Flexible terahertz fiber optics with low bend-induced losses

Takahiro Ito and Yuji Matsuura

Department of Electrical Communications, Tohoku University, 6-6-05 Aoba, Aramaki, Sendai 980-8579, Japan

Mitsunobu Miyagi

Sendai National College of Technology, 4-16-1 Ayashi-Chuo, Sendai 989-3128, Japan

Hiroaki Minamide

Photodynamics Research Centre, RIKEN, 19-1399 Koeji-Nagamachi, Sendai 982-0837, Japan

Hiromasa Ito

Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Sendai 980-8577, Japan

Received November 10, 2006; revised December 14, 2006; accepted December 29, 2006; posted January 16, 2007 (Doc. ID 76965); published April 17, 2007

We developed a metal hollow waveguide as a flexible delivery medium of terahertz waves. Theoretical evaluation shows that a metal waveguide mainly supports TE modes and that the TE_{11} mode shows a high coupling coefficient to linearly polarized light. Also the TE_{11} mode brings less mode conversion to high-order modes than the TE_{01} mode giving the lowest loss. We measured transmission losses in the terahertz region of hollow waveguides with inner silver coating; the losses were ~7.5–8 dB/m at the wavelengths from 190–250 μm for waveguides with an inner diameter of 1 mm. These losses coincide well with theoretical ones, and this shows that in these waveguides, the TE_{11} mode is dominant when a linearly polarized beam is launched into them. The waveguides are flexible because we use a thin-wall glass capillary as the base tubing. Our experiment revealed low additional losses due to bending even when complicated bends were applied to the waveguides. The metal-coated hollow fiber with an inner diameter of 1 mm is sufficiently small and flexible for use in endoscopic applications.

OCIS codes: 060.2310, 350.4010, 060.2280.

1. INTRODUCTION

Applications of terahertz waves have been rapidly expanding in industrial and biomedical fields. Along with the development of terahertz sources and their applications, various types of waveguides have been proposed and developed for the delivery of terahertz waves. Among terahertz waveguides, including dielectric waveguides,[1] photonic crystal waveguides,[2,3] and metal wires transmitting a surface wave,[4–6] hollow waveguides are suitable for applications that require a fiber length of the order of meters. Because the terahertz waves are strongly confined within their hollow core, hollow waveguides can be cabled, and this will be an advantage especially in medical endoscopic applications.

Three types of hollow waveguides have been reported: metal tube waveguides,[7,8] dielectric tube waveguides,[9,10] and plastic tubing with an inner metal coating.[11] Although a stainless-steel tube with a diameter of ~300 μm has been used as a metal waveguide, its transmission efficiency was low. Thus, the length of these waveguides is limited to the order of centimeters. Roughness and inhomogeneity in the inner surface of metal tubing produced by extrusion is the main cause of this limitation. The plastic-based waveguide with an inner metal coating solves this problem by having a smooth metal film deposited inside a flexible plastic tubing. The diameter of this reported waveguide is, however, larger than 2 mm, and inserting it into the working channel of an endoscope is difficult.

Here we report transmission properties of hollow fibers with an inner metal coating and an inner diameter of 1 mm that are small and flexible enough for endoscopic applications. By coupling a linearly polarized beam into the fiber, the TE_{11} mode with a moderate straight loss is excited. We found the bend-induced losses of these fibers to be very small as expected from TE mode transmission.

2. ATTENUATION CONSTANTS AND MODE PROPERTIES OF HOLLOW METAL WAVEGUIDES FOR TERAHERTZ WAVES

When the thickness of their metal film is greater than the skin depth for terahertz waves, hollow plastic or glass hollow waveguides with an inner metal coating work as a metal hollow waveguide. To derive attenuation constants of metal hollow waveguides using parameters described in Refs. 12 and 13, we first define the normalized surface impedance Z_{TE} and admittance Y_{TM} at the boundary be-

0740-3224/07/051230-6/$15.00

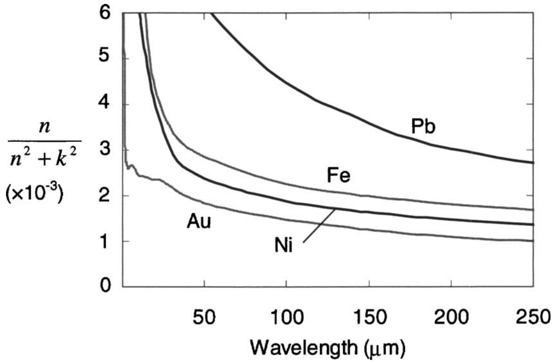

Fig. 1. Calculated $n/(n^2+k^2)$ of various metals as a function of wavelength.

tween the air core and the metal cladding by using the light travel direction z and the lateral direction y as

$$Z_{\mathrm{TE}} = \frac{n_0 k_0}{\omega\mu_0}\frac{E_y}{H_z}, \quad Y_{\mathrm{TM}} = -\frac{\omega\mu_0}{n_0 k_0}\frac{H_y}{E_z}, \tag{1}$$

where k_0 is the wavenumber and μ_0 is the permeability in vacuum. When the complex refractive index of the metal is $\nu = n - jk$, Z_{TE} and Y_{TM} are expressed as

$$Z_{\mathrm{TE}} = \frac{1}{\sqrt{\nu^2 - 1}}, \quad Y_{\mathrm{TM}} = \frac{\nu^2}{\sqrt{\nu^2 - 1}}. \tag{2}$$

When considering common metals, at infrared wavelengths, $|Z_{\mathrm{TE}}| \ll Z_0$ and $|Y_{\mathrm{TM}}| \ll Y_0$ where Z_0 and Y_0 are the normalized impedance and admittance of air and, as a result, modes (HE modes) can exist in the waveguide. In contrast, $|Z_{\mathrm{TE}}| \ll Z_0$, and $|Y_{\mathrm{TM}}| \gg Y_0$ for terahertz and far-infrared regions. In this condition, HE modes cannot exist in the waveguide and TE and some low-order TM modes dominate transmitting modes. This is because the loss differences between TE and TM modes are too large to constitute hybrid modes. The attenuation constant of each mode in a waveguide having a diameter $2T$ is derived as follows by assuming $\nu \gg 1$:

$$\alpha = \frac{u^2}{(n_0 k_0)^2 T^3}\frac{n}{n^2 + k^2}, \qquad \mathrm{TE}_{0q} \text{ mode}, \tag{3}$$

$$\alpha = \frac{1}{T}\frac{n}{n^2 + k^2}, \qquad \mathrm{TM}_{pq} \text{ mode}, \tag{4}$$

$$\alpha = n\frac{u^4}{(u^2 - p^2)}\frac{n}{n^2 + k^2}\left(\frac{1}{k_0^2 T^3} + \frac{p^2}{u^4 T}\right), \qquad \mathrm{TE}_{pq} \text{ mode}. \tag{5}$$

The parameter p in Eq. (5) is the mode index of the TE_{pq} modes. The phase constant u is the qth zero of the Bessel function $J_1(x)$ for TE_{0q}, $J_{p-1}(x)$ for TM_{pq}, and $J'_p(x)$ for TE_{pq} modes. For the TE_{01} mode, $u=3.83$, and $u=1.841$ for the next order, TE_{11} mode.

From the above equations, we found that the smaller the parameter $n/(n^2+k^2)$ is, the lower the attenuation becomes. Figure 1 shows the parameter $n/(n^2+k^2)$ calculated for various metals in far-infrared and terahertz regions. The refractive indices of these metals are taken from the literature.[14–16] We found that gold, which is popularly used for mirrors in the mid-infrared region, is also optimal as a material for waveguides for far-infrared and terahertz regions.

Figure 2 shows the theoretical attenuation of the low-order TE and TM modes in a gold waveguide with an inner diameter of 1 mm. Although the TE_{01} mode gives the lowest loss, a specialized coupling system is necessary to excite the mode when a linearly polarized terahertz source is used. This is because of the circular polarization of the TE_{01} mode, as shown in Fig. 3, and its donut-shaped power distribution.[17] Furthermore, as is known, when an irregularity such as bending is applied to a waveguide, the TE_{01} mode is easily converted to the TM_{11} that has a very high loss because these modes are degenerate. Most of the coherent terahertz sources emit linear polarization; therefore, only the TE_{1q} and TM_{1q} modes having linearly polarized field distributions as shown in Fig. 3 are excited.

Using mode-coupling theory,[18] the coupling coefficient η of TE_{1q} and TM_{1q} modes when excited by a Gaussian beam is derived as

$$\eta = \frac{\beta}{n_0 k_0}\left(\frac{w_0}{T}\right)^2 \exp\left[-\frac{u^2}{2}\left(\frac{w_0}{t}\right)^2\right] \times \begin{cases} \dfrac{1}{(1 - 1/u^2) J_1^2(u)}, & \mathrm{TE}_{1q} \text{ mode} \\[2ex] \dfrac{1}{J_0^2(u)}, & \mathrm{TM}_{1q} \text{ mode} \end{cases}, \tag{6}$$

where $2w_0$ is the beam-waist diameter of the Gaussian beam and β is the phase constant of each modes, that is,

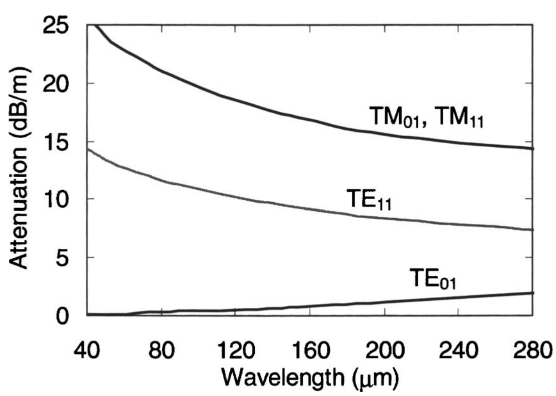

Fig. 2. Theoretical attenuations of low-order TE and TM modes in gold hollow waveguides with an inner diameter of 1.0 mm.

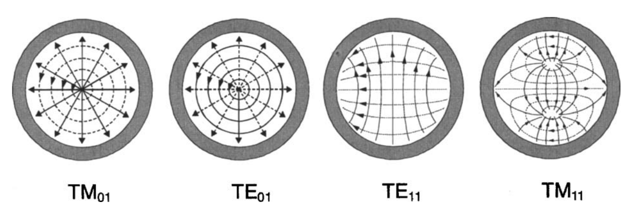

Fig. 3. Lines of current flow (solid curves) and magnetic lines (dotted curves) of low-order TE and TM modes in circular metal waveguides.

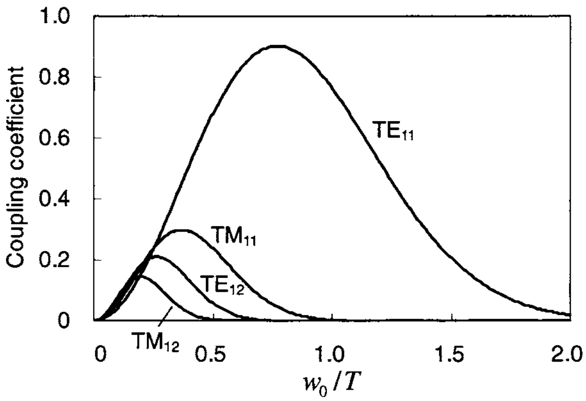

Fig. 4. Calculated coupling coefficients of TE_{1q} and TM_{1q} modes for a Gaussian input beam having a waist size of $2w_0$.

$$\beta = \sqrt{(n_0 k_0)^2 - \left(\frac{u}{T}\right)^2}. \tag{7}$$

Figure 4 shows coupling coefficients of TE_{1q} and TM_{1q} modes calculated using Eq. (6). The figure shows that the TE_{11} mode is dominant when a linearly polarized Gaussian beam is directly launched into circular metal waveguides because the coupling coefficient is as high as 90% when $w_0/T=0.77$, which is much higher than those of other modes.

3. FABRICATION AND TRANSMISSION PROPERTIES OF HOLLOW FIBERS WITH AN INNER METAL COATING FOR TERAHERTZ WAVES

Metal-coated hollow fibers for terahertz waves are fabricated with a conventional silver mirror-plating technique.[19,20] Although refractive indices of silver in terahertz regions have not been reported, the indices of silver are very close to those of gold in the infrared ($\lambda < 30\ \mu$m).[14,15,21] Therefore, we chose silver as the inner metal coating of waveguides expecting the indices of silver and gold are close also in the terahertz region. Another reason why we chose silver is that the silver-coating process is well established for fabricating hollow fiber optics for infrared use.

To investigate the optimal coating conditions for terahertz waveguides, we fabricated fibers under three different sets of conditions that are listed in Table 1. Sample A was formed with the shortest deposition time; therefore, its thickness is the least, roughly 50–70 nm, and it has the smoothest surface. The thickness of the samples B and C are ~100–120 nm, and C is rougher due to the longer deposition time. These differences can be clearly seen in the loss spectra of these waveguides in visible and near-infrared regions, as presented in Fig. 5. All the waveguides are 1 mm in diameter and 60 cm in length. In the experiment, we coupled a halogen lamp to waveguides via a multimode silica–glass fiber with a core diameter of 600 μm. We calculated the loss spectra from the input and output powers of the waveguides, and measured them with a spectrum analyzer. Because its thickness was less than the skin depth for visible and near-infrared wavelengths, the losses of sample A were the highest despite the smoothness of the coating. Sample B, with less roughness, had the lowest losses because scattering due to surface roughness affects the losses in visible and near-infrared wavelengths.

Then we measured loss spectra in the terahertz region of the same samples and the results are shown in Fig. 6. The measurement setup described below was used. The measured losses in this result include coupling losses between the input beam and waveguides. The waveguides are 1 mm in diameter and 60 cm in length. Sample A also had the highest losses because the skin depth of metals used in the terahertz region is similar to that used in the visible region because of the larger refractive indices in

Table 1. Deposition Conditions of Waveguide Samples

Sample	Solution Temperature (°C)	Deposition Time (min)	Measured rms Roughness (nm)
A	18	3.0	10.1
B	19	4.5	14.5
C	18	6.0	18.2

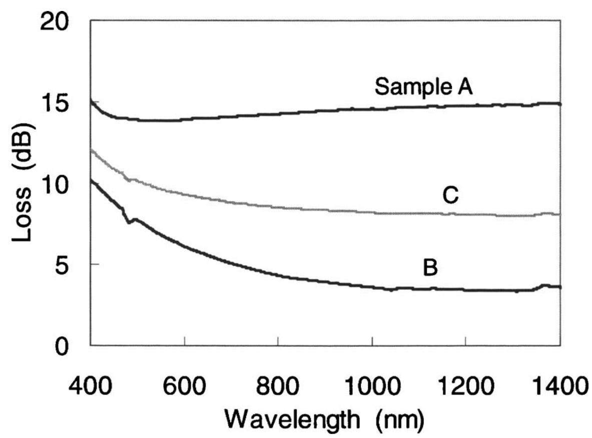

Fig. 5. Measured loss spectra of hollow waveguides in visible to near-infrared regions. The waveguides have an inner coating of silver deposited under the different conditions listed in Table 1. The waveguides are 1 mm in diameter and 60 cm in length.

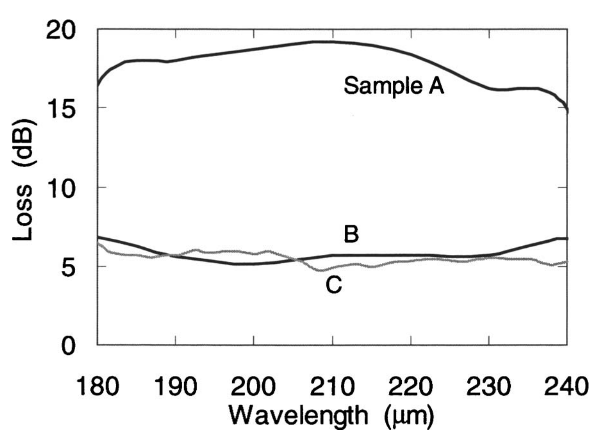

Fig. 6. Measured loss spectra of hollow waveguides in the terahertz region. The waveguides have an inner coating of silver deposited under the different conditions listed in Table 1. The waveguides are 1 mm in diameter and 60 cm in length.

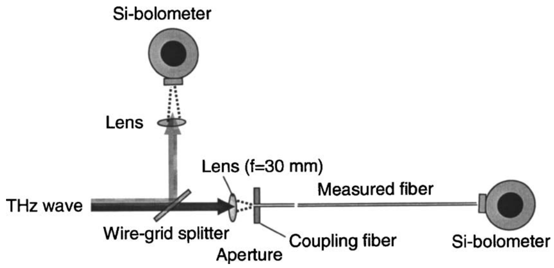

Fig. 7. Experimental setup for measurement of attenuation losses of hollow waveguides in the terahertz region.

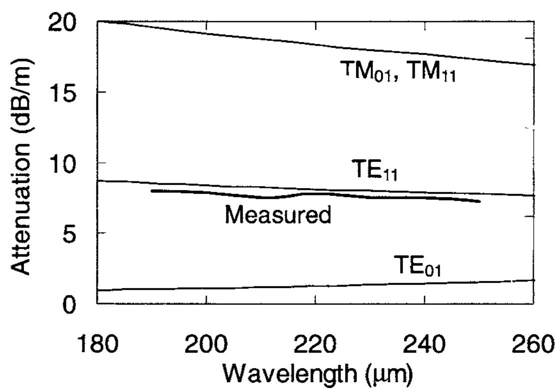

Fig. 8. Measured attenuation of silver-coated waveguides in the terahertz region. The inner diameter of the waveguides is 1 mm. Theoretical losses are also shown for comparison.

the terahertz region. The skin depth of silver at the wavelength of 200 μm was calculated as 65 nm. From the fact that the losses of samples B and C were close, we found that surface roughness does not largely affect attenuation in such long wavelengths. The results shown in Figs. 5 and 6 show that, for terahertz waveguides, the deposition conditions of the sample B is the optimum and that we can use the same deposition conditions for silver for infrared waveguides that have been previously optimized for waveguides used in the infrared. For the fabrication of silver-coated waveguides shown below, this optimum condition was applied.

To compare measured and theoretical losses, we performed a measurement using a coherent terahertz source. Figure 7 shows the setup, and a tunable parametric oscillator with a MgO:$LiNbO_3$ crystal pumped by a Q-switched Nd:YAG laser[22] was used as a terahertz source. We split the input terahertz wave with a wire grid splitter to monitor the power of input beam with a silicon bolometer. A methylpentene polymer lens with a focal length of 30 mm was used to focus the beam into the hollow core of the waveguides. We used a short tip of the waveguide, 10 cm in length, as a coupling waveguide that eliminated lossy modes and effectively coupled the TE_{11} mode. The inner diameter of the waveguide was 1 mm.

Figure 8 shows the attenuation spectrum of the silver-coated hollow waveguides measured with the coherent terahertz source. The attenuation losses were calculated with a cutback method by using waveguides of six different lengths from 10 to 60 cm. The measured attenuations are close to the theoretical ones of the TE_{11} mode, and this shows that the TE_{11} mode was well coupled by a linearly polarized terahertz source with a near-Gaussian power profile. We found a small discrepancy between the measured and theoretical losses that was due to differences in the optical constants of the deposited silver and those presented in the literature.

Figure 9 presents the measured attenuations at a wavelength of 200 μm plotted as a function of the inner diameter of the waveguides. In this experiment, we used coupling waveguides with the same diameter as the measured waveguides to select only low-order modes in each waveguide. The measured losses coincided well with the

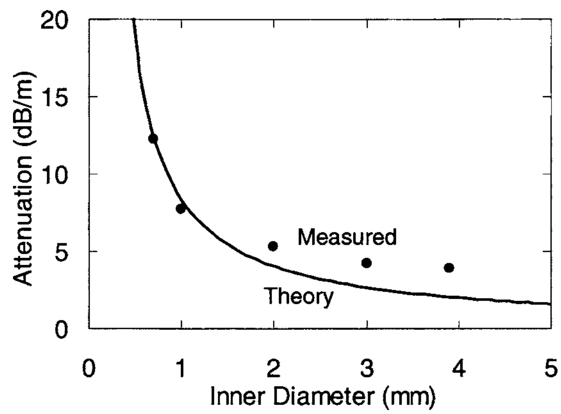

Fig. 9. Attenuation of silver-coated waveguides with different diameters measured at a wavelength of 200 μm. Theoretical attenuation of the TE_{11} mode is also shown for comparison.

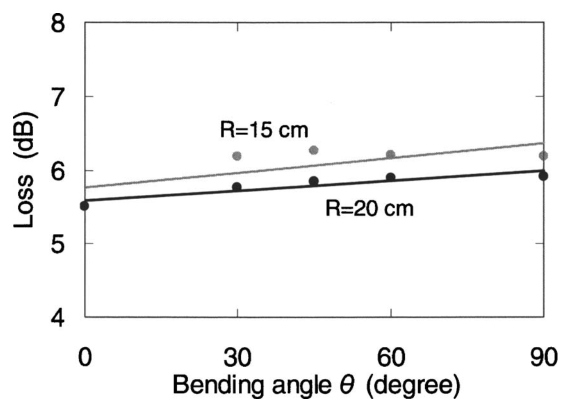

Fig. 10. Measured losses of silver-coated waveguides bent at two different radii. The wavelength is 200 μm and the waveguides have an inner diameter of 1 mm and length of 60 cm.

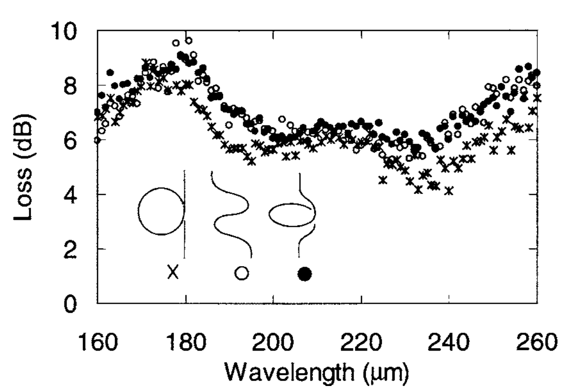

Fig. 11. Measured loss spectra of silver-coated waveguides bent in three different shapes, loop (crosses), S shape (open circles), and screw (closed circles). The waveguides have an inner diameter of 2 mm and length of 1 m.

theoretical ones that have near-$1/T$ dependency as would be expected from Eq. (5). The losses are higher than the theory in larger waveguides because the homogeneity of the silver coating is worse in them. The loss of a 1 mm diameter waveguide that can be inserted into a working channel of a standard endoscope is ~ 8 dB/m, and this is acceptably low for medical diagnosis and imaging systems.

To measure bending losses, we bent the center part of 60 cm long silver-coated waveguides in a uniform curvature. Figure 10 shows measured bending losses of the waveguides bent at two different radii as a function of the bending angle. In the experiment, the polarization is perpendicular to the plane of bending. This condition gives lower losses than polarization parallel to the bending plane. However, for TE modes, the difference is theoretically small and this is shown experimentally later by applying complex bending shapes on the waveguides. Bend-induced losses in Fig. 10 are smaller than 0.5 dB even when the waveguides were bent 90° at a small radius. This is a well-known advantage of using TE-mode-based waveguides for micro- and millimeter waves. In this experiment, a terahertz beam focused by a lens is directly launched into the waveguide and thus, the results include the coupling losses. Since we chose a lens giving the optimum coupling condition for the TE_{11} mode, that is $w_0/T = 0.77$, the coupling coefficient is estimated to be 90% (loss of 0.5 dB) as shown in Fig. 4. The measured losses of ~ 5.5 dB coincide well with theoretical value of the sum of the coupling and transmission losses: $0.5\,\mathrm{dB} + (8.5\,\mathrm{dB/m} \times 0.6) = 5.6\,\mathrm{dB}$. This is more evidence of the TE_{11}-mode transmission in the waveguide.

Figure 11 shows the loss spectra of the waveguides bent into three different shapes: loop, S bend, and screw. We found that none of these complex-bending shapes largely affected transmission losses, and their loss spectra almost coincided with the spectrum of straight waveguides measured under the same conditions. Also this result shows that the transmission losses are not affected with polarization of the input and transmitting terahertz wave as theoretically expected for TE-mode transmission. These characteristics are advantageous for the waveguides when they are applied to endoscopic applications that require complicated and sharp bends in waveguides.

4. CONCLUSION

We developed a hollow metal waveguide as a flexible delivery medium of terahertz waves. Theoretical evaluation shows that a metal waveguide mainly supports TE modes, and that the TE_{11} mode shows a high coupling coefficient to linearly polarized light. Also the TE_{11} mode brings less mode conversion to high-order modes than the TE_{01} mode that gives the lowest loss. We measure transmission losses in the terahertz region of hollow waveguides with an inner silver coating, and found the losses were $\sim 7.5-8$ dB/m at the wavelengths from $190-250\,\mu$m for waveguides with an inner diameter of 1 mm. These losses coincide well with the theoretical ones, and this shows that the TE_{11} mode is dominant in the waveguides when a linearly polarized beam is launched into them. The waveguides are flexible because we used a thin-wall glass capillary as the base tubing, and the experiment revealed low additional losses due to bending even when complicated bend shapes were applied to the waveguides. The metal-coated hollow fiber with an inner diameter of 1 mm is sufficiently small and flexible for endoscopic applications.

Y. Matsuura's e-mail address is yuji@ecei.tohoku.ac.jp.

REFERENCES

1. S. P. Jamison, R. W. McGowan, and D. Grischkowsky, "Single-mode waveguide propagation and reshaping of sub-ps terahertz pulse in sapphire fibers," Appl. Phys. Lett. **76**, 1987–1989 (2000).
2. H. Han, H. Park, M. Cho, and J. Kim, "Terahertz pulse propagation in a plastic photonic crystal fiber," Appl. Phys. Lett. **80**, 2634–2636 (2002).
3. M. Goto, A. Quema, H. Takahashi, S. Ono, and N. Sarukura, "Teflon photonic crystal fiber as terahertz waveguides," Jpn. J. Appl. Phys., Part 2 **43**, L317–L319 (2004).
4. K. Wang and D. M. Mittleman, "Metal wires for terahertz waveguiding," Nature **432**, 376–379 (2004).
5. K. Wang and D. M. Mittleman, "Guided propagation of terahertz pulses on metal wires," J. Opt. Soc. Am. B **22**, 2001–2008 (2005).
6. J. A. Deibel, K. Wang, M. D. Escarra, and D. M. Mittleman, "Enhanced coupling of terahertz radiation to cylindrical wire waveguides," Opt. Express **14**, 279–289 (2006).
7. R. W. McGowan, G. Gallot, and D. Grischkowsky, "Propagation of ultrawideband short pulses of terahertz radiation through submillimeter-diameter circular waveguides," Opt. Lett. **24**, 1431–1433 (1999).
8. G. Gallot, S. P. Jamison, R. W. McGowan, and D. Grischkowsky, "Terahertz waveguides," J. Opt. Soc. Am. B **17**, 851–863 (2000).
9. T. Hidaka, H. Minamide, H. Ito, S. Maeta, and T. Akiyama, "Ferroelectric PVDF cladding terahertz waveguide," in *Optical Information, Data Processing and Storage, and Laser Communication Technologies* J.-P. Goedgebuer, N. N. Rozanov, S. K. Turitsyn, A. S. Akhmanov, and V. Y. Panchenko, eds., Proc. SPIE **5135**, 70–77 (2003).
10. T. Hidaka, H. Minamide, and H. Ito, "Bent-angle dependency of ferroelectric PVDF cladding THz waveguides," in *Proceedings of the 11th IEEE International Conference on Terahertz Electronics* (IEEE, 2003), p. 76.
11. J. A. Harrington, R. George, P. Pedersen, and E. Mueller, "Hollow polycarbonate waveguides with inner Cu coatings for delivery of terahertz radiation," Opt. Express **12**, 5263–5268 (2004).
12. M. Miyagi and S. Kawakami, "Design theory of dielectric-coated circular metallic waveguides for infrared transmission," J. Lightwave Technol. **LT-2**, 116–126 (1984).
13. M. Miyagi, "Waveguide-loss evaluation in circular hollow waveguides and its ray-optical treatment," J. Lightwave Technol. **LT-3**, 303–307 (1985).
14. M. A. Ordal, L. L. Long, R. J. Bell, S. E. Bell, R. R. Bell, R. W. Alexander, Jr., and C. A. Ward, "Optical properties of the metals Al, Co, Cu, Au, Fe, Pb, Ni, Pd, Pt, Ag, Ti, and W in the infrared and far infrared," Appl. Opt. **22**, 1099–1119 (1983).
15. M. A. Ordal, R. J. Bell, R. W. Alexander, Jr., L. L. Long, and M. R. Querry, "Optical properties of Au, Ni, and Pb at submillimeter wavelengths," Appl. Opt. **26**, 774–752 (1987).
16. M. A. Ordal, R. J. Bell, R. W. Alexander, Jr., L. A. Newquist, and M. R. Querry, "Optical properties of Al, Fe, Ti, Ta, W, and Mo at submillimeter wavelengths," Appl. Opt. **27**, 1203–1209 (1988).
17. C. G. Montgomery, R. H. Dicke, and E. M. Purcell, eds., *Principles of Microwave Circuits* (Peter Peregrinus, 1987), Chap. 2.

18. A. W. Snyder and J. D. Love, *Optical Waveguide Theory* (Chapman and Hall, 1983), Chap. 27.
19. J. A. Harrington, *Infrared Fiber Optics and Their Applications* (SPIE, 2004).
20. Y. Matsuura, Y. Shi, Y. Abe, M. Yaegashi, G. Takada, S. Mohri, and M. Miyagi, "Infrared-laser delivery system based on polymer-coated hollow fibers," Opt. Laser Technol. **33**, 279–283 (2001).
21. E. D. Palik, ed., *Handbook of Optical Constants of Solids* (Academic, 1985).
22. K. Kawase, J. Shikata, and H. Ito, "Terahertz wave parametric source," J. Phys. D **35**, R1–R14 (2002).