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レーザ医療用高機能赤外光伝送システムの研究

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Infrared hollow fiber delivery system and their applications in medicine

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ABSTRACT

Techniques for coating hollow glass fibers with layers of silver and cyclic olefin polymer have been developed for low-loss delivery of infrared laser light as well as a visible pilot beam. They have yielded losses of only 0.2 dB/m for Er:YAG and CO_2 laser light and only 0.7 dB/m for red LD laser light.

Debris is kept from entering the hollow output end of a fiber by hermitically sealing it with a quartz cap, and various focusing effects in both air and water have been obtained by controlling distal-end geometry of the caps during fabrication. Controlled focus patterns of Er:YAG laser light with an output energy of more than 400 mJ and a 10-Hz repetition rate have been delivered in saline through the fibers with sealing caps.

Calculi were fragmented *in vitro* by using a hollow fiber with a sealing cap. It has been shown that Er:YAG laser combined with an effective delivery system could be used for minimally invasive calculi fragmentation.

Key words: Hollow fiber, pilot beams, infrared lasers, end-sealing, cyclic olefin polymer, calculus fragmentation

1. Introduction

Hollow fibers [1-5] are widely used as a low-loss transmission medium for infrared laser light, and polymer-coated silver hollow fiber is especially suitable for medical applications because it is non-toxic, durable, and inexpensive. Because cyclic olefin polymers have a low extinction coefficients over a wide infrared region [6], we have developed cyclic olefin polymer-coated silver (COP/Ag) hollow fibers that can deliver Nd:YAG, Er:YAG, CO, and CO_2 laser light with low losses [7-10]. An aiming or pilot beam is usually needed in laser medicine for avoiding a laser hazard or illuminating the target, and these infrared hollow optical fibers carry green (0.53 μm) or red (0.63 μm) pilot beams with low loss [11].

The output end of a hollow fiber used in medical or industrial applications must be sealed to keep the fiber coating from being destroyed by the debris, so the output end of our fiber is hermitically sealed with a quartz cap [12, 13]. The distal-end geometry of the sealing caps can be controlled during their fabrication, and we produced caps with dome, plano-convex, and ball shapes that have different focusing effects for various applications. The fiber with these caps have delivered more than 400 mJ of Er:YAG laser light at a 10-Hz repetition rate in both air and saline.

In the work reported here, an Er:YAG laser light delivery system composed of the hollow fiber and the sealing caps was used in calculus fragmentation experiments using an actual renal calculus and a model calculus made of activated alumina. Calculi in saline were destroyed quickly by the output of the Er:YAG laser light and the shock wave the pulsed laser produced in the saline.

2. Fabrication of hollow fibers

2.1 Optimum thickness of COP layer

For laser light of any specific wavelength, there is an optimum dielectric film thickness for low-loss transmission in a dielectric-coated hollow fiber [1]. For CO_2 (λ=10.6 μm) and Er:YAG (λ=2.94 μm) laser light, the theoretical loss of the HE_{11} mode in a COP/Ag hollow fiber with a 700-μm-bore is shown in Fig. 1 as a function of COP film thickness. The optimum thicknesses minimizing loss are 1.23 μm for CO_2 laser light and 0.35 μm for Er:YAG laser light. Similarly, the optimum thicknesses are 0.64 μm for CO laser light (λ=5.3 μm) and 0.12 μm for Nd:YAG laser light (λ=1.06 μm).

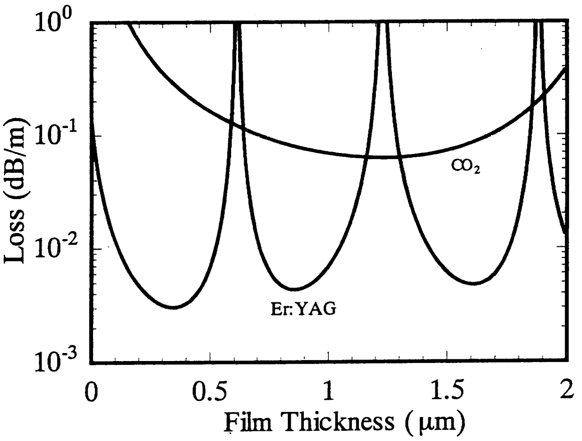


Fig. 1. Theoretical loss of the HE_{11} mode of CO_2 and Er:YAG laser light in a COP/Ag hollow fiber with a 700-μm-bore, and a COP refractive index 1.53.

2.2 Fabrication of COP/Ag hollow fibers

In the fabrication of COP/Ag hollow fibers, a silver layer was plated inside the fused glass capillary tube by using the silver-mirror reaction method. Then, a liquid-phase coating method was used to form a COP layer on the silver layer [14, 15]. The COP concentration and flowing rate are important factors controlling the thickness of COP layer and conditions for the fabrication of COP/Ag hollow fibers transmitting CO_2 and Er:YAG laser light as well as pilot beams were established [16]. The COP/Ag hollow fibers show low-loss properties in the visible wavelength band of 0.5-0.7 μm with little effect on the loss of CO_2 or Er:YAG laser light. In the silver-layer plating, a $SnCl_2$ sensitization [17] has been introduced in the silver-mirror reaction. A silver layer with an inner surface roughness as low as 10 nm has been deposited, and the transmission properties of visible pilot beams in COP/Ag hollow fibers for CO_2 laser delivery have been improved by using an atmosphere of Tetrahydrofuran (THF) solvent during the curing of the liquid-phase COP film. The THF atmosphere decreases the rate of COP solvent (cyclohexane) evaporation, which might lead to a smoother surface on the COP film. This greatly decreased the loss in the visible range. By adjusting the film thickness of the COP layer, we can adjust a low-loss dip in the visible range to an objective wavelength, such as red or green or yellow.

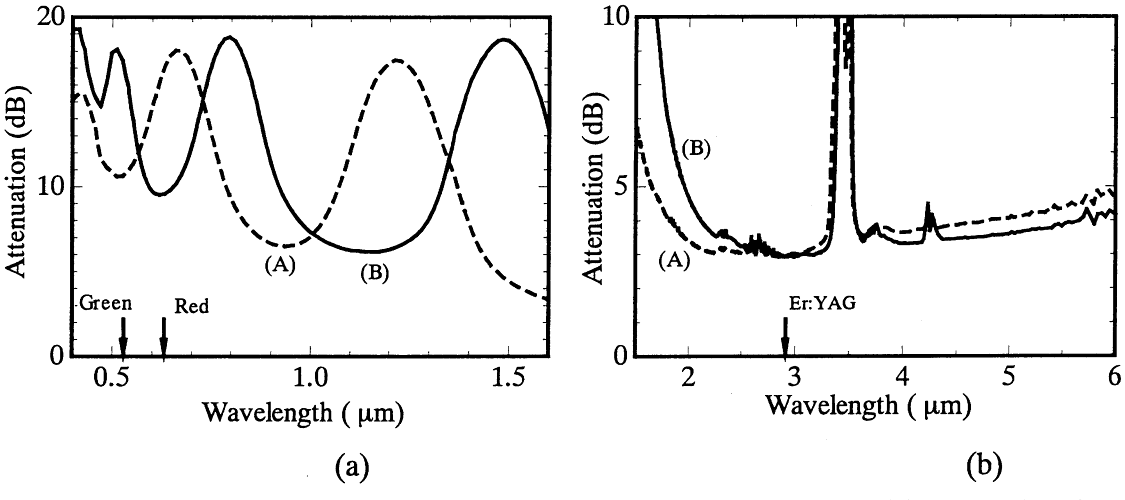
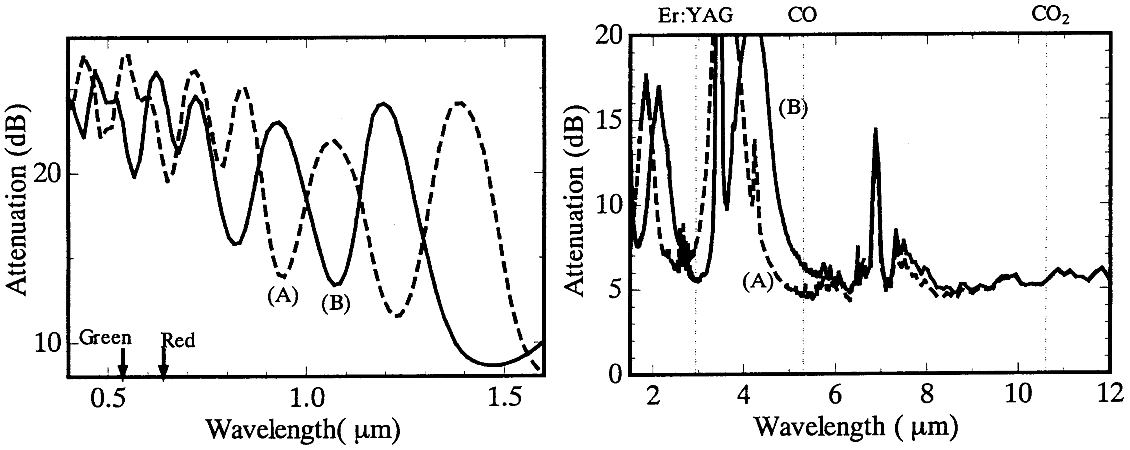


Fig. 2. Loss spectra in (a) visible and near-infrared regions and in (b) infrared region for COP/Ag hollow glass fibers designed for Er:YAG laser. Fibers (700 μmφx1.5m) with film thicknesses of (A) 0.26 μm and (B) 0.32 μm were excited by a Gaussian beam with a FWHM of 10.7° (a) and 12° (b).

The loss spectra of two fibers designed for Er:YAG laser light are shown in Fig. 2. The two fibers have COP film thicknesses of 0.26 μm (A) and 0.32 μm (B), respectively. It is seen in Fig. 2 (b) that the losses of both fibers are the same at the wavelength of Er:YAG laser light. As seen in

Fig. 2 (a), however, their losses are different in the visible and near-infrared regions. The fiber with the thinner COP film has a minimum loss at 0.53 μm, while the fiber with the thicker film has a minimum loss at 0.63 μm. This means that fiber A and fiber B can respectively deliver a green and a red pilot beam at the same time they deliver Er:YAG laser light.

Similarly, the loss spectra of fibers designed for CO_2 laser light are shown in Fig. 3. The two fibers have COP film thicknesses of 0.8 μm (A) and 0.9 μm (B). It is seen in Fig. 3 (b) that losses of both fibers are the same at the wavelength of CO_2 laser light. The fiber A is for a green pilot beam with a 0.53 μm wavelength, and the fiber B is for a red pilot beam with a 0.63 μm wavelength. We also note that the COP films in these two fibers are thinner than the theoretical optimum value, but a thinner COP film normally has a smoother surface and better uniformity along the fiber. When the liquid-phase coating fabrication technique was used, the fibers with a thinner COP film had the same loss properties for CO_2 laser light as that with a theoretically optimum thicker COP film had.



(a) (b)

Fig. 3. Loss spectra in (a) visible and near-infrared regions and in (b) infrared region for COP/Ag hollow glass fibers designed for CO_2 laser. Fibers (700 μmϕ × 2 m) with COP film thicknesses of (A) 0.8 μm and (B) 0.9 μm were excited by a Gaussian beam with a FWHM of 10.7° (a) and 12° (b).

3. Transmission properties

3.1 Delivery of Er:YAG laser light

Straight and bending losses of COP/Ag hollow fibers designed for the delivery of Er:YAG laser light are shown in Fig. 4. A lens with the focal length of 25 cm and a 15-cm-long glass taper coupler were used in these measurements. The input power was about 1 W and the pulse repetition rate was 5 Hz. The straight losses in the fibers with bores of 1 mm, 700 ? m, and 540 ? m were respectively 0.1, 0.2, and 0.6 dB/m. The fiber with a 540-μm bore had an additional loss for bending that was smaller than that of the fiber with the 1-mm bore. When the fiber with a 700-μm-bore was bent to an angle of more than 270° with a bending radius of 15 cm, the transmittance of the fiber was more than 80% (0.8dB). Similar transmission properties for bending losses were obtained for various-bore fibers designed for the delivery of CO_2 laser light.

3.2 Delivery of pilot beams

Randomly polarized red visible light from a laser diode with 3 mW of output power was used in the pilot beams delivery experiments. It was coupled into the hollow fiber through a 10-cm-long hollow capillary with an inner diameter the same as that of the measured fiber. Figure 5 shows the bending losses of an Er:YAG hollow fiber with a low-loss dip at 0.63 μm. At a constant bending radius of 30 cm, loss increases with increasing bending angle. Owing to the smoother surface of the COP layer, the COP/Ag hollow fiber showed a loss lower than that of the Ag tube. When the 1-m-long fiber was bent to 180° with the bending radius of 30 cm, the loss was about 2.2 dB. Because hollow fibers designed for CO_2 laser light need to have a thicker COP film than that of hollow fibers designed for Er:YAG laser light, the surface of that film tends to be a bit rougher and makes the loss for a red pilot beam 2-3 times as large as that of the hollow fibers designed for Er:YAG laser light. When an LD with 3mW output is used, however, the red light output from the hollow end is sufficient for a pilot beam.

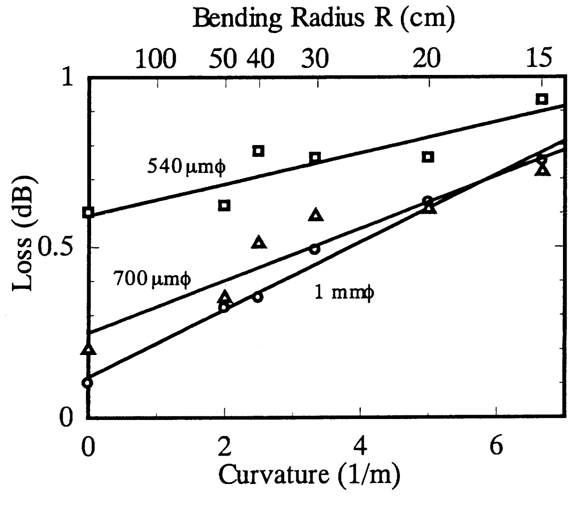


Fig. 4. Bending losses of 1-m-long COP/Ag hollow fibers designed for Er:YAG laser light and having inner diameters of (□) 540 μm, (△) 700 μm, and (○) 1 mm.

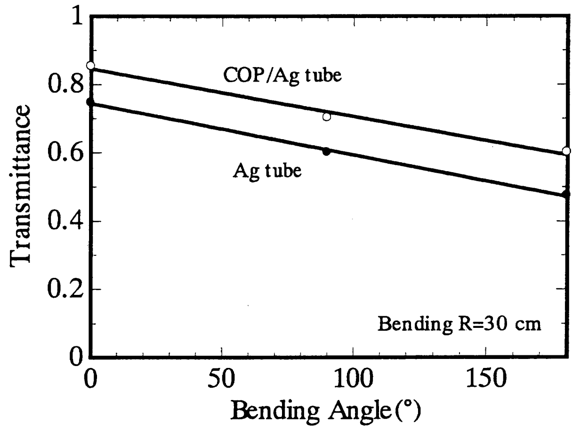


Fig. 5. Bending losses of red pilot beam for hollow fibers (700 μm bore, 1m length) designed for Er:YAG laser light. The bending radius is 30 cm.

4. Sealing caps for the hollow fibers

Output end-sealed hollow fibers were used to deliver Er:YAG laser light underwater [18]. A quartz tube was used as the base material to fabricate the sealing caps because quartz has a high transmission coefficient for Er:YAG laser light [19], is mechanically stable, and is non-toxic to human tissue. Sealing caps fabricated in our laboratory with various distal-end geometries are shown in Fig. 6. The hollow fiber used in this experiment had an inner diameter of 0.7 mm and an outer diameter of 0.85 mm. A free-running Er:YAG laser with an output pulse width of 250 μs was used as the laser light source.

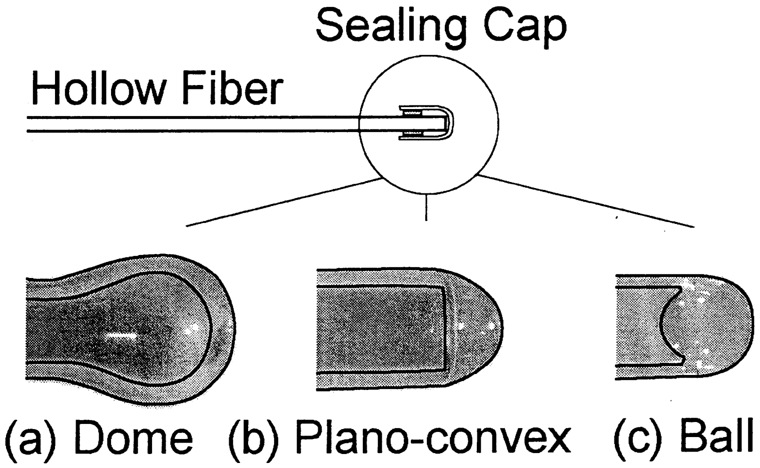


Fig. 6. Sealing caps with various output geometries.

To observe the focusing effect under actual calculus fragmentation conditions, we delivered Er:YAG laser light in a 0.9 wt% NaCl solution. The output energy from the caps was 160 mJ/pulse, and a digital camera was used to record the shape of the bubble channel induced by the laser irradiation. The dome-shaped cap (Fig. 7a) shows a slow divergence of the laser light; the plano-convex cap (Fig. 7b) has an obvious focal distance at D=1.5 mm; the ball-shaped cap (Fig. 7c) has a focusing point at exactly D=0, and the laser light diverges quickly. The channel shapes in Fig. 7 were consistent with the focusing effect measured in air by a simple burn-pattern method using heat-sensitive paper [20].

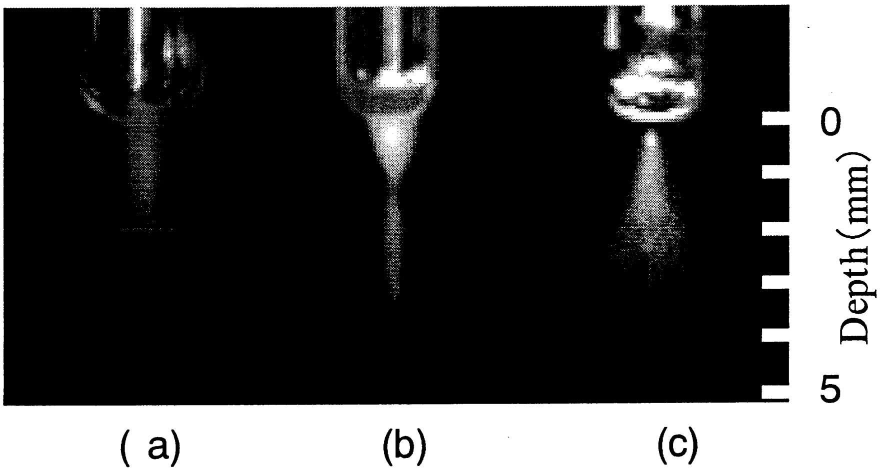
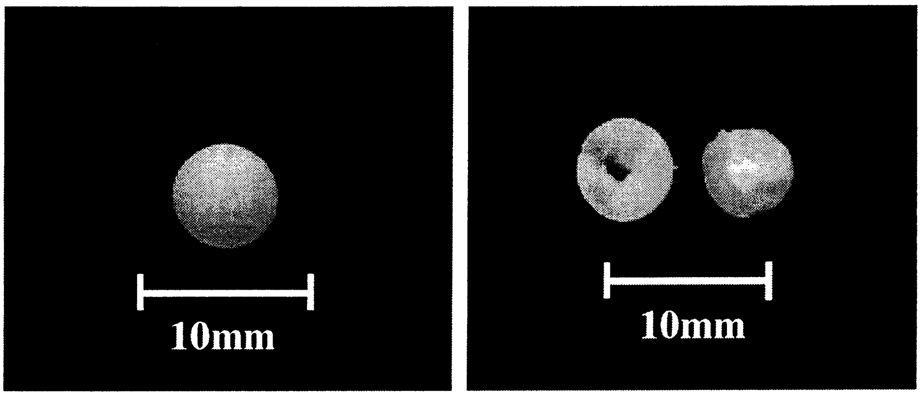


Fig. 7. Focusing effect of Er:YAG laser light in water for various caps: (a) dome-shaped, (b) plano-convex, and (c) ball-shaped.
The output energy was 160 mJ and the repetition rate was 5 Hz.

5. Calculus fragmentation by Er:YAG laser light

A hollow fiber (700 μmϕ×1.5 m) and a plano-convex cap were used to deliver Er:YAG laser light underwater [20]. In the underwater irradiation, a free-running Er:YAG laser with an output pulse width of 250 μs was used. The pulse energy was 400 mJ and the repetition rate was 10 Hz.

Figure 8 shows an activated alumina ball (6 mm in diameter) before and after 23-second irradiation with Er:YAG laser light. The ball, fixed in water during the experiment, broke into two parts in less than half a minute.



(a) (b)

Fig. 8. Activated alumina ball (a) before and (b) 23 seconds after irradiation with Er:YAG laser light (400-mJ output energy and 10-Hz repetition rate).

Figure 9 (a) shows a renal calculus consisting of 60% $MgNH_4PO_4$, 33% $Ca(H_2PO_4)_2 \cdot H_2O$ and 7% $CaCO_3$. As shown in the picture, the calculus was 20 mm long and 9 mm thick. Figure 9 (b) shows the calculus after 1 minute and 45 seconds of laser light irradiation. The calculus was broken into small parts. We had some difficulty finding the small fragments because they were scattered by the shock waves the pulsed laser light produced in saline. We think that Er:YAG laser light fragmentation is suitable for cutting relatively large calculi, which can improve the efficiency of calculus fragmentation.

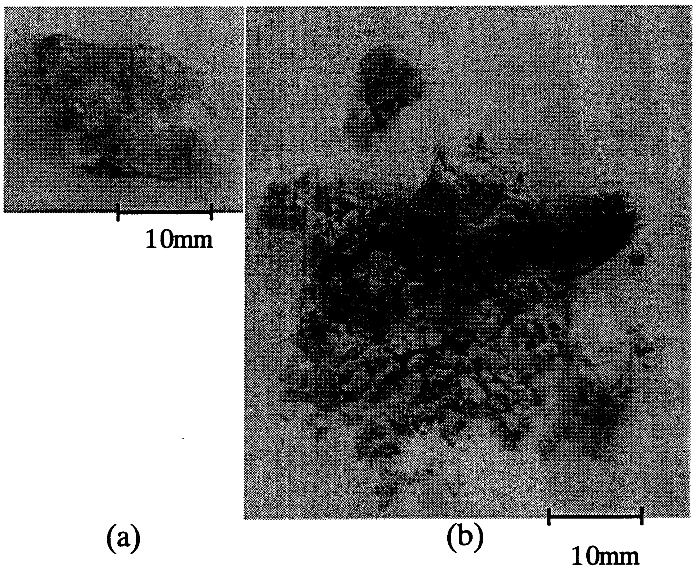


Fig. 9. Renal calculus (a) before and (b) 1 minute and 45 seconds after irradiation with Er:YAG laser light (400-mJ output energy and 10-Hz repetition rate).

6. Conclusion

COP/Ag hollow fibers with low losses at both visible and infrared wavelengths were made by using $SnCl_2$ sensitization before the silver-mirror reaction and using a THF atmosphere curing process for COP coating. Transmission losses of 0.2 dB/m for infrared laser light and 0.7 dB/m for red pilot beam were obtained. These fibers can thus deliver infrared laser light and a pilot beam with low loss at the same time.

Output sealing caps hermitically sealing the hollow end of the fiber were developed. The properties of the output laser light beam from the hollow fiber can be adjusted for various applications by using caps with various geometries. Quartz caps have been shown to have a power capability larger than 400 mJ with a repetition rate of 10 Hz in water.

Calculus fragmentation was performed *in vitro* by using an Er:YAG laser delivery system with a sealed, COP-coated hollow fiber. When a model calculus in saline and a real calculus in saline were irradiated with Er:YAG laser light, both of them broke within two minutes.

References

1. M. Miyagi and S. Kawakami, "Design theory of dielectric-coated circular metallic waveguides for infrared transmission," J. Lightwave Technol. **LT-2,** 116-126 (1984).
2. M. B. Levy and K. D. Laakman, "Flexible waveguides for CO_2 laser surgery," in Optical and Laser Technology in Medicine, R. J. Landry, D. Sliney, and R. Scott, eds., Proc. Soc. Photo-Opt. Instrum. Eng. **605,** 57-58 (1986).
3. N. Croitoru, J. Dror, and I. Gannot, "Characterization of hollow fibers for the transmission of infrared radiation," Appl. Opt. **29,** 1805-1809 (1990).
4. R. K. Nubling and J. A. Harrington, "Hollow waveguide delivery system for high-power, industrial CO_2 lasers," Appl. Opt. **35,** 372-380 (1996).
5. Y. Fink, D. J. Ripin, S. Fan, C. Chen, J. D. Joannopoulos, and E. L. Thomas, "Guiding optical light in air using an all-dielectric structure," J. Lightwave Technical. **17,** 2039-2041 (1999).
6. M. Matsuo, "Recent development of cyclic olefin polymers: polymers derived from dicycopentadience (DCPD)," High Polymers **45,** 652-656 (1996) (in Japanese).
7. H. Jelinkova, J. Sulc, P. Cerny, Y. W. Shi, Y. Mastuura, and M. Miyagi, "High-power Nd:YAG laser picosecond pulse delivery by polymer-coated silver hollow-glass waveguide," Opt. Lett. **24,** 957-959 (1999).
8. S. Sato, K. Shimizu, Y. W. Shi, and M. Miyagi, "High-power 5-μm-band CO laser and its new hollow waveguides for industrial applications," in Gas and Chemical Lasers and Intense Beam Applications, E. A. Dorko and J. L. Moler, eds., Proc. Soc. Photo-Opto. Instrum. Eng. **3268,** 47-56 (1998).
9. Y. W. Shi, Y. Wang, Y. Abe, Y. Matsuura, M. Miyagi, S. Sato, M. Taniwaki, and H. Uyama, "Cyclic olefin polymer-coated silver hollow glass waveguides for the infrared," Appl. Opt. **37,** 7758-7762 (1998).
10. A. A. Serafetinides, K. R. Rickwood, N. Anastassopoulou, Y. Wang, Y. W. Shi, and M. Miyagi, "Pulsed HF laser radiation transmission through fluorocarbon polymer-coated silver hollow glass waveguides," in Biomedical Systems and Technologies II, A. Katzir ed., Proc. Soc. Photo-Opt. Instrum. Eng. **3199,** 119-126 (1998).
11. Y. W. Shi, Y. Abe, Y. Matsuura, and M. Miyagi, "Low loss smart hollow waveguides with new polymer coating material," Opt. & Laser Technol. **31,** 135-140 (1999).
12. M. Miyagi, Y. Matsuura, and Y. Abe, "Sealing-cap for hollow fiber terminal," Japanese patent, 2000-219907 (July 21, 2000).
13. S. Mohri, T. Kasai, Y. Abe, Y. W. Shi, Y. Matsuura, and M. Miyagi, "Optical properties of end-sealed hollow fibers," Appl. Opt. **41,** 1251-1255 (2002).

14. Y. Kato, M. Osawa, and M. Miyagi, "A new method of fabricating dielectric-coated hollow waveguides based on liquid phase," 368th Electromagnetic and Optical Waves Engineering, Tohoku University, June 1993 (in Japanese).
15. Y. Wang, A. Hongo, Y. Kato, T. Shimomura, D. Miura, and M. Miyagi, "Thickness and uniformity of fluorocarbon polymer film dynamically coated inside silver hollow glass waveguides," Appl. Opt. **36,** 2886-2892 (1997).
16. Y. W. Shi, Y. Matsuura, and M. Miyagi, "Pilot beams for polymer-coated silver hollow glass fibers," in Optical Fibers and Sensors for Medical Applications, Proc. SPIE **4253**, 50-57 (2001).
17. Y. Abe, K. Iwai, R. Toyo-oka, T. Katagiri, R. Kanamori, Y. W. Shi, Y. Matsuura, M. Miyagi, J. Ohishi, and Y. Okagami, "Improvement of transmission properties of visible pilot beam for hollow fibers designed for CO_2 laser delivery," Rev. Las. Eng. **30,** 472-474 (2002)(in Japanese).
18. M. Nemec, H. Jelinkova, J. Sulc, J. Paska, M. Miyagi, Y. W. Shi, Y. Matsuura, Y. Abe, and Iwai, "The delivery of mid-infrared laser radiation by sealed waveguides and their application in ophthalmology," Fine Mechanics and Optics, **6,** 187-190 (2001) (in Czech).
19. E. D. Palik, Handbook of Optical Constants of Solids (Academic, London, 1985), 749-763.
20. K. Iwai, Y. W. Shi, K. Nito, Y. Matsuura, T. Kasai, M. Miyagi, S. Saito, Y. Arai, N. Ioritani, Y. Okagami, M. Nemec, J. Sulc, H. Jelinkova, M. Zavoral, O. Kohler, and P. Drlik, "Er:YAG laser lithotripsy by using a flexible hollow waveguide with an end-sealing cap," Appl. Opt. **42,** 2431-2435 (2003).