Hollow fiber using silver-clad stainless steel pipe with inner dielectric layer for CO_2 laser light transmission

Akihito Hongo[1], Hiroaki Takamiya[1], and Tadashi Koike[2]

[1] *Photonics Research and Development Center, Research and Development Group, Hitachi Cable, Ltd., Hitachi-shi, Ibaraki-ken, 319-1414, Japan*

[2] *Engineering Department, High Performance Materials and Component Products Group, Hitachi Cable, Ltd., Tuchiura-shi, Ibaraki-ken, 300-0026, Japan*

We have developed a rigid hollow fiber composed of a silver-clad stainless steel pipe. The inside wall of the pipe was polished to a mirror-smooth state, and after that a cyclic olefin polymer (COP) as a transparent dielectric material was coated on the inside of the silver layer. Transmission of CO_2 laser light through the hollow fiber of 20-cm length with a 0.75-mm inside diameter was 95% under straight condition, and more than 75% under the condition of a 90° bend with a 4-cm bending radius. This metallic hollow fiber is not very long or flexible, but it has great mechanical strength. For this reason, this sturdy metallic hollow fiber can be used for a laser probe mounted at the tip of a long optical transmission line.

OCIS codes: 160.4670, 190.4400, 210.4810, 220.4000, 230.4000.

Some high-power laser sources operate in the mid-infrared wavelength, for example the Er:YAG laser, CO laser, and CO_2 laser. These lasers are useful for dental or medical treatment as well as material processing. Above approximately 2 μm in wavelength, conventional silica-based optical fibers used for communications cannot be employed for the laser light delivery systems because of the intrinsic infrared absorption of silica material. For infrared light transmission, various types of optical fibers have been studied thus far, for example, fluoride glass or single-crystal sapphire fibers for Er:YAG lasers, chalcogenide glass fibers for CO lasers, and polycrystalline silver halide fibers for CO_2 lasers[1]. In general, however, such solid core infrared fibers have mechanical properties inferior to silica fibers, that is, they are more fragile. In addition, some infrared fibers have unfavorable properties. Fluoride glass is hygroscopic, and surface crystallization may occur due to moisture. Most chalcogenide glass contains toxic materials such as arsenic and selenium. Polycrystalline silver halide is photosensitive, i.e., exposuring to visible or ultraviolet (UV) radiation creates colloidal silver, and it is corrosive to many metals with the exceptions of titanium and gold.

As an alternative to such solid-core fibers, we developed a flexible hollow fiber constructed of a glass capillary, a metal layer formed on the inside wall of the glass capillary, a dielectric layer formed on the metal layer, and a hollow region. The dielectric layer is transparent in the wavelength band of light to be propagated, while the metal layer has large optical absorption. A cyclic olefin polymer (COP) was used as the transparent dielectric material, and silver was used as the metal material[2]. Light propagating through the hollow fiber is repeatedly reflected by the boundary between the hollow region and the dielectric layer and the boundary between the dielectric layer and the metal layer. Most light energy propagates in the air region. The glass capillary is a base material for holding the mechanical strength of the hollow fiber. This type of the hollow fiber has been proven to have excellent characteristics for transmission of high power infrared laser light, and it has already been employed in practical laser equipment systems for dental applications.

Now, instead of using the glass capillary, we have developed a rigid-type hollow fiber that is composed of a silver-clad stainless steel pipe as the base material. This metallic hollow fiber is not very long and flexible, but it has great mechanical strength and high thermal conductivity compared with the glass capillary fiber. This sturdy metallic hollow fiber will be useful for a laser probe mounted at the tip of the flexible long fiber to transmit the laser light.

Figure 1 presents the structure of the hollow fiber using a silver-clad stainless steel pipe with inner COP layer. It was integrally formed as a metal pipe made of a silver-clad layer and a stainless steel layer by extruding a cylindrical silver pipe arranged inside to a stainless steel pipe arranged outside. We made the silver-clad stainless steel pipe with inner and outer diameters of 0.75 and 1.2 mm, respectively. The inside wall of the silver-clad layer was polished to a mirror-smooth state with a mechanochemical process. After that the COP layer was coated onto the polished silver layer with thickness designed according to the wavelength of the propagating light. The hollow fiber with the silver-clad stainless steel pipe is mechanically strong and rigid. Therefore, it can be fixed under a condition of small bending without

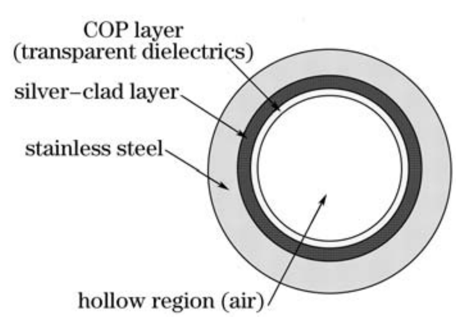

Fig. 1. Structure of rigid hollow fiber.

breaking. The inner silver-clad layer pressure-bonded onto the stainless steel pipe is not likely to be peeled off the stainless steel layer used as the base material of the hollow fiber. Figure 2 is a photograph of the bent rigid hollow fiber with a fiber-optic cable (FC) connector.

Optimizing the thickness of COP layer enhances reflection from the inner wall of the hollow fiber. Figure 3 shows the theoretical transmission loss of the lowest HE11 mode as a function of inner COP layer thickness when the hollow fiber is used in CO_2 laser light transmission. Here the fiber inner diameter is 0.75 mm, and the refractive index of COP is 1.53, the complex refractive index of silver is $13.5 - i75.3$ at 10.6 μm wavelength[3]. The dotted line indicates the transmission loss of a silver hollow fiber without the COP layer. The transmission loss changes periodically according to the inner COP thickness. Theoretically, the optimum thickness of the COP layer is 1.37 μm for CO_2 laser light transmission. Practically, higher order modes with higher transmission loss also propagate through the hollow fiber. However, the optimum thickness of the inner dielectric layer that gives minimum transmission loss is independent of the propagating HE_{pq} modes as well as the fiber diameter.

To successfully fabricate a hollow fiber with low transmission loss, the inner surface of the hollow fiber is very important. It should have an extremely smooth surface. Using the measurement setup shown in Fig. 4, we evaluated the roughness of the inner surface of silver hollow fibers using three different methods. Figure 5 shows the loss spectra in short wavelength of each kind of silver hollow fiber, each of which was 40 cm long. Figure 5(a) describes the transmission loss of a hollow fiber that is a polished silver-clad stainless steel pipe. The hollow fibers described by Figs. 5(b) and (c) are, respectively, a silica glass capillary and a polished stainless steel pipe.

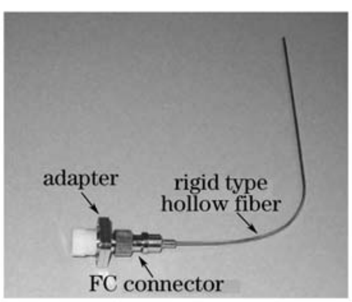

Fig. 2. Photograph of bent rigid fiber fabricated of silver-clad stainless steel pipe.

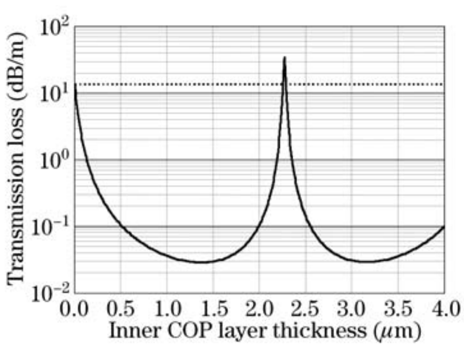

Fig. 3. Theoretical transmission loss of lowest HE_{11} mode as a function of inner COP layer thickness.

For the latter two (Figs. 5(b) and (c)), the silver layer was formed on the base material of each by plating. As shown in Fig. 5(a), the transmission loss of the polished silver-clad stainless steel pipe is approximately on the same level as the silver-plated glass capillary in Fig. 5(b). While the silver-plated polished stainless steel pipe of Fig. 5(c) has a spectrum in which loss increases in a short wavelength band. This means the inner roughness of the silver-plated polished stainless steel pipe of Fig. 5(c) is larger than the other two pipes (Figs. 5(a) and (b)). For this reason, we used the polished silver-clad stainless steel pipe as the sturdy base material for making the COP-coated silver hollow fiber, rather than the silver-plated polished stainless steel pipe.

Figure 6 shows the transmissions of CO_2 laser light through hollow fibers when using the silver-clad stainless steel pipe with the inner COP layer of a thickness

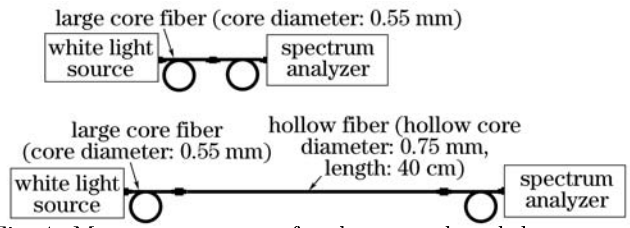

Fig. 4. Measurement setup for short wavelength loss spectra of hollow fibers with the upper as a reference.

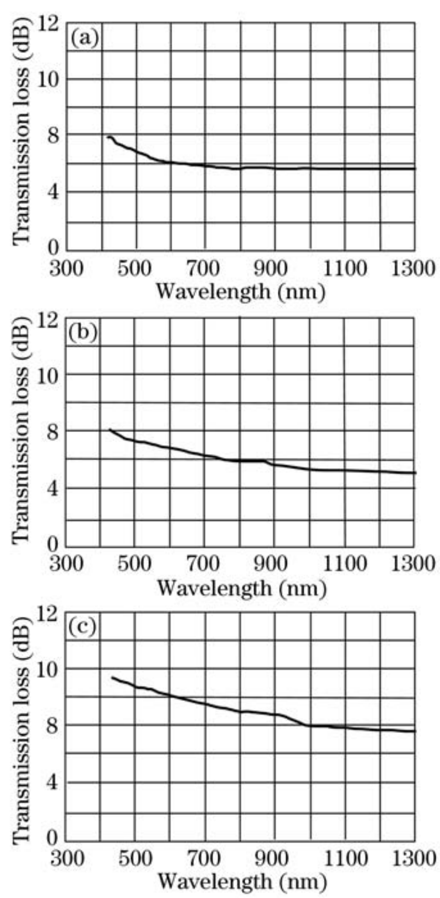

Fig. 5. Loss spectra of silver hollow fibers made using three different methods. (a) Polished silver-clad stainless steel pipe; (b) silver-plated glass capillary; and (c) silver-plated polished strainless steel pipe.

optimized for CO_2 laser light transmission as a function of the fiber length. For comparison, the transmissions through silver hollow fibers without COP and stainless steel hollow fibers without COP are also shown in Fig. 6. All the hollow fibers have 0.75-mm inside diameters, and we measured the transmissions of straight fibers. The input CO_2 laser power was 1.5 W. To efficiently excite the lower order modes that have lower transmission losses, the CO_2 laser beam was launched into the hollow fibers at the position of the beam waist after an incident lens. The transmission of CO_2 laser light was around 95% through the COP-coated silver hollow fiber of 20-cm length. The hollow fiber can be fixed in a bend as shown in Fig.2.

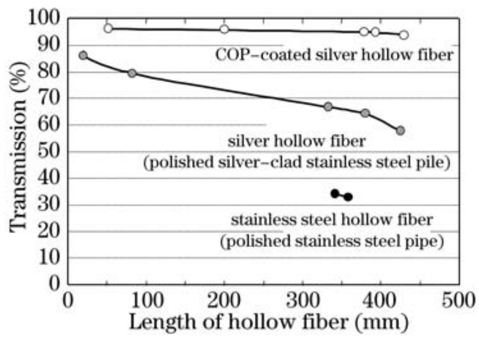

Fig. 6. Transmissions of CO_2 laser light through COP-coated silver hollow fiber, silver hollow fiber, and stainless steel hollow fiber as a function of the length of hollow fiber.

Under the condition of 90° bending with 4-cm bending radius through a 20-cm-long hollow fiber, the transmission of CO_2 laser light was 75% when the polarization of the incident CO_2 laser light was parallel to the plane of curvature, and 78% when the polarization was perpendicular to the plane of curvature.

We fabricated hollow fibers of a polished silver-clad stainless steel pipe with an inner COP layer for CO_2 laser light transmission. By adjusting the thickness of the COP layer, the hollow fiber can be used to transmit other infrared laser light such as an Er:YAG laser light. The hollow fiber fabricated with metallic pipe as the base material is mechanically strong, not plastically deformed by external pressure and impact, and does not break even under small radius bending. For these reasons, this rigid-type metallic hollow fiber is useful for a laser probe mounted at the tip of a flexible long fiber to transmit the infrared laser light.

A. Hongo's e-mail address is hongo.akihito@hitachi-cable.co.jp.

References

1. J. A. Harrington, *Infrared Fibers and Their Applications* (SPIE Press, Bellingham, WA 2004).
2. M. Miyagi and A. Hongo, "Hollow waveguide and method of making same" US patent 5995696 (1999).
3. E. D. Palik, (ed.) *Handbook of optical constants* (Academic, Orlando, 1985).