad (6)$$

By setting the power lost in a section Δz equal to the total heat flow and taking the limit as $\Delta z \rightarrow 0$, that is,

$$\frac{P_0}{2\pi} \exp(-\alpha z) \lim_{\Delta z \rightarrow 0} \frac{[1 - \exp(-\alpha \Delta z)]}{\Delta z} = \frac{T_i - T_1}{R_1} + \frac{T_i - T_2}{R + R_2}, \qquad (7)$$

we obtain the equation

$$\frac{\alpha}{2\pi} P_0 \exp(-\alpha z) = \frac{T_i - T_1}{R_1} + \frac{T_i - T_2}{R + R_2}, \qquad (8)$$

where

$$R_1 = \frac{1}{h_1 r_i}, \qquad R = \frac{\ln\left(\frac{r_o}{r_i}\right)}{k}, \qquad R_2 = \frac{1}{h_2 r_o}, \tag{9}$$

α is in inverse centimeters and z is in centimeters. We calculate the temperature of the inner wall of the waveguide, T_i, from Eq. (8). To get T_o, the temperature of the outer wall of the waveguide, we use the fact that the heat flow Q through the waveguide wall must be equal to Q_2 that is,

$$Q = \frac{T_i - T_o}{R} = \frac{T_i - T_2}{R + R_2}. \tag{10}$$

Accordingly, we obtain the following equations for the temperature along the length of the waveguide:

$$T_i = \frac{R_1(R + R_2)}{R_1 + R + R_2} \times \left[\frac{0.23\alpha}{2\pi} P_0 \exp\left(\frac{-\alpha z}{434}\right) + \frac{T_2}{R + R_2} + \frac{T_1}{R_1}\right], \tag{11}$$

$$T_o = \frac{R_1 R_2}{R_1 + R + R_2} \left\{\frac{0.23\alpha}{2\pi} P_0 \exp\left(\frac{-\alpha z}{434}\right) + \left[1 + \frac{R(R_1 + R + R_2)}{R_1 R_2}\right]\frac{T_2}{R + R_2} + \frac{T_1}{R_1}\right\}, \tag{12}$$

where the coefficients 0.23 and 434 are used so that α is expressed in decibels per meter instead of inverse centimeters.

These equations indicate an exponential decay of temperature along the waveguide. To assess the power handling capability of our waveguides, we calculated the temperature at the inner wall of the input end, which should be the hottest point along the waveguide. Furthermore, we anticipate that on some industrial lasers with poor mode quality the coupling loss could be quite high, so an attenuation of 3 dB/m was used in the calculations as a worst case to account for the possibility of a high coupling loss. Figure 3 shows the calculated temperature at the input end of the three waveguides used with a cooling water flow of 5 L/m. The thermal conductivities of sapphire and glass, the heat-transfer coefficient to air h_1, and the heat-transfer coefficient to water h_2 used in our calculations were 27.7 W m^{-1} K^{-1}, 1.38 W m^{-1} K^{-1}, 22 W m^{-2} K^{-1}, and 4000 W m^{-2} K^{-1}, respectively. The heat-transfer coefficients were calculated with the theory presented by Gregory.[19] Figure 3 shows that even with the exaggerated coupling loss used in the theoretical calculations, the temperature of the input end of the guides will be below 200 °C for an input power of 5000 W. We expect that the waveguides should be safe for continuous use at input powers of up to 3000 W and possibly up to as much as 5000 W. We tested each of the waveguides for 15 min of continuous use at its respective maximum input power and observed no deterioration in transmission.

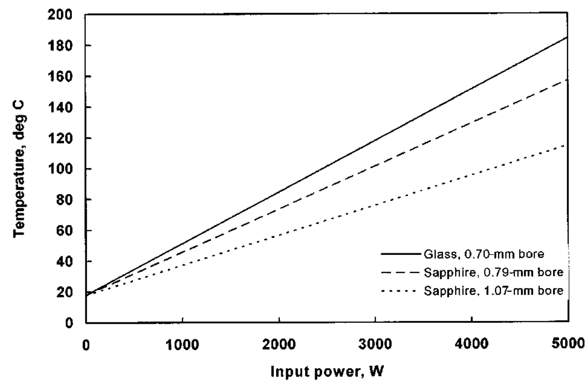

Fig. 3. Calculated temperature of the inner wall at the input end of a 700-µm-bore hollow-glass waveguide (solid line), a 790-µm-bore hollow-sapphire waveguide (dashed line), and a 1070-µm-bore hollow-sapphire waveguide (dotted line) for an attenuation of 3 dB/m. Calculations were based on forced convective water cooling with a water temperature of 18 °C.

4. Experimental Setup

A schematic of the waveguide cooling jacket and special fittings is shown in Fig. 4. Each end of the waveguide was epoxied into high-conductivity metal fittings (Cu at the input and brass at the output). The epoxy used was a high-temperature, two-part epoxy made by Duralco. The water jacket was formed from 1/4-in. (0.635-cm) polyethylene tubing that was inserted over the sapphire or glass tubing and into two, watertight, standard Cajon pipe fittings used as end mounts. Cooling water (18 °C) was then forced over the waveguide during use at a flow rate of approximately 5 L/min. No gas cooling through the bore was used in this experiment.

Because these waveguides will melt when directly exposed to just tens of watts of CO_2 laser power, extreme precautions had to be taken to ensure that none of the high-power beam would impinge on the waveguide wall during operation as a result of slight misalignment or beam spillage. To ensure that no laser energy struck the waveguide walls, we placed a Cu cone over the input end of the fiber. The hole in the cone was slightly smaller than the bore of the fiber, and the Cu cone was polished or diamond

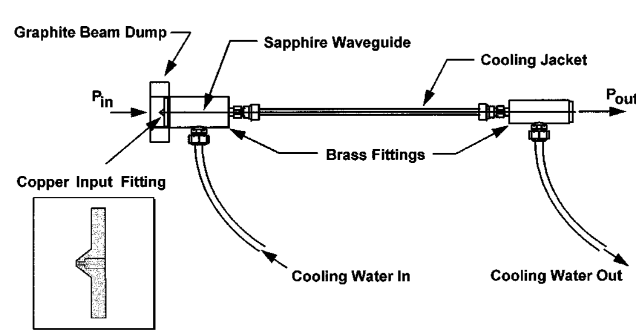

Fig. 4. Structure of hollow-waveguide cooling jacket and Cu input fitting.

turned and Au coated to have a highly reflective surface. In the original design, the Cu cone had a concave surface instead of the convex surface shown in Fig. 4. Although the concave surface worked to some degree to direct any misaligned beam into the waveguide bore, damage did occur when the input power was above 1 kW because the beam was simply reflected into the waveguide at acute angles. The convex surface was designed to reflect any misaligned beam completely away from the waveguide and into a graphite beam dump. There was never any damage to the waveguides when this convex input fitting was used for CO_2 laser input powers up to 2.5 kW.

The CO_2 laser light was launched into the waveguides by a 1.5-in.-diameter, 10-in. focal length ZnSe lens placed 0.5 m from the output coupler of the laser. The input and the output powers were measured with a 5-kW Laser Power Optics power meter. Three PRC Corporation lasers were used for our tests: Models PRC 1501, PRC 2000, and PRC 3000. All three lasers were randomly polarized and had a half-angle beam divergence of <1 mrad. Figure 5 shows the beam patterns of these lasers made by irradiating acrylic blocks. The $1/e^2$ beam diameter of the 1500- and the 2000-W lasers was approximately 13 mm, and that of the 3000-W laser was approximately 16 mm. The beam out of the 2000- and the 3000-W lasers was a mixture of TEM_{00} + TEM_{01^*} (D-mode, with an M^2 estimated to be ~2). This laser mode decreases the energy density on the center of the cavity optics, thus substantially diminishing thermal lensing problems. The D-mode is popular for industrial applications because it approximates a tophat profile and delivers a more uniform heat distribution to target. However, as is seen below, the D-mode does not couple as well to the waveguides. We also note in Fig. 5 that the beam diameters get larger and their spatial profiles change as the laser power is increased. Unfortunately, this can decrease the coupling efficiency to the waveguides, which leads to lower transmission at higher powers.

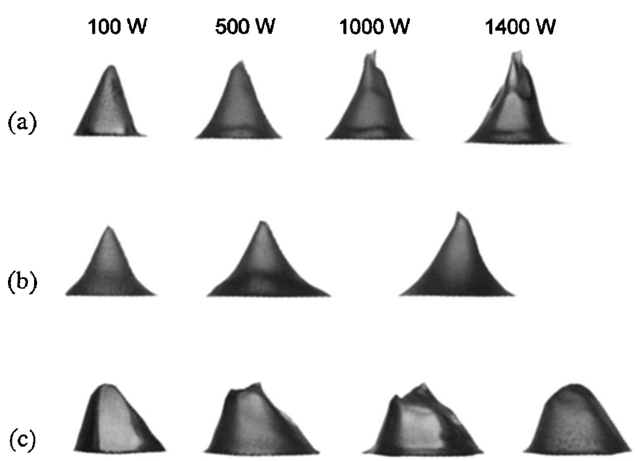

Fig. 5. Beam patterns of (a) 1500-W laser, (b) 2000-W laser, and (c) 3000-W laser taken from burns made in acrylic blocks.

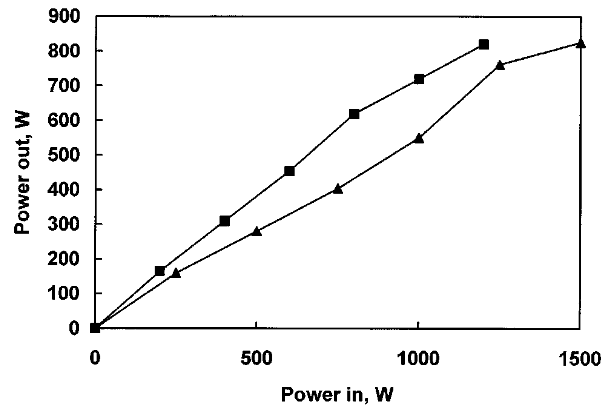

Fig. 6. Transmission of a straight, 790-μm-bore, 1.2-m-long hollow-sapphire waveguide on the 1500-W laser (■) and the 2000-W laser (▲).

The output mode of the 1500-W laser was nearly TEM_{00}, with an M^2 of between 1.2 and 1.5. For optimal coupling of a Gaussian input beam, the spot size should be focused to a diameter that is 0.64 times the waveguide bore diameter.[18,20,21] However, with a multimode beam it is impossible to achieve the optimum coupling. Therefore we compromised on a focusing lens with a focal length f of 254 mm (10.0 in.). The diameter of the focused spot size d, calculated with

$$d = 1.27\lambda \frac{f}{D} M^2, \tag{13}$$

was found to be approximately 355 μm for the 1500-W laser and 530 μm for the 2000- and the 3000-W lasers. The multimode nature of the beam will increase the loss of the waveguide in two ways: first, the higher-order, lossy waveguide modes are excited and, second, less than optimum coupling conditions must be used.

5. Results of Power Testing

A. Hollow-Sapphire Waveguides

A plot of the output power versus input power is shown in Fig. 6 for the straight 790-μm-bore sap-

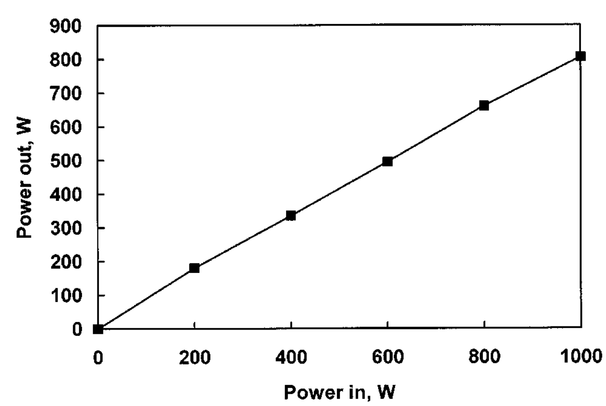

Fig. 7. Transmission of a straight, 1070-μm-bore, 1.5-m-long hollow-sapphire waveguide on the 1500-W laser.

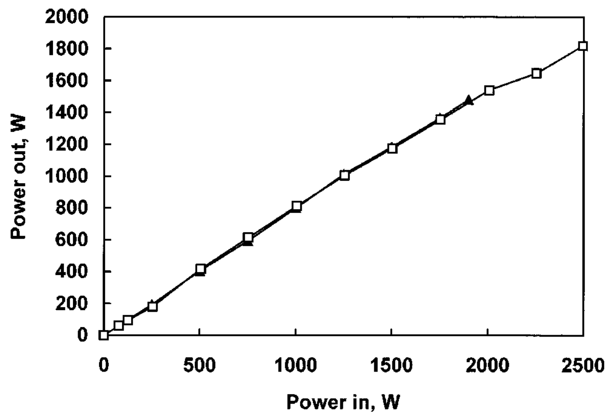

Fig. 8. Transmission of a straight, 1070-µm-bore, 1.2-m-long hollow-sapphire waveguide on the 2000-W laser (▲) and the 3000-W laser (□).

phire waveguide on the 1500- and the 2000-W lasers. The transmission of the 1500-W laser was ~75% but for the 2000-W laser it was only ~55%. It is clear that the transmission is significantly improved when a near-Gaussian beam is used. The length of this waveguide was 1.2 m, so 75% and 55% transmission correspond to 1.04 and 2.16 dB/m, respectively. Even at 1.04 dB/m, the losses are higher than the losses (0.8 dB/m) measured with ideal input conditions. This graph shows quite dramatically how sensitive the losses are to input-beam quality. It also demonstrates a major difficulty in using hollow waveguides for high-power delivery, and that is the difficulty in achieving optimum coupling with less than optimum beam quality. The transmission curves in Fig. 6 also show an apparent change in slope at higher input powers, which we attribute to the change in input-beam quality as the laser power is increased. Nevertheless, 1.04 dB/m is close to the 0.8 dB/m measured with a low-power, high-quality input beam. The maximum power out of the 790-µm-bore hollow-sapphire waveguide was 825 W, corresponding to 168 kW/cm^2 at the output end of the waveguide.

The output and the input powers for the straight 1070-µm-bore hollow-sapphire waveguide with the 1500-, 2000-, and 3000-W lasers are shown in Figs. 7 and 8. The length of the waveguide used on the 1500-W laser was 1.5 m, whereas the length of the waveguide used on both the 2000- and the 3000-W lasers was only 1.2 m. The transmission on the 3000-W laser was ~76% (0.99 dB/m), ~80% (0.81 dB/m) on the 2000-W laser, and ~75% (0.83 dB/m) on the 1500-W laser. For reference, the measured loss with optimum coupling was ~0.45 dB/m for these waveguides. We again observe a loss that is dependent on beam quality; however, because our choice of input lens focal lengths was limited, we were unable to achieve optimum coupling, even on the 1500-W

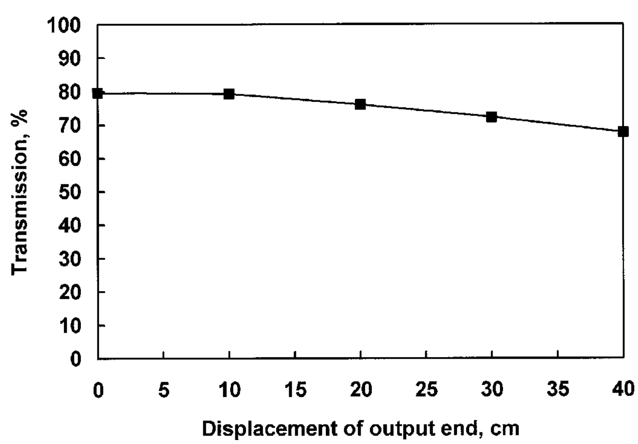

Fig. 9. Bending loss of a 1070-µm-bore, 1.2-m-long hollow-sapphire waveguide a 3000-W laser operating at 500 W.

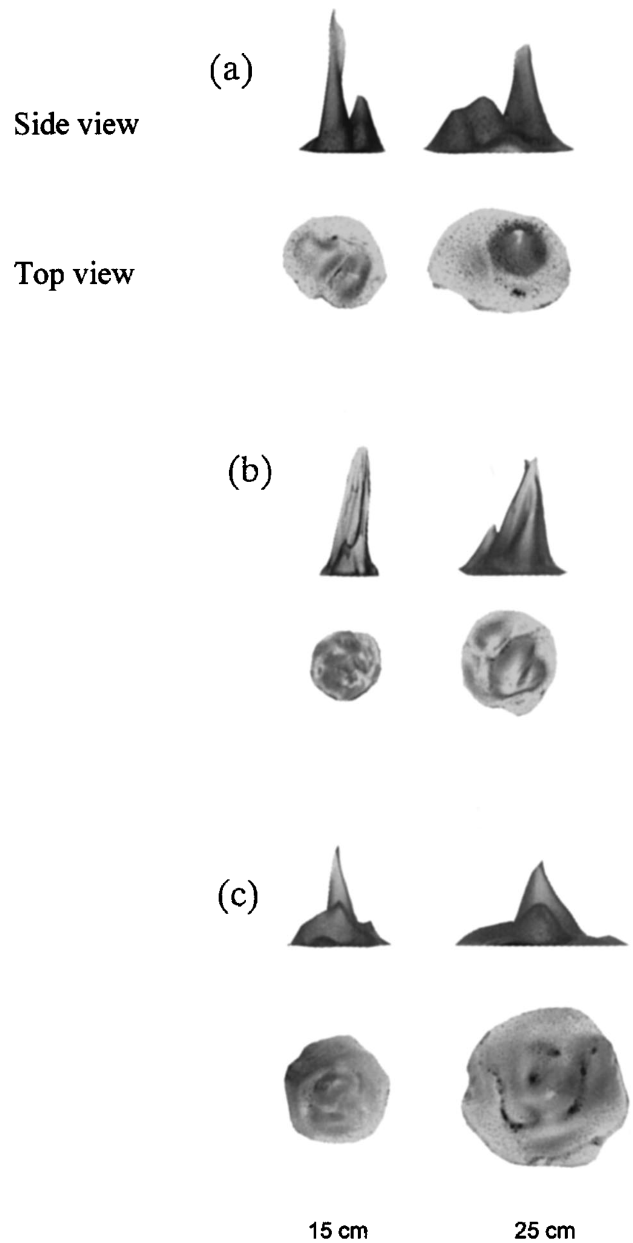

Fig. 10. Output-beam profiles on the 1500-W laser of (a) 790-µm-bore hollow-sapphire and (b) 1070-µm-bore hollow-sapphire waveguides and on the 2000-W laser of (c) 1070-µm-bore hollow-sapphire waveguide.

laser. A focal length closer to 15-in. (instead of the 10-in. focal-length lens used) would have been better. We did try a 20-in. focal-length lens, which did not improve the transmission of the waveguide appreciably. This waveguide was able to deliver up to 1.8 kW without damage, corresponding to 200 kW/cm^2 at the output end. If we had had a better output-beam quality from the 3000-W laser and the optimum lens, it is our belief that we would have obtained even more power transmitted through the guide.

Bending data were taken for the 1070-µm sapphire waveguide with the 3000-W laser operating at 500 W. These data are shown in Fig. 9. In an attempt to simulate the bending that might be encountered in an actual industrial application, bending loss was measured by the deflection of the output end of the fiber by a distance d. For a deflection of 40 cm, the transmission dropped to 85% of the straight transmission. As these single-crystal sapphire guides are quite stiff (Young's modulus E of sapphire is 350 GPa) and somewhat fragile (strain to failure ϵ is less than 0.5%), the amount that the waveguides could be bent was limited. In fact, the 1070-µm-diameter-bore waveguide broke after 10 min while bent 90°.

Figures 10(a) and 10(b) show the output-beam profiles, with the 1500-W laser, 15 and 25 cm from the output ends of the straight 790- and 1070-µm-bore hollow-sapphire waveguides, respectively. Figure 10(c) shows the output-beam profile of the 1070-µm-bore hollow-sapphire waveguide on the 2000-W laser. There appears to be considerable mode mixing occurring even with the near-TEM$_{00}$ mode, 1500-W laser. However, comparing Figs. 10(b) and 10(c) shows that the output-beam profile is considerably better on the 1500-W laser. The output-beam profile is highly dependent on appropriate launching conditions. Slightly adjusting the input alignment but not enough to affect the transmission can significantly change the output-beam profile. It is not unreasonable to expect that, with sufficient care, the input could be aligned so that the output beam is very nearly Gaussian (given a Gaussian input beam).

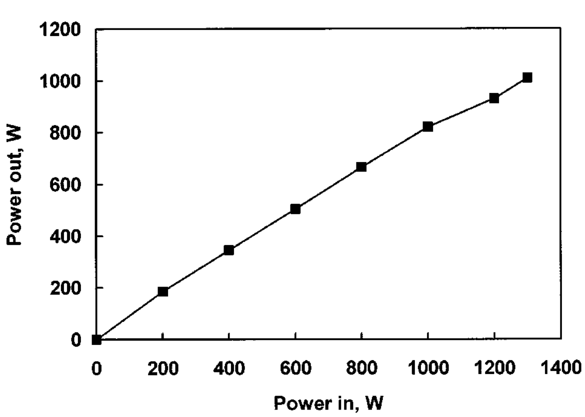

Fig. 11. Transmission of a straight, 700-µm-bore, 1.54-m-long hollow-glass waveguide on the 1500-W laser. The maximum output power was 1010 W.

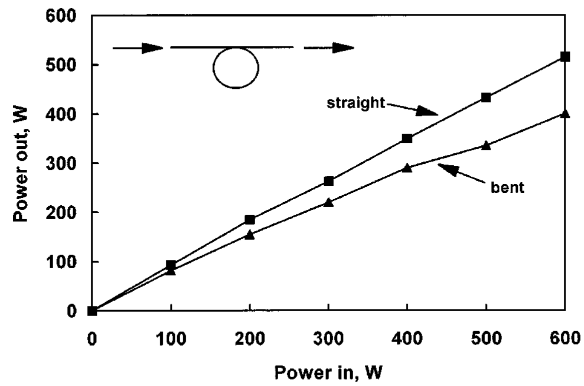

Fig. 12. Transmission of straight (■) and bent 360° (▲) 700-µm-bore, 1.54-m-long hollow-glass waveguides on the 1500 W laser.

B. Hollow-Glass Waveguides

All the tests with the hollow-glass waveguides were carried out on the 1500-W laser with a near-TEM$_{00}$ beam. The maximum output power from this straight waveguide, Fig. 11, was 1010 W, or 262 kW/cm^2. This is the highest power density delivered by any CO_2 fiber optic to date. The length of this waveguide was 1.54 m, and the average transmission was 85% (0.46 dB/m). The transmission did drop off to only ~80% at the highest powers. To determine whether this drop off was due to damage to the waveguide or to a change in input-beam quality, we immediately retested the transmission at 200 and 400 W. The transmission at these lower powers was identical to the value before the input power was increased to 1300 W, indicating that no damage had occurred to the waveguide.

Figure 12 shows the transmission for the same hollow-glass waveguide used above but bent in a 15-cm-radius 360° loop; the transmission of the straight guide is shown for comparison. The input power was taken to only 600 W to ensure that we had the best input-beam quality possible. The average transmission straight was 88% (0.36 dB/m), but bent in a loop it was 73% (0.89 dB/m). The transmission increased to ~88% after the bent guide was straightened, so there was no damage to the guide on bending. Other bending data are shown in Fig. 13. This figure shows that the transmission is nearly

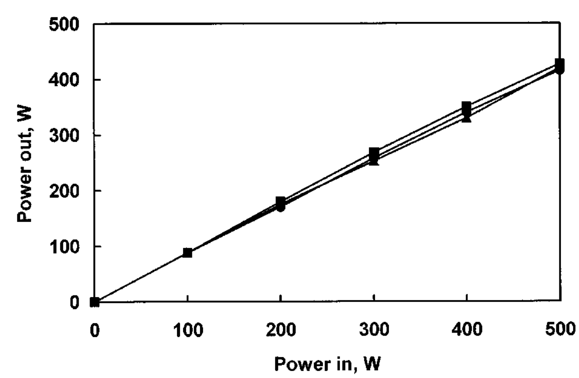

Fig. 13. Transmission of straight (■), bent 90° (▲), and bent 180° (●) 700-µm-bore, 1.54-m-long hollow-glass waveguides.

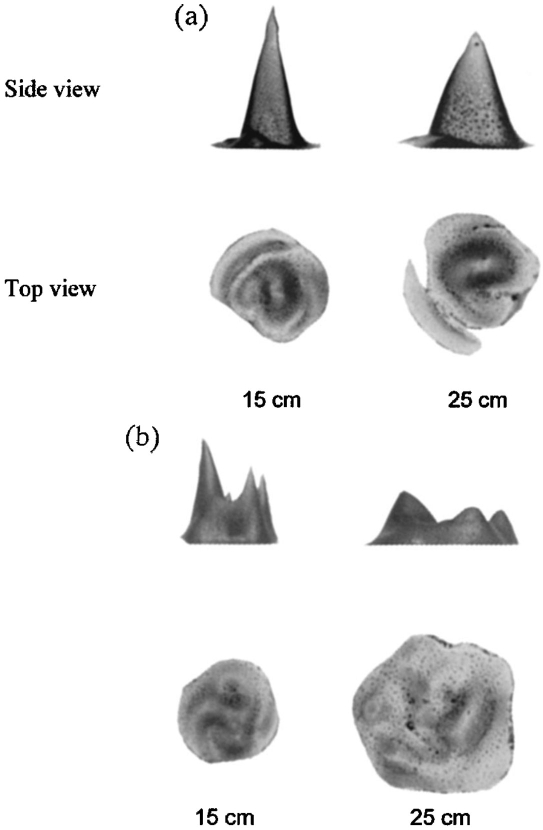

Fig. 14. Output-beam profiles on the 1500-W laser of a 700-μm-bore, 1.54-m-long hollow-glass waveguide (a) straight and (b) bent 360°.

constant, even for bends up to 180° (or approximately a 40-cm bend radius).

The output-beam profiles from the hollow-glass waveguide when straight and bent 360° are shown in Fig. 14. The beam profile out of the straight waveguide is very nearly single mode; this is in stark contrast to the beam profiles out of the sapphire waveguides shown in Fig. 10. There are two reasons why the sapphire waveguides might excite more higher-order modes than the hollow-glass waveguides do: (1) the inner wall of the sapphire waveguides is much rougher than that of the hollow glass, which not only increases the loss, but decreases the modal purity[11,19]; and (2) the smaller diameter of the hollow glass leads to less propagation of higher-order modes.[13] Nevertheless, the input must still be perfectly aligned for an output beam of such high quality to be achieved irrespectively of whether the waveguide is hollow sapphire or hollow glass. Slight misalignments can alter the output-beam profile considerably.

6. Conclusions

We have shown that both hollow-sapphire and hollow-glass waveguides show promise as delivery systems for industrial CO_2 laser energy. Our calculations indicate that the threshold for power delivery is probably quite high for these hollow structures. We estimate that up to 5 kW is possible if the guide is kept cool. Although water jacketing is a logical approach to cooling, we have also used a cooling gas (air or N_2) through the bore of the tube. This seems to work well for powers up to several hundred watts. An added feature of the gas purge is that the output end of the fiber is kept clean. This is essential because debris entering the guide creates hot spots that quickly destroy the tube. More critical than the cooling is the input alignment. The proper input fitting has proved essential in avoiding damage to the input end that is due to slight misalignments.

When the two types of waveguides investigated are compared, the hollow-sapphire waveguides have the advantages of a high melting temperature and high strength. If the hollow-sapphire tubing is contaminated, it can be cleaned with a solvent such as acetone and used over and over again. The hollow-glass waveguides are more fragile because of the coatings but have much lower losses, better output-beam quality, less loss on bending, and a smaller minimum bend radius.

There is still considerable work to be done to assess the overall efficacy of this approach. In particular, it is necessary to compare the cutting or welding ability of a beam delivered through the fiber versus the free-beam configuration. The multimode aspects of the output beam clearly present a problem, but with better input beams the waveguides should produce better quality output. The bending loss inherent to hollow guides is unavoidable. Perhaps a feedback loop could be used to keep the output power constant by adjusting the input power. A TEM_{00} input beam is by far the most desirable. Low loss, minimal loss on bending, and high output-beam quality are all achieved if the input is single mode. But this may be possible only with CO_2 lasers that have outputs of less than 2000 W, at least at this time. Probably the best industrial applications for these waveguides are those that require CO_2 lasers with output powers from 500 to 2000 W. Finally, hollow waveguides have been shown at low power to preserve the polarization of the input beam. We anticipate the same will be true with high-power lasers. This could be of key importance for many industrial laser applications.

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