Characterization of bending loss in hollow flexible terahertz waveguides

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Abstract: Attenuation characteristics of hollow, flexible, metal and metal/dielectric coated polycarbonate waveguides were investigated using an optically pumped far infrared (FIR) laser at 215 µm. The bending loss of silver coated polycarbonate waveguides were measured as a function of various bending angles, bending radii, and bore diameters. Minimal propagation losses of 1.77, 0.96 dB/m were achieved by coupling the lowest loss TE_{11} mode into the silver or gold coated waveguide, and HE_{11} mode into the silver/polystyrene coated waveguides respectively. The maximal bending loss was found to be less than 1 dB/m for waveguides of 2 to 4.1 mm bore diameters, with a 6.4 cm bend radius, and up to 150° bending angle. The investigation shows the preservation of single laser mode in smaller bore waveguides even at greater bending angles.

OCIS codes: (230.7370) Waveguides; (040.2235) Far infrared or terahertz; (110.6795) Terahertz imaging.

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1. Introduction

The Terahertz (THz) frequency regime of an electromagnetic spectrum is a rapidly developing area in source and receiver technologies with a wide range of applications in security screening and remote sensing [1]. The high sensitivity of THz radiation to water concentration, resulting from the low energy interaction with the low frequency molecular motions, has expanded its applications into the areas of imaging and spectroscopy [2]. Due to its non-ionizing property (unlike X-rays), THz technology has become increasingly important for biological applications. As cancerous tissues show higher hydration compared to the healthy ones (Evident from PET and MRI studies) [3], the water detection by THz techniques can be an alternative and easy way for cancer identification. The currently available commercial THz imaging systems (TPI imaga 1000, et.al.) for cancer identification were limited to the *in vivo* tissue analysis of externally growing tumors. A flexible cylindrical waveguide with good mode selectivity is essential to guide the THz radiation in the field of interior *in vivo* medical imaging. The functionality of the imaging system can be improved by using low-loss, hollow, flexible terahertz waveguides with minimal transmission loss and specific bending characteristics.

Terahertz waveguides have been fabricated from a variety of materials [4–6] and with different cross sectional designs [7–10]. Practical hollow core THz waveguides with reduced transmission losses below the level of 1 dB/m were reported recently [11–15]. Most of the reported terahertz waveguides were either rigid or not quite flexible at larger bore diameters greater than 5 mm [11]. On the other hand, the bendable terahertz waveguides were neither cylindrical [7,10] nor provide low-loss (below 2 dB/m) [16,17]. However the flexible cylindrical waveguides shown in the literature that provide low loss (1.3 dB/m) [12] do not meet the small diameter requirement, as the fabrication technique is not feasible for bore diameters less than 3 mm. Here we report the transmission and bending characteristics of low loss (less than 2 dB/m), hollow, flexible, cylindrical terahertz waveguides with an inner metal, and metal/dielectric coatings that are small enough in diameter for endoscopic applications (2 mm bore diameter). These cylindrical hollow THz waveguides for medical imaging were fabricated using flexible polycarbonate (PC) tubing, through an extrusion process that provides a smooth inner surface. For this investigation silver (Ag) and gold (Au) were chosen to be the germane metals, due to their high reflectivity values at 214.6 µm wavelength. A dielectric layer is added to the flexible metal coated waveguides to improve reflectivity within specific wavelength ranges. Polystyrene (PS) was chosen to be the dielectric, due to its low extinction coefficient, that enhances the transmission through the waveguide [18].

2. Experiment

Metal films were deposited inside the rigid or flexible tubes using an electro-less liquid phase chemical deposition (ELPCD) process. The inner surface of the polycarbonate tubing was coated with Ag using the ELPCD process in an open-loop configuration, whereas the deposition of Au involved in a closed-loop [19] ELPCD process. Maximum transmission through the THz waveguide can be achieved by depositing a metal film with a thickness much greater than its skin depth at the desired wavelength. The duration of the deposition process was about 2 to 4 minutes to obtain a several micron thick layer of Ag or Au, which is much smaller than the time reported for a micron thick metal coatings in the literature. The polystyrene coating was obtained by sending 5 to 8 ml of 16 to 20 wt% polystyrene/ cyclohexane solution through the metal coated waveguide with a maximum flow rate of 40 ml/min [20]. The thickness of the polymer coating increases linearly with time, and as example, two SEM images taken at different coating times are shown in the insets of Fig. 1. The desired 26.8 μm thick uniform PS film was achieved by coating the PC tube for 10 minutes using the closed-loop ELPCD process.

The source used for this experiment was a CO_2 optically pumped far-infrared (FIR) gas laser operating at 1.39 THz. The laser line used was 214.6 μm, horizontally polarized transition in CH_2F_2, pumped by the 9R34 transition of the CO_2 laser. Near the laser face, the measured terahertz laser output power was 370 mW. The beam waist of the 1.4 THz laser was measured as 2.36 mm. Maximal transmission in cylindrical THz waveguides can be achieved by coupling the lowest loss TE_{11} mode into the metal coated waveguide and HE_{11} mode into the metal/dielectric coated waveguides with maximum mode coupling efficiency. An optical system was designed in such way that the ratio of the laser beam waist and bore radii, ω_0/r, as 0.77, 0.64 mm to couple 90.3%, 98.1% of the lowest order TE_{11}, HE_{11} mode into the metal, and metal/dielectric coated hollow waveguides respectively [16,21].

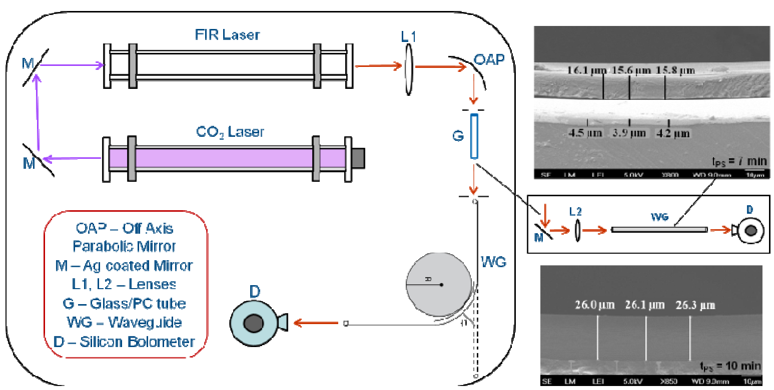

Fig. 1. Schematic of experimental layout for the measurement of total loss in bent metal coated waveguides. Insets show straight loss measurement and cross sectional SEM images of Ag/PS waveguides at different PS coating times.

A 76.2-cm focal length TPX lens was used to collimate the THz beam. By using an 18-cm focal length off-axis parabolic mirror (OAP), the collimated THz beam was focused into a 3.2 mm polycarbonate/glass tube (G) that cleans the higher order modes. A high-density polyethylene lens was used to obtain the desired ω_0/r ratio to couple TE_{11}, HE_{11} mode into the metal, metal/dielectric coated waveguides of various bore diameters respectively. A liquid helium cooled silicon bolometer was used as the detector. The noise equivalent power (NEP) of the detector was 1.13E–13 $W/Hz^{1/2}$ and the system responsivity was 2.75E + 05 V/W. The bolometer had a response time of 5 milliseconds with a gain of 200. An automated two axis scan stage raster scanned the beam at both the ends of the waveguide to obtain the spatial intensity variation. The resolution of both the horizontal and vertical axes was set to 0.01 mm.

The motion control and data acquisition software was programmed using National instruments LabView®. A signal to noise (SNR) ratio of 68dB was achieved by using a lock-in amplifier. The amplitude information from the silicon bolometer was sent to a Lock-In amplifier and the data from the amplifier was collected by the program using a data acquisition card from National Instruments. The software synchronized the motion control and data acquisition, and generated an amplitude intensity map of the scanned area (≈1.5 cm from the waveguide edge). The intensity amplitude sum is directly related to the power. The power ratio of the input and output ends of the waveguide in Eq. (3) was obtained by taking the corresponding ratio of the total intensity amplitudes, while maintaining the scanned area (number of pixels) as constant in both the cases. The spatial profiles of the input laser beam and output beam from the waveguide were verified by using a pyroelectric array detector Spiricon Pyrocam III (≈1.5 cm away from the facet). Also, the total power values measured exiting the waveguide for cutback loss measurements were verified using power meter with a thermal sensor.

The set-up for measuring bending loss is shown in Fig. 1. The bending loss of the waveguide depends on the bending angle, θ, and the bend radius, R. To facilitate the bending radius measurement, an aluminum disc was used to bend the flexible waveguide as shown in the experimental setup. R can be varied by changing the aluminum disc radius. In this investigation three discs of different radii 4.2 cm, 5.1 cm, and 6.4 cm were used to bend the silver coated waveguides of inner diameters 4.1 mm, 3.2 mm, and 2 mm up to 150°. The power coupled into the waveguide was measured to be 3 mW.

3. Results and discussion

3.1 Propagation loss

The total transmission loss of a waveguide, α_{tot}, is the sum of propagation and bending losses,

$$\alpha_{tot} = \alpha_{pq} L + \alpha_{\theta} L_R \tag{1}$$

where α_{pq} represents the propagation loss and α_{θ} is the bending loss of the waveguide in dB/m. L represents the length of the waveguide, and L_R is the bend length.

The attenuation coefficient, α_{pq}, for TE_{pq} modes of hollow metal terahertz waveguides is given by [16],

$$\alpha\left(TE_{pq}\right) = 10 \cdot \frac{u^4}{u^2 - p^2} \frac{n}{n^2 + \kappa^2} \left(\frac{1}{k_0^2 r^3} + \frac{p^2}{u^4 r} \right) \tag{2}$$

where r represents the bore radius of the waveguide, $\tilde{n} = n - i\kappa$ is the complex refractive index of the metal, p is the mode index, $k_0 = 2\pi / \lambda_0$ is the wave number, and u is the phase constant representing q^{th} zero of the Bessel function $J_p^{'}(x)$.

The straight losses for the hollow flexible 50 - 60 cm long silver, and gold coated THz waveguides of different bore sizes were measured at 214.6 µm. The total transmission loss of a waveguide was found experimentally using Beer-Lambert's law as follows,

$$\alpha = \frac{10}{L} \log\left(\frac{P_{in}}{P_{out}}\right) dB/m \tag{3}$$

where L represents the length of the waveguide, and P is the power. A cutback technique was used to accurately determine the absorption coefficient for each straight waveguide. The loss measurement for the entire length of the waveguide determines the value of P_{out}. The loss in the residual short length waveguide that was left after the cut, determines the value of P_{in}. The length of the waveguide is the difference between the long and short length of waveguide. The attenuation coefficients were calculated with cutback method by using waveguides of six

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different lengths from 10 to 60 cm. The transmission losses increase linearly with the waveguide length. The linear fit to the data allows an estimation of total transmission loss and experimental coupling efficiencies of the waveguide. The theoretical and experimental attenuation coefficients in cylindrical metal coated waveguides were obtained from Eq. (2) and (3) respectively. Figure 2 shows the theoretical and experimental attenuation coefficients of both silver and gold coated waveguides as a function of bore diameter, d. The theoretical and experimental results were found to be in good agreement. The experimental propagation losses of the waveguides were generally higher than the theoretical losses. The predicted trend of decreasing loss with increasing bore diameter, and the convergence of the attenuation coefficient difference between silver and gold coated waveguides at larger bore diameters were clearly visible from Fig. 2. The better agreement between experimental and theoretical losses in case of gold coated waveguides can be due to the greater uniformity resulted from closed loop ELPCD process. Propagation losses of 1.77 dB/m, and 2 dB/m were achieved with 4 mm bore diameter Ag, Au coated terahertz waveguides respectively. Twelve tested 2 - 4.1 mm bore diameter silver, gold coated waveguides had experimental coupling efficiencies between 74% and 79%.

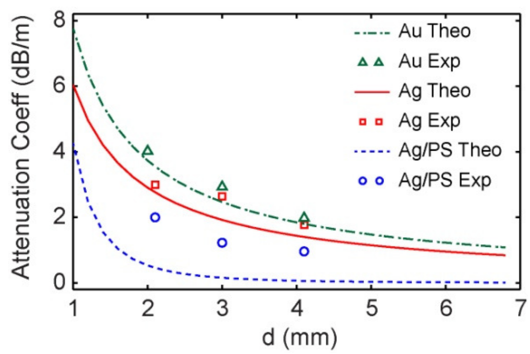

Fig. 2. Experimental and theoretical attenuation coefficients as a function of bore diameter for silver, gold, and silver/polystyrene coated terahertz waveguides.

Maximum transmission in metal/dielectric coated THz waveguides was achieved by coupling the lowest loss HE_{11} mode. The theoretical attenuation coefficient for hollow metal/dielectric coated THz waveguides is given by [22],

$$\alpha\left(HE_{pq}\right)=10\cdot\frac{u^2}{\left(n_0k_0\right)^2r^3}\left[\frac{n}{n^2+\kappa^2}\right]\cdot\frac{1}{2}\left(1+\frac{{n_d}^2}{\sqrt{{n_d}^2-1}}\right)^2 \tag{4}$$

where $n - i\kappa$ represents the complex refractive index of metal, u is the q^{th} zero of $J_{p-1}(x)$. Here $\tilde{n}_d$ is the complex refractive index of the dielectric, which is assumed to be lossless. Both the theoretical and experimental attenuation coefficients for silver/polystyrene coated 40 – 50 cm long terahertz waveguides were plotted as a function of bore diameter d, as shown in Fig. 2. The maximum measurement error for each individual data point calculated using the standard deviations in the power measurement is less than 0.2 dB. The predicted trend of decreased loss with increasing bore diameter, and the abatement in the difference of Ag, and Ag/PS coated waveguides loss at larger bore diameters was clearly visible from Fig. 2. Also, the Ag/PS coated waveguides show higher transmission compared to Ag coated waveguides for all bore diameters. The discrepancy between theoretical and experimental attenuation coefficients can be due to the edge coupling effect, roughness of metal or non-uniformity of the dielectric coating. Also, the theoretical attenuation coefficients were calculated by assuming a lossless dielectric (κ_d = 0). Due to the nonzero absorption coefficient of polystyrene, with complex refractive index of 1.58 – i3.58x10^{-3}, the theoretical attenuation coefficients in Fig. 2 should be at a higher level. In this investigation, the propagation loss of less than 1 dB/m was achieved in 4 mm diameter silver/polystyrene coated terahertz waveguides. Five out of the six tested 2 – 4.1 mm bore diameter Ag/PS coated waveguides had experimental coupling efficiencies between 84% and 89%. The outlier has a coupling efficiency of 77%, due to the non uniformity caused in 29.5 μm thick polystyrene coating. Maximum coupling efficiency of 89% was achieved in 26.2 μm thick PS coated waveguide.

3.2 Bending loss

The bending loss in hollow flexible THz waveguides depends on the bend radius (R), angle of bending (θ), and bore radius (r). In the mid-IR region it has been shown that, this additional bending loss varies as r^3/R [23]. The total loss for bent terahertz waveguides at 214.6 μm wavelength is shown in Fig. 3. All the measurements were taken using 50 to 60 cm long silver coated waveguides with the laser polarization perpendicular to the plane of bending (s-pol). If the bending loss, α_θ, is proportional to r^3/R then,

$$\alpha_{tot} = \alpha_{pq} L + \alpha_\theta L_R = \alpha_{pq} L + \left(C \cdot \frac{r^3}{R} \right) (R\theta) = \alpha_{pq} L + C r^3 \theta \tag{5}$$

which means, if α_{tot} is plotted as a function of θ at different bending radii for silver coated waveguides of fixed bore diameter the slope must be constant. Figure 3(a) shows the total attenuation coefficient, α_{tot}, for a 3 mm bore diameter silver coated waveguide as a function of bending angle, θ, at different bending radii 4.2 cm, 5.1 cm, 6.4 cm. It is observed that the total loss increases rapidly with increasing bending angle or by decreasing bend radius. The Y-intercept of Fig. 3(a) gives the straight loss, which is the total transmission loss, measured when the bending angle was 0°. A bending loss of 0.8 dB/m was measured in 2 mm silver coated waveguides with a bend radius of 6.4 cm. From Fig. 3(a), it is evident that the slope, C, is invariant for the silver coated waveguides bent at different bending radii. As the slope of the bending loss curve is independent of the bend radius, which confirms the result predicted by Eq. (5) that, the bending attenuation coefficient α_θ varies inversely with bend radius R.

Also, as the propagation loss, α_{pq}, is proportional to $1/r^3$,

$$\alpha_{tot} / r^3 = \left(\alpha_{pq} L + \alpha_\theta L_R \right) / r^3 = \left(\left(\frac{C_1}{r^3} \right) L + \left(C \cdot \frac{r^3}{R} \right) R\theta \right) / r^3 = C_1 \left(\frac{L}{r^6} \right) + C\left(\theta\right) \tag{6}$$

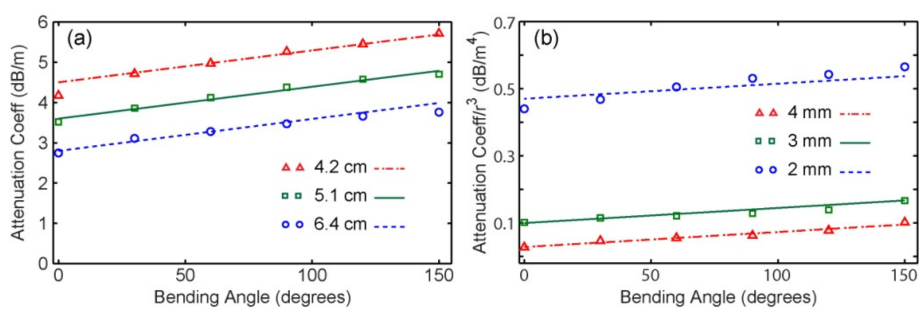

Fig. 3. Total attenuation coefficient as a function of bending angle for the silver coated waveguides of a) 3 mm inner diameter at various bending radii, b) different bore diameters with 6.4 cm bend radius.

Figure 3(b) shows the total attenuation coefficient per r^3, α_{tot}/r^3, of the silver coated waveguide with 6.4 cm bend radius as a function of bending angle for several bore diameter tubes namely 2 mm, 3.2 mm, and 4.1 mm. It shows the direct dependence of total loss on bending angle. Also it is observed that smaller bore diameters lead to a rapid increase in the

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attenuation coefficient α_{tot}/r^3, as predicted by the presence of $1/r^6$ term in Eq. (6). Further, the maximal bending loss was determined to be less than 1 dB/m for all silver coated waveguides with bore diameters greater than 1 mm. As the slope of bending loss curve in Fig. 3(b), C, is invariant for the waveguides of different bore diameters, it is evident that the bending loss varies as the cube of the bore radius as predicted from theory. The bending losses in 2 – 4.1 mm bore 40 cm long Ag/PS coated waveguides were measured up to 20^{0} bending angle by using an aluminum disc of 6.4 cm diameter. Due to the great difficulty involved in bending a 30 µm thick PS coated polycarbonate waveguide, bending losses are hard to measure at greater bending angles without suppressing the uniformity of the PS layer. The maximum bending loss measured in 2 – 4.1 mm bore diameter Ag/PS coated waveguides with 20^{0} bending angle and 6.4 cm bend radius was 0.3 dB/m.

3.3 Modal characteristics

The output mode profile is most important for applications that require good beam quality and preservation of Gaussian type modes. Modal characteristics of 50 cm long flexible silver coated waveguides were obtained by using the experimental setup shown in Fig. 1. Spatial intensity distributions of the propagated terahertz radiation through the silver coated waveguides of different bore diameters, at various bending angles in linear scale were shown in Fig. 4 and Fig. 5. The TE_{11} mode is dominant out of all the propagated modes in hollow core metal coated waveguides, when excited with a linearly polarized THz wave, because of the lowest attenuation constant among linear polarization modes. Hence an optical system was designed to couple the TE_{11} mode efficiently into the metal coated waveguides. From the input and output beam profiles of the 3.2 and 2 mm Ag coated waveguides with 0° bending angle, it is evident that the launched TE_{11} mode fully developed at the output when propagated through the silver coated waveguide. For the 4 mm diameter straight silver coated waveguide we see that the output mode is not single mode but as the bore diameter decreases to 2 mm the output converges to a single mode. This confirms the result shown by Harrington et.al, when bore size is about 17λ the guide is multimode but when it is 12λ or less then the waveguide becomes essentially single mode [8]. By maintaining ω_0/r ratio as 0.77, we are coupling only 90.3% of TE_{11} mode, there exist higher order modes in the waveguide. These higher order modes attenuate rapidly in smaller bore waveguides as the loss is relatively higher as shown in Fig. 4.

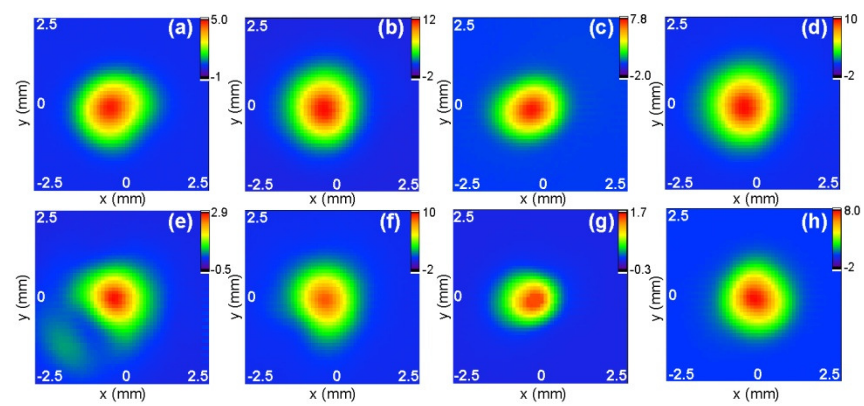

Fig. 4. The spatial intensity distribution of input for (a) 4-mm Ag, (b) 3-mm Ag, (c) 2-mm Ag, (d) 3-mm Ag/PS and the output from (e) 4-mm Ag, (f) 3-mm Ag, (g) 2-mm Ag, and (h) 3-mm Ag/PS coated straight terahertz waveguides.

In principle, metal waveguides do not preserve a single mode launched into the waveguide while bending. The existence of higher order modes were observed in the output beam profiles of 4mm diameter waveguide as it was bent. Even at greater bending angles, as

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compared to 4 mm waveguide, guides with 3 mm bore diameter showed less mode mixing. The smallest bore waveguides exhibit the least amount of mode mixing, as would be predicted bythe general dependence of α_{pq} on the mode parameter u in Eq. (2). That is, the loss for higher order modes is relatively greater in small bore waveguides compared to large bore sizes. This effect can be seen qualitatively in the mode profile data in Fig. 5 for three different bore diameters of 4.1 mm, 3.2 mm and 2 mm.

The 2 mm diameter waveguide remains largely single mode even when bent to a radius of 6.4 cm, whereas the 3 mm diameter guide preserves the mode up to 50° of bending. But the 4 mm diameter waveguide shows a distinctly multimode pattern even when straight, and bending further mixes the modes. The dramatic difference in modal properties between the two sizes is largely due to their relative bore diameter sizes compared to the incident wavelength. It was observed that the mode mixing was not severe in hollow glass waveguides, as compared to PC waveguides at 0° bending angle, due to their inherent smooth surface. Hence the discrepancy in modal properties may be due to the scattering from surface roughness, which leads to coupling of energy into the higher order mode**s.** When the metal

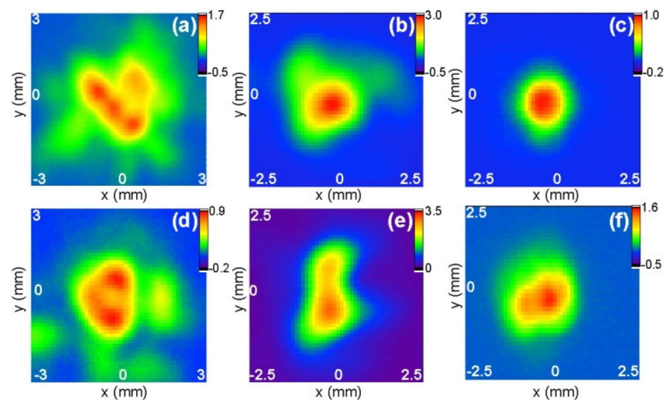

Fig. 5. Spatial profile of output from Ag coated waveguides of bore diameters (a) 4-mm, θ = 60°, (b) 3-mm, θ = 60°, (c) 2-mm, θ = 60°, (d) 4-mm, θ = 120°, (e) 3-mm, θ = 120°, and (f) 2-mm, θ = 120° with 6.4 cm bending radius.

coated waveguides were loaded with a dielectric film, attenuation of TM modes will be lowered, as a result HE_{11} mode becomes dominant out of all the propagated TE_{0n}, TM_{0n}, HE_{mn}, and EH_{mn} modes [20]. It has been observed that the horizontal polarization of the source beam is largely maintained in the Ag/PS coated waveguides, by inserting the horizontal and vertical grid polarizers between the output end of the waveguide and the detector. The mode profile of the straight silver/polystyrene coated waveguide of 3 mm bore diameter shown in Fig. 4(d) and 4(h) is made up almost entirely horizontally polarized radiation, and the intensity profile is the characteristic of the launched HE_{11} mode which confirms the preservation of the single mode. That is, even when the bore size is about 15λ the output mode was distinctively single mode. There is no significant change in the bending loss and modal profiles of 3.2, 2 mm bore Ag/PS coated waveguides with 20° bending angle. When the 4.1 mm waveguide was bent to 20°, due to the deformation of the circumferential geometry can be caused in bending a larger bore diameter waveguide, some of the HE_{11} mode energy is coupled into higher-order modes.

4. Conclusion

In conclusion, the propagation losses of Ag, Au, and Ag/PS coated waveguides of several bore diameters were investigated at 214.6 μm wavelength. Total losses as low as 1.77 dB/m and 2 dB/m were achieved in 4 mm Ag, Au coated waveguides respectively by coupling the TE_{11} mode. The propagating modes transitioned from TE_{11} dominant to HE_{11} dominant as the

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film thickness increased from 0 to 26.8 µm. Propagation losses as low as 0.96 dB/m were achieved in a 4 mm metal/dielectric coated waveguide with 26 µm PS film thickness. Straight Ag/PS coated terahertz waveguides of bore sizes up to 15λ showed the preservation of single laser mode. The bending loss of silver coated waveguides for several bore diameters were characterized as a function of bending angle, and bend radii. The total loss in a bent waveguide increases rapidly with increasing bending angle or decreasing bend radius. The maximum bending loss was determined to be as low as 0.8 dB/m for bore diameters greater than 1 mm. Even when the bending radius was reduced from 6.4 cm to 4.2 cm, the increment in the bending loss was found to be less than 2 dB/m. It was observed that the bending loss varies proportionally to the cube of the bore diameter and inversely with bending radius. At larger bending angles, output beam profiles of 4 mm bore waveguides showed higher mode mixing, whereas the smallest bore 2 mm waveguides exhibited the least amount of mode mixing. Our investigation indicates that the small-bore silver, silver/polystyrene coated flexible waveguides preserves the single laser mode in addition to possessing a low bending loss. The development of these waveguides can lead to increased applications in THz sensing, communication and biomedical imaging applications.

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