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DESIGN AND FABRICATION OF HIGH-PERFORMANCE INFRARED HOLLOW FIBER FOR MEDICAL LASER POWER DELIVERY

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We proposed a method to evaluate the material dispersion of the dielectric film in dielectric-coated silver hollow fiber. By taking into consideration the derived material dispersion, the wavelengths of the loss peaks and valleys in the loss spectra of the hollow fiber can be predicted more accurately. Then, we fabricated the dielectric-coated silver hollow fiber according to the parameters obtained by using the improved design method. The measured data showed good agreement with the calculated results. The loss for medical laser of Er:YAG and CO_2 was less than 0.3 dB/m. The loss for green or red pilot beams was around 5 dB/m, which is sufficiently low for the purpose of pilot beam transmission. The derived material dispersion plays an important role in the design and fabrication of the hollow fiber for multiwavelength delivery.

Keywords: Waveguide; medical laser; calculus fragmentation; dielectric film.

1. Introduction

Dielectric-coated metallic hollow fiber has found applications for delivering infrared laser light in medical and industrial fields.[1–4] Theoretical analysis has proven that hollow fiber has the potentiality for delivering multiwavelength laser light with low-loss property. One of the useful applications of the potentiality is the simultaneous transmission of infrared and visible laser light, which can be used as the pilot beam for the invisible infrared laser light.

It is important to accurately locate wavelengths of low-loss windows when designing a hollow fiber for multiwavelength transmission. The position of the low-loss windows depends greatly upon the dielectric's material dispersion that shows refractive indices at different wavelengths. In the design of hollow fiber,[5] it is necessary to take material dispersion into consideration. We have used the material dispersion properties in handbooks or published literatures[6–9] in the design of the hollow fiber, but theoretical results did not agree well with measured data.

We propose a method[10] to evaluate the material dispersion of the dielectric film by using the Cauchy's formulas that characterize the dispersion property. The Cauchy's formulas were obtained for commonly used dielectric materials by using the measured data of loss spectra of the hollow fibers. The wavelengths of the loss peaks and valleys in the loss spectra can be predicted more accurately when taking material dispersion into consideration. Hollow fiber fabricated according to the designed parameters obtained low-loss properties simultaneously at several wavelengths. Multilaser light delivery for infrared lasers or visible pilot beams is possible through the high-performance hollow fiber.

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2. Materials and Methods

2.1. *Background and objective*

In the fabrication of the dielectric-coated silver hollow fiber, silver reaction method and liquid-phase coating method are normally used to form silver and dielectric layers on the inner wall of a supporting tube. The supporting tube can be capillaries with smooth inner surface such as glass capillary, plastic tubing, and stainless steel tube. There exists an optimum dielectric film thickness[11] for a target wavelength λ to obtain low loss:

$$d_{opt} = \frac{\lambda}{2\pi(n_d^2-1)^{1/2}}\left\{\tan^{-1}\left[\frac{n_d}{\left(n_d^2-1\right)^{1/4}}\right]+s\pi\right\},\quad s=0,1,\ldots \tag{1}$$

where n_d is the refractive index of the dielectric layer. Normally we take $s = 0$ in the fabrication because a thinner film is easier to form in the liquid-phase coating method and also, a thinner film has a smoother surface that causes less additional loss.

Figure 1 is the typical loss spectra of a polymer-coated silver hollow fiber optimized for Er:YAG laser light at the wavelength of 2.94 μm. Figure 1(a) shows the loss spectrum in the visible and near infrared regions (VIS-NIR). Figure 1(b) shows the loss spectrum in mid-infrared region (MIR). It can be seen in Fig. 1(b) that low-loss property in the wavelength of 3 μm was obtained. We note that in Fig. 1(a), low-loss property in the wavelength of 0.53 μm for a green pilot laser beam was also obtained. The fiber can be used to simultaneously deliver green and Er:YAG laser light.

In the film thickness design, it is found that low-loss valleys in the loss spectrum do not agree well with the measured data. As shown in Fig. 2, the position of loss valley for calculated spectrum 3 is quite different from the measured data. We believe that this is mainly caused by the material dispersion of dielectric film, because we did not consider material dispersion in calculated spectrum 3. In the calculated loss spectrum 2, we take material dispersion into consideration. And the dispersion data is taken from handbook or published literature. The result was obviously not satisfactory. The disagreement should be caused by the special film coating method. Material dispersion data in handbooks often come from the measurement of bulk materials, while in the fabrication of hollow fiber the inner film is coated by using special method.

In this paper, we proposed a method to evaluate dispersion property by using measured loss spectra of hollow fibers with various film thicknesses. Cauchy's formulas for several commonly used materials were obtained. Because Cauchy's formulas were derived from measured data, it should correctly characterize the dispersion property of the coated film.

2.2. *Materials and methods*

Loss spectra of hollow fiber with various dielectric film thicknesses were needed in the evaluation of material dispersion. To prepare the samples, we

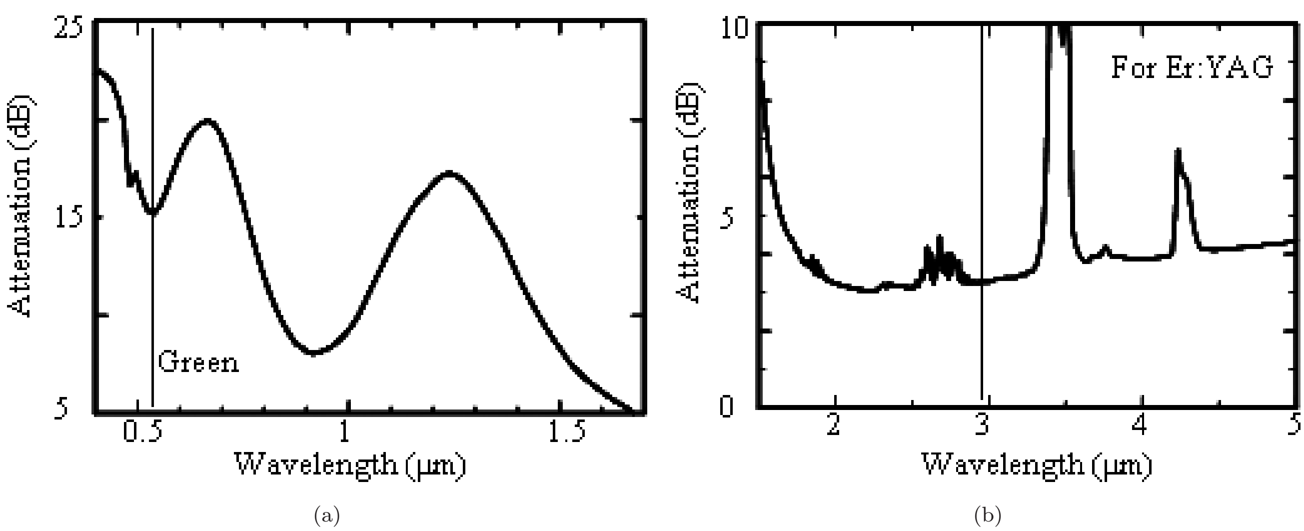

Fig. 1. Loss spectra of a polymer-coated silver hollow fiber optimized for Er:YAG laser light in VIS-NIR regions (a) and in MIR region (b).

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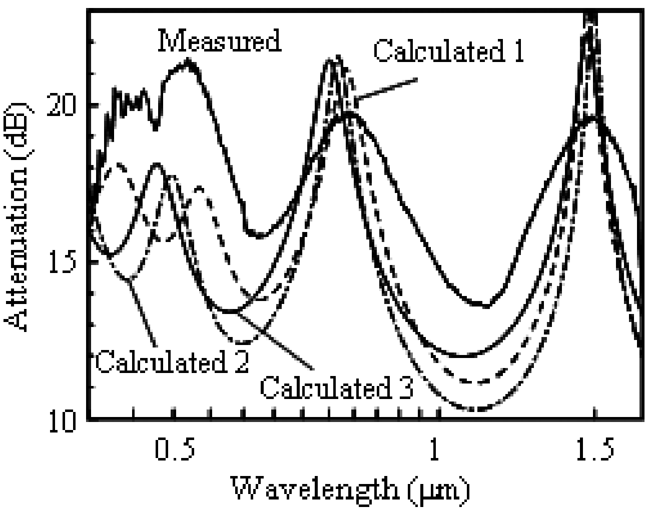

Fig. 2. Measured and calculated loss spectra for a dielectric-coated silver hollow fiber.

used the chemical deposition method[12] to plate the silver layer on the inner surface of a glass capillary. Then, the dielectric layer was coated upon the silver layer. The dielectric layer with different film thicknesses could be formed by modifying the concentration of the coating solution or the flowing speed in the fabrication process.[13] For all of the hollow fiber samples made for the evaluation, the bore diameter is 0.7 mm and the length is around 25 cm.

Then, the prepared samples were measured by using the system schematically shown in Fig. 3. An incoherent white light was coupled into the hollow fiber through a GI fiber with 600 μm core diameter. The light at the output end was received by the spectrum analyzer (Advantest Q8344A). Loss spectra of the hollow fiber, with typical result as shown in Fig. 1(a), were obtained by comparing the output light with the input light as the background.

The peaks at various wavelengths contain information of refractive index for the dielectric film. We use Cauchy's formula[14]

$$n(\lambda) = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4} \qquad (2)$$

to approximately evaluate the dispersion. In order to calculate the constants A, B, and C in the Cauchy's formula, we need measured loss spectra of hollow fiber with different film thicknesses, which can provide a number of data $n_i(\lambda_i)$.

Due to the difference of film thicknesses among samples, loss peaks and valleys appeared at various wavelengths in their loss spectra. For each loss spectrum, we define λ_m as the mth wavelength from longer to shorter wavelength at which loss peak appears. Also, $n_i(\lambda_m)$ is defined as the refractive index at the wavelength of λ_m in the ith loss spectrum. The order of the loss spectra was arranged randomly. Here, we briefly describe the method for calculating the constants A, B, and C.

(1) $n_1(\lambda_1)$, the refractive index of the dielectric at the wavelength of λ_1 in the first loss spectrum, is assumed to be 1.53 as the initial value in the calculation circles.
(2) Make λ_1 in the theoretical loss spectrum agree with the λ_1 in the measured loss spectrum by adjusting the film thickness, and we get a film thickness d.
(3) According to film thickness d in step (2), we get the refractive indices of dielectric at wavelengths of all the peaks in this measured loss spectrum, $n_1(\lambda_m)$.
(4) Repeat steps (1) to (3) for all the measured loss spectra. We get a number of refractive index–wavelength data $n_i(\lambda_m)$ for the dielectric material ($i = 1, 2, 3, \ldots, m = 1, 2, 3, \ldots$).
(5) Use Cauchy's formula to fit the data of $n_1(\lambda_m)$. We get an empirical formula of material dispersion for dielectric film.
(6) Repeat steps (1) to (5) and new formulas are obtained in every cycle. Stop the process when the difference between film thicknesses d in two continuous circles is smaller than 1% for all the measured loss spectra.

Finally, an empirical formula of material dispersion for the dielectric film in the hollow fiber is derived.

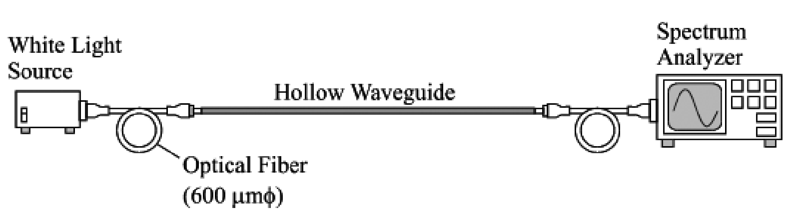

Fig. 3. Schematic set-up of the system for loss spectrum measurement.

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3. Results

3.1. *Calculation results*

We have applied this method to polymer Arton[15] in the hollow fiber. For polymer Arton, we derived the Cauchy's formula as

$$n(\lambda) = 1.52743 + \frac{0.01855}{\lambda^2} + \frac{0.00028}{\lambda^4} \qquad (3)$$

Figure 4 shows the measured loss spectra of Arton-coated silver (Arton/Ag) hollow fiber. The fiber was optimized for low-loss transmission of CO_2 laser light. It obtains low-loss property for red pilot beam at the same time. The fibers are 1 m long and 0.7 mm in diameter. The theoretical loss spectra taking material dispersion in consideration from the empirical formulas are also included. The loss valleys between calculated and measured data agreed well. This shows the effectiveness of the derived material dispersion property on predicting the positions of low-loss window accurately for high-performance hollow fiber at multiwavelength delivery.

In Fig. 2, we show the loss spectra for AgI film. By applying the above-mentioned method, the dispersion property of the AgI film is obtained as

$$n(\lambda) = 2.0216 + \frac{0.0878}{\lambda^2} - \frac{0.0024}{\lambda^4}. \qquad (4)$$

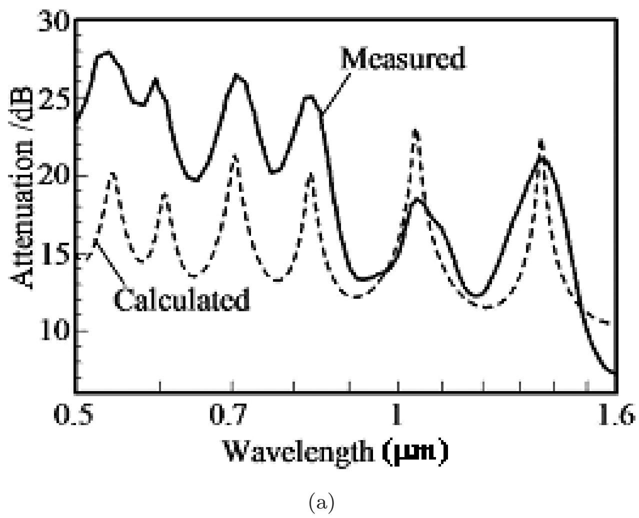

Fig. 4. Loss spectra of polymer-coated silver hollow fiber optimized for CO_2 laser light in VIS-NIR regions (a) and in mid-IR region (b).

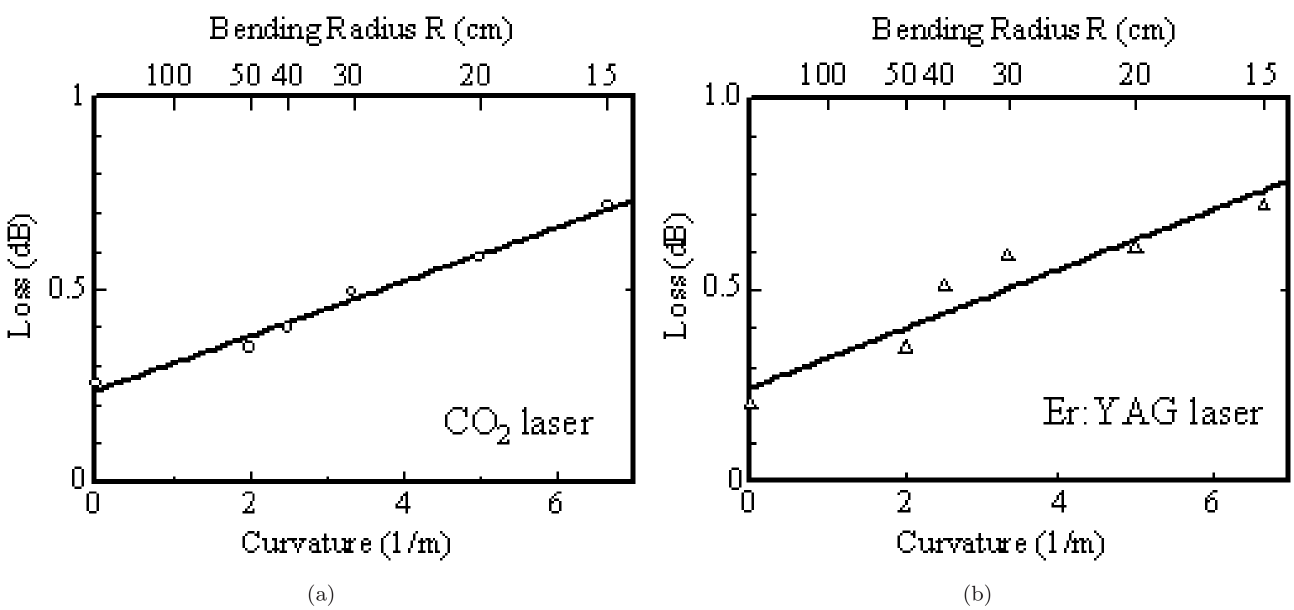

Fig. 5. Bending loss property for hollow fiber of 0.7 mm bore size for CO_2 laser (a) and Er:YAG laser (b).

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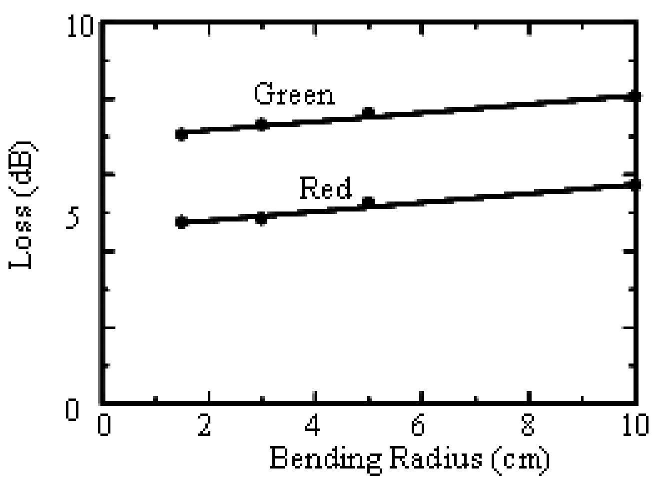
The calculated 1 plot in Fig. 2 is the result using above formula. It can be seen that calculated 1 agrees well with the measured data, which means that the formula correctly characterizes the dispersion property for the AgI film in the hollow fiber.

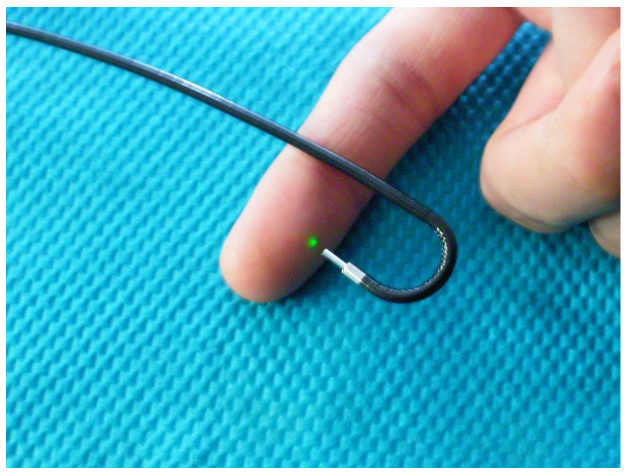
3.2. *Laser power delivery*

Figure 5 shows the bending loss property for hollow fiber of 0.7 mm bore size and 1 m length. Figure 5(a) and 5(b) are properties for CO_2 and Er:YAG lasers, respectively. The transmission loss was smaller than 0.25 dB/m (transmission efficiency 94%) in straight configuration. When the fiber was bent with a radius of 15 cm to the angle of 270°, the transmittance was around 85%.

Figure 6(a) shows the bending loss property for red and green pilot laser beams. The loss was around 6 dB/m, which was larger than that of the infrared lasers. However, a pilot was used for aiming purpose. It is sufficient for the visible laser beam point, provided it can be seen clearly in a bright room. Figure 6(b) shows the output green laser beam transmitting through a hollow fiber installed in a medical endoscope.



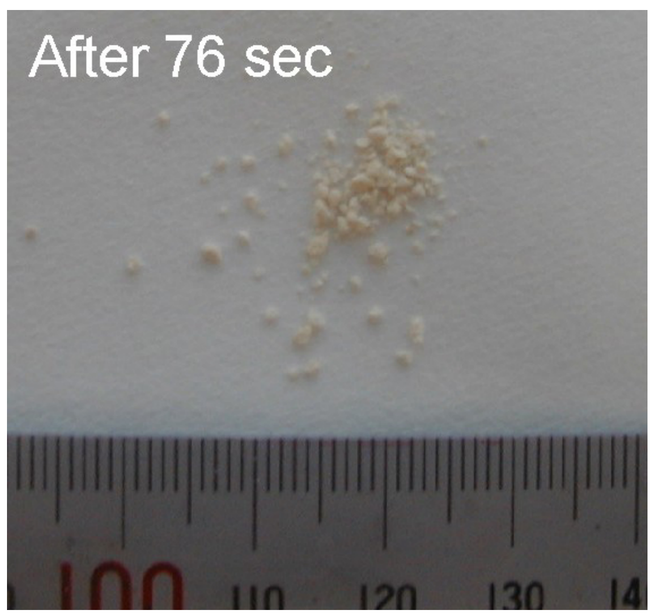
(a)



(b)

Fig. 6. Transmission property of pilot beam for the hollow fiber.

(a)



(b)

Fig. 7. Calculus fragmentation using Er:YAG laser light through the hollow fiber.

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3.3. *Calculus fragmentation*

Calculus fragmentation experiments were made by using Er:YAG laser light with an energy density of 60 J/cm^2. For the calculus (MAP + CaP + $CaCO_3$), it took 76 s to break into small pieces, as shown in Fig. 7(b).

4. Conclusions

Material dispersion plays an important role in the design of high-performance dielectric-coated metal hollow fiber. We proposed a method to evaluate the material dispersion of dielectric film in hollow fiber. The empirical formulas of dielectric film materials were derived according to the Cauchy's formula of material dispersion. By taking into consideration the material dispersion in these formulas, the wavelengths of the low-loss valleys in the VIS-NIR regions can be predicted more accurately in the structural design of the hollow fiber. Simultaneous low-loss delivery for infrared and visible laser light was possible by using improved design method. Primary experiments showed high efficiency for the Er:YAG laser light in fragmenting calculus.

Acknowledgments

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