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Abstract: Hollow glass fibers for delivery of mid-infrared lasers are drawn from a glass-tube preform to produce a long and flexible hollow fiber at low cost. To utilize the interference effect of the thin glass wall, the wall thickness is controlled by the drawing speed. A Pyrex-glass hollow fiber with an inner diameter of 280 μm and a wall thickness of 9.92 μm shows a low loss at 2.94 μm of the Er:YAG laser wavelength when coated with a silver film on the outer surface.

OCIS codes: (060.2390) Fiber Optics; infrared, (140.3070) Infrared and far-infrared lasers

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1. Introduction

Hollow fibers have attracted a lot of interest as flexible delivery media of high-powered infrared lasers used in medical and industrial fields. Some hollow fibers are already employed in laser systems due to the flexibility, ruggedness, high power capability, and low losses. These fibers are usually fabricated by depositing a metal and dielectric films on the inner surface of pre-drawn glass or plastic tubing [1-4]. Therefore, the manufacturing cost tends to be high due to the elaborate processes and the lengths of produced fibers are usually limited to 2-3 m.

Hidaka, *et al* proposed a infrared glass-hollow waveguide utilizing attenuated total reflection of some oxide glasses resulted from the anomalous dispersion of glass materials at a specific wavelength [5,6]. Although the target wavelength can be shifted by mixing some different glasses, the wavelength span is limited. Recently, a group of MIT reported that a

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multilayered hollow fiber was drawn from a glass preform using a drawing tower for fiber optics [7]. For fabrication of mid-infrared fibers, however, it is difficult to find a pair of glass materials which have large difference in refractive indices and are highly transparent at wavelengths longer than 3 µm.

In this paper, we propose a hollow glass fiber for mid-infrared lasers which are useful in variety of medical and industrial applications. The fiber is drawn from a glass preform, and thus, a long fiber is easily produce at low cost. A tubing with thin glass wall forms the fiber and the wall thickness is fine-adjusted for utilizing the interference effect to obtain a low transmission loss. A metal coating can be applied on the glass tube for further loss reduction and to optically shield the transmitted beam from external environment.

2. Design

The concept of the hollow fiber presented here is based on the dielectric tube-leaky waveguide [8] and the dielectric-coated metal hollow waveguide [9] proposed by Miyagi, *et al*. In the tube-leaky waveguide which is formed by a dielectric tube, the transmission loss of the HE modes are minimized when the optical thickness of the tube's wall is $(2m+1)\lambda/4$ ($m=0,1,2\ldots$). For reduction of the transmission loss of the tube-leaky waveguide, it is effective to coat the outer surface of the glass tube with a metal film and this type of fiber is called dielectric-coated metal hollow waveguide. Since the phase is shifted π between TE and TM waves at the dielectric-metal boundary, the optimum thickness of the dielectric wall for the HE modes is smaller than $(2m+1)\lambda/4$ ($m=0,1,2\ldots$) [9],

$$d=\frac{1}{\sqrt{n^2-1}}\cdot\frac{\lambda}{2}\left(m+\frac{1}{\pi}\tan^{-1}\frac{n}{(n^2-1)^{1/4}}\right)\qquad(m=0,1,2,\ldots)\qquad(1)$$

where n is the refractive index of the dielectric tube and d is the wall thickness.

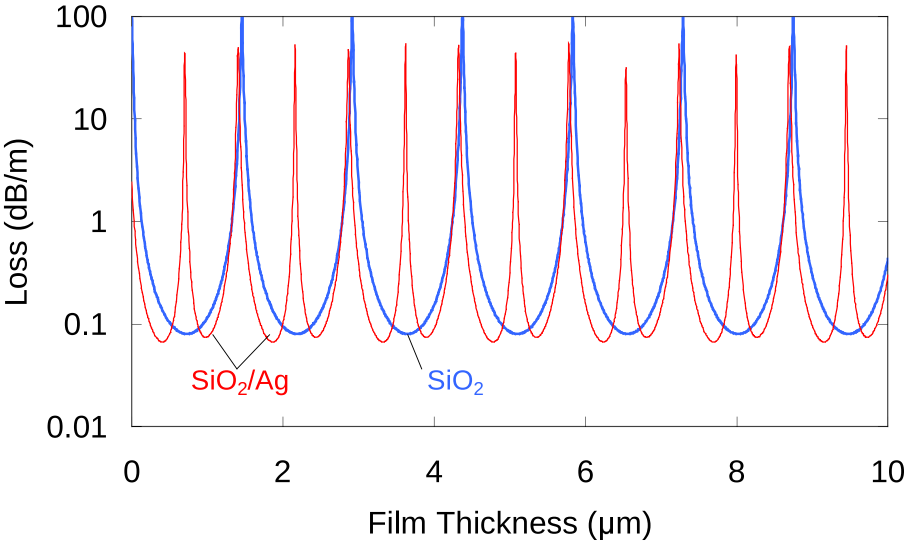

Fig. 1. Theoretical losses of the HE_{11} mode in the SiO_2 tube waveguide and SiO_2/Ag waveguide with an inner diameter of 280 µm.

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Figure 1 shows the theoretical losses of the HE_{11} mode in the tube-leaky and the dielectric/metal waveguides as a function of the dielectric wall thickness. We assume a tube of SiO_2 glass for the tube leaky and a SiO_2-tube covered with a silver film for the dielectric/metal waveguides. Parameters used in the calculation are the wavelength of 2.94 µm (assuming Er:YAG laser light), the inner diameter of 280 µm, and refractive indices of 1.42 for SiO_2 and 1.26-*j*17.8 for Ag [10]. It is shown that the low loss regions appear at the interval of $\lambda/2$- and $\lambda/4$-optical thickness for the tube leaky and the dielectric/metal waveguides, respectively. Therefore, the dielectric wall can be thick enough to support the tube shape when the absorption coefficient of the dielectric material is very small. The allowable variation in the thickness to keep the loss lower than 0.1 dB/m is around 0.3 µm in the SiO_2/Ag waveguide. In actual use, the hollow fibers show much higher losses than those in Fig. 1 because a large number of higher-order modes are excited by a laser beam that does not have a perfect HE_{11}-mode profile. However, it has been shown that the attenuation coefficients of higher-order modes are proportional to those of the HE_{11} mode [9]. Thus, one can estimate the transmission losses during actual launching conditions based on the results in Fig. 1.

3. Fabrication

Tube-leaky fibers are fabricated by prototype, capillary drawing machine using a Pyrex glass as a dielectric material. The preform which is 50 mm in diameter and with a wall thickness of 1.6 mm is drawn at the temperature of 900 °C. To establish a steady state of fiber drawing, the preform is slowly shifted downward (around 20 µm/min) and the fiber drawing speed is around 50 cm/min. In this condition, the ratio of the inner diameter to the outer of the drawn fiber is the same as the preform and thus, the wall thickness of the fiber are precisely controlled by choosing a proper drawing speed. In this trial, the inner diameter of the drawn tube is around 280 µm and the target wall thickness is 9.73 µm which gives the minimum loss to the SiO_2/Ag waveguide as shown in Fig. 1. As far as the drawing speed is well controlled, the fibers with aimed thickness are drawn in high repeatability and the fluctuation in the wall thickness is less than 3% for the 10-m long fiber.

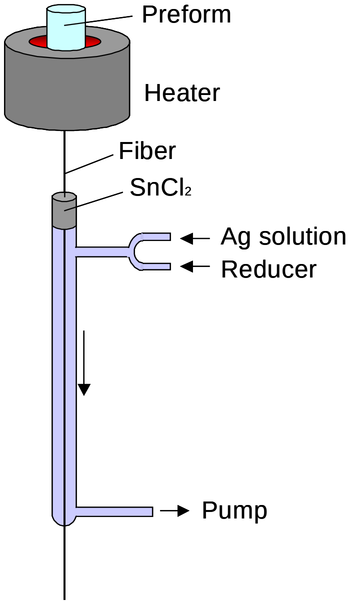

Fig. 2. Schematic view of silver coating setup.

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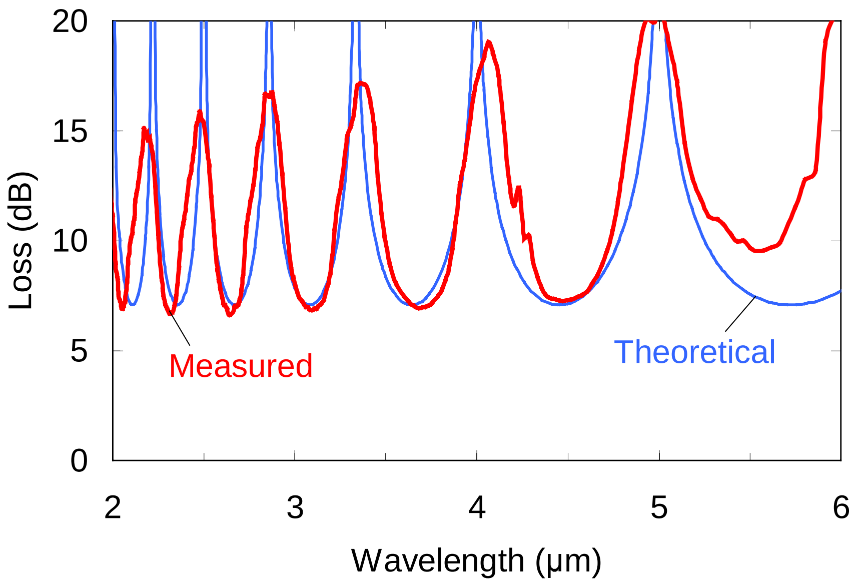

Fig. 3. Measured and theoretical loss spectra of SiO_2-tube-leaky fiber with an inner diameter of 280 μm and a wall thickness of 9.92 μm. The fiber is excited by an incoherent beam with a divergence angle of 10° at FWHM.

To reduce the transmission loss, a silver coating is applied on the drawn glass tube by using a silver plating setup fixed directly below the electric furnace as shown in Fig. 2. For rapid deposition of silver, the fiber is firstly passed through a wet sponge which is soaked with $SnCl_2$ solution for sensitizing of glass surface. The fiber is then coated with a silver film in a glass vessel filled with mixture of silver nitrate and reducing solutions. The fiber drawing speed is around 0.5 m/min and the fiber longer than 20 m is easily drawn and spooled.

Since the thickness of glass tube is smaller than 10 μm, the mechanical stability of the drawn fiber can be low sometimes. We found that this is mainly because of small cracks on the drawn fiber and that the transmission losses of the fiber with cracks are higher than those without cracks due to scattering. However, thorough cleaning of the preform and keeping the furnace away from dust drastically reduce the number of cracks. In our experimental setup, the fibers drawn from the cleaned preform in the dust-free condition show sufficient mechanical strength and the minimum bending radius of is around 5 cm. Since the thickness of the outer silver coating is as thin as 0.2 μm, it does not act as a protective coating and the fibers can be crushed by squeezing with fingers. Thus, a hermetic, protective coating of thick metal or hard plastic is necessary for actual uses of the fiber.

4. Results and discussion

We measured transmission spectra of the fibers in mid-infrared wavelengths by using a Fourier-transform infrared spectrometer. The fibers are excited by an incoherent beam with a divergence angle of 10° at FWHM which is much larger than the angle of the lowest order, HE_{11} mode (less than 0.5°). This results in higher transmission losses than those in Fig. 1 because a large numer of high order modes are excited.

Figure 3 shows the measured loss spectrum of the tube-leaky waveguide with an inner diameter of 280 μm and a length of 15 cm. A theoretical spectrum whose dielectric thickness was chosen to fit to the measured spectrum is also shown in Fig. 3 and the thickness is estimated

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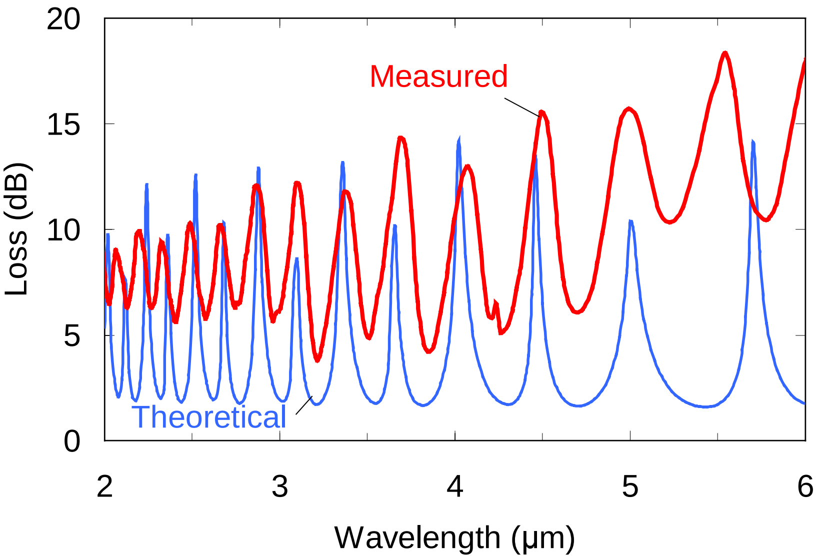

Fig. 4. Measured and theoretical loss spectra of SiO_2-hollow fiber with a silver cover film. The inner diameter is 280 μm and the wall thickness of SiO_2 is 9.92 μm. The fiber is excited by an incoherent beam with a divergence angle of 10° at FWHM.

as 9.92 μm. It is shown that the interference peaks of the measured spectrum coincide well with the theoretical ones and that losses also show good agreement. Therefore, we found that the wall thickness is uniform and close to the target thickness of 9.73 μm.

Figure 4 shows measured and theoretical spectra of a SiO_2-coated Ag waveguide with the same dimensions as the tube-leaky guide in Fig. 3. As predicted from Fig. 1, additional peaks appear between those of the tube-leaky waveguide. Although the location of the interference peaks agree well, the losses of the measured spectrum are higher than the theory. This is mainly due to absorption slightly existed in the Pyrex glass. Our theoretical evaluation shows that a calculated spectrum fits well to the measured when assuming that imaginary part of the complex refractive index of Pyrex glass is 0.001.

5. Conclusion

Hollow fibers for delivery of infrared laser light are fabricated by using a glass drawing technique to produce a long and flexible fiber at low cost. When the wall thickness of the glass tube is properly designed and controlled, the fiber shows low loss property at a target wavelength region. When the fiber is coated with a silver film, it shows lower loss because transmitted light is well confined in the air-core region. Since the metal layer is not thick enough for reinforcement of the fiber, a thick and firm protective jacket is necessary for actual use of the fiber. For further low loss, it is effective to use a glass with a lower absorption coefficient such as silica although much higher temperature is necessary for the furnace. Also highly clean environment is necessary to remove the defect on the glass and this will result in high mechanical strength of the fiber as well as lower losses. By choosing a glass material, such as chalcogenide glasses, which is transparent at longer wavelengths, the fiber is applied to any wavelength in the infrared

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