Dual-frequency Characterization of Bending Loss in Hollow Flexible Terahertz Waveguides

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Abstract. Low-loss, hollow, flexible, metal-coated waveguides were designed and fabricated for the maximal transmission of terahertz radiation. Since recent terahertz skin, colon, and breast cancer studies showed a contrast between normal and diseased tissues between 500 to 600GHz frequencies, flexible metal-coated waveguides with various bore diameters were studied at both 584GHz and 1.4THz frequencies for endoscopic applications. Attenuation characteristics of 2µm thick silver-coated waveguides with 99% reflective inner surface were measured as a function of wavelength, bore diameter, bending angle and bend radius. Though the theoretical attenuation coefficient in metal-coated waveguide varies directly as square of wavelength, the propagation loss was found to be smaller at higher wavelengths. This study demonstrates that flexible waveguides with bore diameters less-than 10\(\lambda\) preserve the linearly polarized mode and hence exhibit low bending losses even at smaller bend radii. Also, in contrast to the lower propagation losses in larger bore tubes, the analysis shows higher transmission in smaller bore tubes at larger bending angles. Finally, the dual-frequency investigation of bending and modal characteristics confirms the feasibility of using these metal-coated flexible waveguides at various terahertz frequencies, to obtain low transmission losses even at greater flexures, in addition to the Gaussian mode preservation.

Keywords: flexible waveguides, far infrared, terahertz, hollow waveguides, metal coating, bending loss, mode preservation.

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1 Introduction

The Terahertz (THz) frequency regime of an electromagnetic spectrum extends from 0.1 to 10 THz and lies between the microwave and infrared regions. This spectral region with wavelengths ranging from millimeters to microns is a rapidly developing area in source & detection 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 low energy interactions with the low frequency molecular motions, has expanded its applications into the areas of imaging and spectroscopy [2]. In addition, due to the shorter wavelengths associated with THz rays, they provide better spatial resolution as compared to microwaves. Terahertz technologies have become increasingly important for biological applications due to its non-ionizing property, unlike X-rays [3]. Recently, researchers have shown that THz frequencies can also be used in cancer screening, as they can penetrate through several millimeters of tissue and enable the detection of differences in water content and tissue density [4].

For biomedical endoscopic applications, it is necessary to propagate terahertz radiation through a flexible tube that has low loss even at large bending angles. For imaging applications mode-quality is crucial. Therefore, a flexible terahertz waveguide with low propagation and bending losses along with reasonable mode preservation...
characteristics is an essential tool in the field of interior in vivo terahertz medical imaging. Previously, terahertz waveguides have been fabricated from a variety of materials and with different cross sectional designs [5-8]. The majority of reported terahertz waveguides are either rigid or not quite flexible at larger bore diameters [6,7]. On the other hand, flexible terahertz waveguides suffer from higher propagation losses [9,10]. Matsuura et. al., demonstrated flexible low-loss cylindrical waveguides, however, the fabrication technique employed is not feasible for bore diameters less than 3 mm [11]. We reported the transmission characteristics of low-loss (less than 1 dB/m), hollow, flexible, cylindrical terahertz waveguides fabricated with an inner metal, and metal/dielectric coatings that are small enough in diameter for endoscopic applications (1-2 mm bore diameter). These waveguides were designed and characterized at 1.4 THz (215 µm) frequency [12,13].

Since recent terahertz skin, colon, and breast cancer studies exhibited a contrast between normal and diseased tissues between the frequencies of 500 to 600 GHz [14,15], the Ag coated waveguides with various bore diameters (of the order of 3 to 8λ) were fabricated for the transmission of 584 GHz (513 µm). The primary goal of this study is to characterize the fabricated flexible hollow-core terahertz waveguides at both 1.4 THz and 584 GHz frequencies to confirm the feasibility of using the same waveguide at various terahertz frequencies. This work involves characterizing waveguide operational parameters such as propagation loss as a function of bore diameter, bending loss as a function of bend angle, and modal characteristics as a function of bore diameter and bend angle.

2 Material selection and Fabrication

To obtain flexible terahertz waveguides, the base material was chosen to be polycarbonate (PC). PC tubing is quite flexible even at larger bore sizes and has an advantage over Polyethylene/Teflon due to its smoother inner surface (with nano-meter surface roughness) comparable to silica glass. Since low-loss waveguides not only require highly reflective metal coating but also an adequate uniform layer, both material selection and subsequent quality of the layer deposition are vital elements in obtaining ideal waveguides. The flexible polycarbonate tube was coated with a layer of silver/gold using liquid phase chemical deposition process, described elsewhere [12]. Due to the higher reflectivity values calculated using the Drude parameters, silver (Ag) and gold (Au) were chosen to be germane metals at THz frequencies. To attain 99% reflectivity inside the waveguide, the thickness of the silver film 1 – 2 µm was chosen to be at least 10 times its skin depth. The skin depth of the metal can be computed using Equation 1.

$$\delta = \sqrt{\frac{2\rho}{2\pi f \mu_0 \mu_r}}$$

Here $\rho$ is the resistivity, and $f$ represents the input frequency. The skin depth for silver and gold at 1.4 THz are 0.05 µm, and 0.07 µm respectively; for 584 GHz it is 0.08 µm, and 0.1 µm respectively. Since coating thickness is directly proportional to the coating time, the desired 2 µm thickness of Ag or Au coating (suitable for all terahertz frequencies) can be achieved either by increasing the coating time or solution concentration.

Polystyrene (PS) was chosen to be the dielectric, due to its low extinction coefficient, which enhances the transmission through the waveguide. The thickness of the dielectric coating can be calculated using Equation 2;

$$d_{\text{die}} = \frac{\lambda}{2\pi \sqrt{n_d^2 - 1}} \tan^{-1} \left[ \frac{n_d}{\sqrt{4n_d^2 - 1}} \right]$$

where $\lambda$ represents wavelength and $n_d$ represents the refractive index of the dielectric material at the specific wavelength. The optimal thickness of the polystyrene coating varies directly with wavelength. At 1.4 THz (215 µm wavelength), it is 26.8 µm and for 584 GHz (513 µm wavelength), it is given by 64 µm. The optimal polystyrene layer can be deposited inside a silver coated polycarbonate tube using dynamic liquid phase chemical deposition process. The detail of the fabrication process for the metal and dielectric coatings can be found elsewhere [12]. The desired thickness can be achieved by increasing either coating time, or concentration of polystyrene in the cyclohexane solution. However obtaining a uniform 64 µm thick polystyrene coating is not feasible with the current
deposition technique. Also, once the optimal 27 – 64 µm polystyrene coating for the higher wavelengths such as 300 µm – 513.2 µm is made, it is difficult to bend the Ag/PS waveguides without damaging the polystyrene coating [13]. In addition, the optimal dielectric coating thickness varies as a function of incident wavelength as shown in Equation 2, hence the same metal/dielectric coated waveguide cannot transmit all THz wavelengths. Therefore, 2 µm thick metal only coated waveguides will be used to transmit all THz frequencies, without suppressing the uniformity of the metal coating while bending.

3 Experimental Setup

The source used for this experiment was a dual CO₂ optically pumped far-infrared gas (FIR) laser system operating at 1.4 THz and 584 GHz frequencies. The 1.4 THz line in CH₂F₂ was pumped by the 9R34 transition of the CO₂ laser and 584 GHz line in HCOOH by the 9R28 transition. Near the laser face, the measured terahertz laser output power was 370 mW for the 1.4 THz line. A dielectric waveguide was placed at the output of the FIR laser to attenuate the higher order modes and obtain a Gaussian output mode [16]. In the case of 584 GHz beam, the measured output power before and after the dielectric tube were 33 mW and 10.23 mW, respectively. Since the beam emerging from the FIR laser is a few millimeters in diameter and expands rapidly as it propagates, an optical system was designed to couple the terahertz radiation efficiently into the waveguide. The considerations for the system design were to focus down both THz beams onto the same plane at the input end of dielectric tube that cleans the higher order modes. Maximum transmission in hollow cylindrical metal (metal/dielectric) coated waveguides can be attained by maintaining the ratio of \( \omega_0/r \) as 0.77 (0.64) to couple 90.3% (98.1%) of the lowest order transverse electric (hybrid) TE\(_{11}\) (HE\(_{11}\)) mode [17,18]. The waist of a Gaussian beam is defined to be the radius of the beam where the intensity drops to 1/e² of its peak value.

Fig.1 Experimental setup for the loss measurement in metal, inset: metal/dielectric (a) 4 mm Ag (top), 3 mm Ag, 2 mm Au, and 2 mm Ag, (b) 3 mm Ag/PS (top), 2 mm Au/PS, 4 mm Ag/PS coated terahertz waveguides.

Fig.1 shows a schematic of the optical layout. The measured waist of the 1.4 THz and 584 GHz beams exiting from the dielectric waveguide was 2.36 mm and 2.15 mm, respectively. The laser beam was then allowed to expand in free space before being collimated using a 76 cm focal length TPX lens (L₁) to 22 – 25 mm in diameter. A front surface gold-coated mirror (KM), sitting on the kinematic base, was used to switch between the 1.4 THz and 584 GHz laser frequencies. The collimated beam was propagated 127 cm before reaching an off-axis parabolic mirror (OAP), with 18 cm focal length and 7.6 cm diameter that focuses the beam into a dielectric tube (G). This 3.2 mm
polycarbonate/Pyrex tube was used as a dielectric tube to clean the unwanted higher order modes, as described in section 4. The modal profile of the THz beam at 2.5 cm from the OAP focus is shown in Fig. 2. To characterize the metal only coated polycarbonate tubes, the Gaussian beam exiting from the dielectric tube G was coupled directly into the cylindrical waveguides under investigation. But in the case of the metal/dielectric coated waveguides, a terahertz beam with a finite spot size is required for loss characterization. Therefore, a polyethylene lens of 7 cm focal length with 7.5 cm diameter was used to further focus down the beam exiting from G. The focused Gaussian beam with a 1 mm waist was then coupled into a metal/dielectric coated waveguide of 3.2 mm inner diameter, to excite the HE_{11} mode, by maintaining the ratio of \( \omega_0/r \) as 0.64. A liquid helium cooled silicon bolometer mounted on a scan stage was used as a detector. The two axes XY scanning stage was used to raster scan the beam. The motion control and data acquisition software was written using LabView. The mode profile of the propagating THz radiation was obtained by measuring the spatial intensity variation at the output end of the waveguide. The system SNR was found to be on the order of 65 dB.

4 Mode Cleaning

A short hollow dielectric tube can act as a dielectric waveguide. It can transform the highly diverging multimode FIR laser beam into the lowest order dielectric waveguide hybrid mode, EH_{11}, which then couples efficiently to the free-space Gaussian mode, TEM_{00}. In general, there exist 3 different waveguide modes inside a dielectric tube; transverse magnetic TM_{0m}, transverse electric TE_{0m}, and hybrid EH_{nm} modes. The attenuation for the lowest order transverse electric TE_{01} mode is comparable to EH_{11} in a Pyrex or glass tube. Since the laser beam and the lowest order hybrid mode are both linearly polarized, as a result, the EH_{11} mode is preferentially excited [16]. The coupling between laser source and the transverse magnetic mode, TM_{01}, is very poor as it is not linearly polarized and produces much higher attenuation. Thus, the EH_{11} mode is expected to be dominant inside the tube. The attenuation constant for EH_{nm} modes in dB/m is given by [16],

\[
\alpha_{nm} = 8.686 \left( \frac{u_{nm}}{2\pi} \right)^2 \left( \frac{\lambda^2}{r^3} \right) \text{Re}(v_n)
\]  

\[
&v_n = \frac{N^2 + 1}{2\sqrt{N^2 - 1}}
\]

where N is the complex index of refraction (CIR) of the tube material, \( \lambda \) represents wavelength, and 2r is the inner diameter of the tube.

**Fig. 2** Two-dimensional mode profiles of the propagated terahertz beam acquired using silicon bolometer

a) 20 cm after OAP, b) after 5 cm Polycarbonate tube, and c) 15 cm PC tube.

A polycarbonate tube with CIR 1.64 – i 0.05 was used as a dielectric tube to clean the higher order modes. 5 cm long PC tube provides attenuation constants of 1.25 dB, 6.6 dB, and 16.2 dB for EH_{11}, EH_{12}, and EH_{13} modes,
respectively. 98% of the EH\textsubscript{11} mode was coupled into the dielectric tube by maintaining the ratio of \(\omega_0/r\) as 0.64. Fig.2(b) shows the presence of higher order modes even after transmitting through a 5 cm long polycarbonate tube. Therefore, a long 15 cm polycarbonate tube with 3.2 mm inner diameter was used to clean the modes, with attenuation constants of 3.76 dB, 19.79 dB, and 48.7 dB for EH\textsubscript{11}, EH\textsubscript{12}, and EH\textsubscript{13} modes. Fig.2(c) shows the cleaned output Gaussian mode exiting from the dielectric tube, acquired using a bolometer.

5 Results and Discussion

5.1 Propagation Loss Measurement

The total transmission loss of a waveguide is the sum of the propagation and bending losses. The transmission loss in a waveguide can be found experimentally by using Beer-Lambert’s law as follows,

\[
\alpha = \frac{10}{L} \log \left( \frac{P_m}{P_{out}} \right) \text{dB/m}
\]

where, \(L\) represents the length of the waveguide, \(P_m\) and \(P_{out}\) are the input and output power of the terahertz beam respectively. The theoretical attenuation coefficient for the TE\textsubscript{pq} modes in hollow metal straight terahertz waveguides is given by [17],

\[
\alpha(TE_{pq}) = 10 \cdot \frac{u^4}{u^2 - p^2} \cdot \frac{n}{n^2 + \kappa^2} \left( \frac{\lambda_0^2}{(2\pi)^2 r^3} + \frac{p^2}{u^4 r} \right) \text{dB/m}
\]

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, \(\lambda_0\) is the wavelength of the laser, and \(u\) is the phase constant representing \(q\)th zero of the Bessel function \(J_q(x)\).

In this study, Equation (4) was used to calculate the experimental attenuation coefficient values. The theoretical attenuation coefficient in metal-coated terahertz waveguides at 1.4 THz and 584 GHz frequencies were calculated using Equation (5). To obtain maximum transmission in metal-coated waveguides and to couple 90.3% of the lowest order TE\textsubscript{11} mode, the ratio of the beam waist and bore radii (\(\omega_0/r\)) has to be maintained as 0.77 [17]. Therefore, to couple terahertz radiation efficiently into a 2 mm bore diameter waveguide, a spot size of 0.77 mm is required. Nonetheless, the beam waist acquired at the output end of the dielectric tube, after cleaning the higher order modes, was 1mm.

![Fig. 3 Experimental and theoretical attenuation coefficients as a function of bore diameter for silver coated terahertz waveguides at 1) 1.4 THz and 2) 584 GHz.](image)

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Due to the higher coupling losses involved in coupling a 1 mm wide beam (instead of 0.77 mm), a cutback technique was used to accurately determine the absorption coefficient for each straight waveguide. If the sensitivity setting and attenuators were fixed for all measurements, the attenuation coefficient can be obtained by taking the ratio of the input and output powers of the waveguide. The Power can be calculated by adding the intensity of each pixel, and maintaining the same pixel number in both the input and output beam profiles. Fig. 3 shows the theoretical and experimental attenuation coefficients of silver coated waveguides as a function of bore diameter, d, at both 1.4 THz and 584 GHz. Since, equation (5) shows the direct dependence of attenuation coefficient on square of the wavelength, the loss in metal waveguides is expected to be higher for greater wavelengths. However, as the complex refractive index of the metal also varies as a function of wavelength, the resultant propagation loss in the waveguide decreases as the wavelength increases. The experimental attenuation coefficients for all 4.1, 3.2, and 2 mm bore diameter silver-coated waveguides (as shown in Fig. 3) were smaller at 513 µm than 215 µm. From Fig. 3, the theoretical and experimental losses were found to be in good agreement and the predicted trend of decreasing loss with increasing bore diameter is clearly visible at both frequencies. In general, the experimental propagation loss of the waveguides will be higher than the theoretical losses. The discrepancy between theoretical and experimental attenuation coefficients can be due to the edge coupling effect, roughness, and non-uniformity of the coating layer.

<table>
<thead>
<tr>
<th>Bore Diameter</th>
<th>1.4 THz</th>
<th>584 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Loss (dB/m) in Ag</td>
<td>Loss (dB/m) in Au</td>
</tr>
<tr>
<td>4mm</td>
<td>1.44</td>
<td>1.77</td>
</tr>
<tr>
<td>3mm</td>
<td>1.8</td>
<td>2.64</td>
</tr>
<tr>
<td>2mm</td>
<td>2.9</td>
<td>3.5</td>
</tr>
</tbody>
</table>

The straight losses for hollow flexible 50 - 55 cm long silver, and gold coated THz waveguides of different bore sizes were measured at 1.4 THz and 584 GHz frequencies. The list of theoretical and experimental attenuation coefficients for Ag and Au coated waveguides for various bore diameters were summarized in Table 1 as a function of frequency and bore diameter. Twelve tested 4.1 – 2 mm bore diameter silver, gold coated waveguides had experimental coupling efficiencies between 75% and 80%. The standard deviation of the power measurements are less than 0.25 dB. From Table 1, the better agreement between experimental and theoretical losses in the case of all gold coated waveguides, unlike silver coated waveguides, could have resulted from the greater uniformity of the layer achieved using a closed loop LPCD fabrication process [12]. Propagation losses of 1.77 dB/m and 1.62 dB/m were attained with 4 mm bore diameter silver coated waveguides at 1.4 THz and 584 GHz frequencies, respectively.

5.2 Bending Loss Measurement

The bending loss in hollow flexible terahertz waveguides varies as a function of wavelength, bend radius, bending angle, and waveguide bore diameter. In order to show the dependence of $r^3$, the attenuation coefficient per bore diameter cubed was plotted as a function of bending angle for the three silver coated waveguides attained at 584 GHz in Fig. 4. All the loss measurements were acquired with the laser polarization perpendicular to the plane of bending (s-pol). Here, the experimental total attenuation coefficients for 55 – 60 cm long flexible waveguides, with a fixed 6.5 cm bend radius, were obtained using cutback technique. Fig. 4 shows the direct dependence of attenuation coefficient on bending angle for all bore diameters. It is also observed that the total loss increases abruptly for smaller bore diameters, as predicted by the theory. The Y-intercept multiplied with bore diameter cubed...
yields the straight loss, which is the total transmission loss when the bending angle was 0°. Since the slope of the bending loss curve in Fig. 4 is invariant for various bore diameter waveguides (similar to the inset graph with the attenuation coefficients measured at 1.4 THz frequency [13]), it is evident that the bending loss varies as the cube of the bore radius.

Table 2 summarizes the total transmission loss at 584 GHz in metal-coated waveguides of different bore diameters at various bending angles. The total transmission loss in metal-coated waveguides consists of two terms with the first being propagation loss as a function of the bore diameter; and the second being bending loss as a function of bore diameter at fixed bend radius. Though the propagation loss decreases with increasing bore diameter as shown in Table 2, it is noticed that the total transmission loss in bent 4 mm diameter Ag coated waveguides increases abruptly with bending angle. This may have resulted from the bending loss term which varies as the bore diameter cubed that leads to rapid changes in bending loss with the accretion of bore radius. However, the bending loss variation inside a 2 mm silver coated waveguide with a 6.5 cm bend radius was measured to be less than 0.7 dB/m. In addition, the attenuation coefficient in 2 mm silver coated waveguide is invariant (<0.2 dB/m) for 60° to 150° bending angles, which can be explained from the relation 2r ≈ 4λ for 2 mm tubes at 513 µm wavelengths. As the theoretical attenuation coefficient calculations were based on the 2r >> 10λ assumption (which is invalid in this case), hence an unpredicted behavior is expected as described in section 5.3.

Table 2 Total transmission loss of Ag coated waveguides as a function of bending angle and bore diameter.

<table>
<thead>
<tr>
<th>Bending Angle (degrees)</th>
<th>Total transmission loss (dB/m)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>ID 4 mm</td>
</tr>
<tr>
<td>0°</td>
<td>1.62</td>
</tr>
<tr>
<td>30°</td>
<td>2.98</td>
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<tr>
<td>60°</td>
<td>4.38</td>
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<tr>
<td>90°</td>
<td>5.7</td>
</tr>
<tr>
<td>120°</td>
<td>7.51</td>
</tr>
<tr>
<td>150°</td>
<td>8.4</td>
</tr>
</tbody>
</table>

5.3 Modal Characteristics

The output mode profile is crucial for biomedical imaging applications that require preservation of free space Gaussian TEM00 mode. Modal characteristics for 55 cm long silver-coated waveguides were obtained at both 1.4 THz and 584 GHz using the experimental setup shown in Fig. 1. The spatial intensity distributions of the terahertz radiation propagated through silver coated waveguides were obtained as a function of bending angle by coupling the linearly polarized radiation and exciting the lowest order transverse electric TE11 mode. The intensity distributions at both frequencies were plotted for metal-coated waveguides as a function of various bore diameters (rows), and 0° to 120° bending angles (columns). In the case of the silver coated waveguides characterized at 1.4 THz frequency, it is evident that the launched TE11 mode develops fully at the output when propagated through straight 3.2 mm, and 2 mm bore diameter tubes. But, the 4 mm inner diameter waveguide exhibits a distinctly multimode pattern even when it is kept straight. In addition, both 4.1 mm and 3.2 mm bore diameter tubes exhibit the existence of higher order modes.
modes when they were bent to 6.5 cm bend radius. However, the smallest 2 mm bore waveguide shows the least amount of mode mixing compared to large bore sizes. As predicted from mode coupling theory, by maintaining the ratio of $\omega_0/r$ as 0.77, only 90.3% of $TE_{11}$ mode will be coupled into the waveguide and hence, the higher order modes will exist in the metal-coated waveguide [17]. On the contrary, in smaller bore waveguides these higher order modes attenuate rapidly as the loss increases. Also, due to the deformation caused while bending larger bore diameter waveguides, some of the mode energy will be coupled into higher order modes.

On the other hand, when the 2 to 4.1 mm (4 to 8λ) inner diameter waveguides were characterized at 584 GHz, they exhibited largely single mode output and no existence of higher order modes, even when bent to 120° bending angle with a bend radius as small as 6.5 cm. By inserting the wire grid polarizers between the waveguide and the detector, it has been observed that the vertical polarization of the source beam is largely maintained in 2 mm tubes at both frequencies as well as in the 3.2 mm and 4 mm tubes at 584 GHz. This demonstrates that the output mode in waveguides with very large bore diameter (compared to the wavelength) is not a single mode but converge to the linearly polarized Gaussian mode as the bore diameter decreases. This proves the hypothesis that when bore size is 12λ or less, the waveguide becomes essentially single mode [19,13]. The propagation loss in 4.2 mm diameter waveguide is small compared to 2 mm waveguide but the bending loss is high for larger bores. In contrast, the smaller bore tube inherently provides higher propagation loss but low bending loss and preserves the launched Gaussian mode. Therefore, applications that require low transport losses and good mode quality over long distances, tubes with bore diameters <12λ are preferable.

![Spatial output profile from silver coated waveguides](image)

**Fig. 5** Spatial output profile from silver coated waveguides at (I) 1.4 THz, (II) 584 GHz as a function bore diameter as first index (2) 2 mm, (3) 3 mm, (4) 4 mm; and bending angle as second index (1) 0°, (2) 60°, (3) 120°.

### 6 Summary

In conclusion, flexible terahertz polycarbonate waveguides with Ag and Au coatings have been fabricated successfully using a liquid phase chemical deposition process. These waveguides were characterized for the transmission of terahertz radiation at both 1.4 THz and 584 GHz frequencies. The experimental data was calibrated by measuring the beam profile exiting the waveguide. Propagation losses as small as 1.7 dB/m were achieved with 4 mm inner diameter silver coated waveguides at both frequencies. The propagation loss in larger diameter tubes is less as compared to smaller bores. However, the total transmission loss increases abruptly in larger bore tubes since the bending loss varies directly as the bore diameter cube. In addition to the preservation of launched Gaussian mode, 2 mm metal-coated waveguides exhibited the least variation in total transmission loss (less than 1 dB/m) for 0° to 150° bending angles. Our investigation demonstrates the feasibility of using the same 2 mm diameter 1 µm
thick silver-coated waveguides for both frequencies to obtain low loss single mode outputs. The development of these waveguides can lead to applications in terahertz communication, sensing, and biomedical endoscopic applications.

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References


