Silver-coated Teflon hollow waveguides for the delivery of terahertz radiation

Jeffrey E. Melzer*[a], Miguel Navarro-Cía[b,c], Oleg Mitrofanov[b], and James A. Harrington[a]
[a]Dept. of Materials Science & Engineering, Rutgers University, Piscataway, NJ 08854; [b]Dept. of Electronic and Electrical Engineering, University College London, London WC1E 7JE, UK; [c]Dept. of Electrical and Electronic Engineering, Imperial College London, London SW7 2BT, UK

ABSTRACT

Significant research exists regarding the successful implementation of hollow waveguides for the low-loss transmission of infrared radiation in applications ranging from laser power delivery to spectroscopy. With the continued development of terahertz (THz) technologies and applications, it is often advantageous to have a waveguide for the transmission of THz radiation. This study focuses on the fabrication of novel silver-coated polytetrafluoroethylene (PTFE) waveguides for the transmission of terahertz radiation. The hollow structure described in this paper is made by depositing a thin film of Ag on the outer surface of a dielectric tube. This is in contrast to depositing metallic and dielectric thin film coatings on the inner surface of capillary tubing as is commonly done for IR and some THz transmissive waveguides. In this work, the Teflon tubing itself is the dielectric layer that is used to enhance the reflectivity of the Ag. Theoretical loss calculations will be presented and compared to the loss obtained for the guides measured at THz frequencies. In addition the spectra of the guides in the infrared region are also measured as a means to study the uniformity of the Teflon "layer" and to confirm the wall thickness of the Teflon tubing. The surface topography of the silver / PTFE waveguides is obtained and the resulting surface roughness related scattering losses are calculated. The implications of the terahertz fiber for applications ranging from nondestructive evaluation (NDE), security, and medical imaging are briefly discussed.

Keywords: terahertz waveguides, hollow fiber optics, Teflon, dielectric tube waveguides

1. INTRODUCTION

The ongoing research and development of terahertz (THz) technologies for the potential application to fields such as imaging, nondestructive evaluation, and security,[1] has led to the desire for a passive optical component to guide such radiation. Hollow waveguides are an obvious choice to fill this role due to their successful implementation in the visible and infrared (IR) regions of the electromagnetic spectrum, attaining low propagation losses and good modal properties. Significant research has been performed on conventional visible and IR Hollow Glass Waveguides (HGWs), which contain a metal or metal / dielectric film structure often deposited via dynamic liquid phase deposition (DLPD) on the inner surface of a fused silica capillary. While the metallic layer serves as an internal mirror to confine radiation to the hollow core, an optional thin dielectric layer may subsequently be deposited to enhance the reflectivity of the structure, thereby reducing the attenuation losses. To fabricate an analogous metal / dielectric waveguide designed for the delivery of THz radiation, the approach must be modified to meet key design requirements, most notably the larger dielectric film thickness. Waveguides with target operating wavelengths located in the IR region require dielectric film thicknesses ranging from tens to hundreds of nanometers, while in the THz region, dielectric films must be on the order of tens to hundreds of microns thick. As a result, the current DLPD fabrication procedure for the deposition of the dielectric film is not viable, as it is difficult to deposit uniform films thicker than 15 microns. Figure 1 below illustrates the difference between the conventional IR fiber and the THz fiber.

*jeffrey.melzer@gmail.com; phone 1 609 203-3385; irfibers.rutgers.edu

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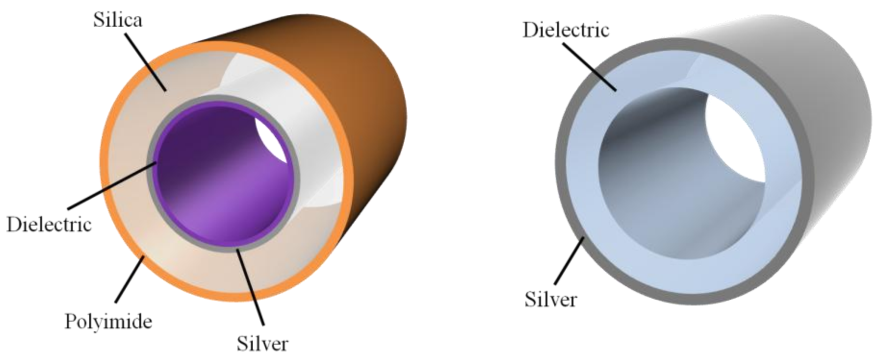

Figure 1. A typical infrared waveguide (left) and a terahertz waveguide (right). The IR waveguide consists of a silica capillary with protective polymer coating with inner coatings of a silver and a dielectric layer. The THz waveguide is a dielectric tube with an outer silver coating.

The new fabrication approach entails the deposition of a metallic film on the outer surface of a dielectric tube of desired wall thickness. This approach creates the same metal / dielectric structure, while overcoming the obstacle of depositing such a thick dielectric film, as the dielectric tube can be extruded to the necessary specifications for the operating wavelength in question. In determining a suitable dielectric material, polymers were investigated due to their low absorption coefficients throughout the THz frequency region. PTFE, commonly known by its trade name Teflon, was chosen due to its ease in acquisition and customizability, along with its good THz optical properties, with absorption coefficients reported to be lower than 0.9 cm^{-1} at frequencies below 1 THz.[2] The choice of Teflon as the dielectric tube material, however, does require the etching of the outer tube surface prior to silver deposition owing to Teflon's exceptionally low coefficient of friction, and thus poor adhesion properties. Silver is chosen as the outer metal coating as it has high reflectivity in the THz regime and its deposition procedure is well established in HGW research.[3]

2. DESIGN AND THEORY OF SILVER / TEFLON THZ WAVEGUIDES

2.1 The metallic film

The metallic film for the THz waveguide is chosen to be silver due to its high value of reflectivity throughout the THz frequency range and its ease in deposition through liquid phase methods. The thickness of the silver film must exceed the skin depth, δ, of the radiation in use to ensure that light does not penetrate through the layer and is contained within the waveguide hollow core. The skin depth of radiation in materials is proportional to the square root of the resistivity, as shown in Eq. 1, and thus materials with low resistivities have small skin depth values.

$$\delta = \sqrt{\frac{\rho\lambda}{2\pi c \mu_r \mu_0}} \tag{1}$$

where ρ is the resistivity of the material; c is the speed of light; μ_r is the relative permeability of the material; and μ_0 is the permeability of free space. Figure 2 shows the variation of skin depth with wavelength and frequency of various metals. Incidentally, silver has the highest resistivity of metals thereby resulting in the smallest required film thickness at all wavelengths. Silver film thicknesses upwards of approximately 40 nanometers are required so that the THz radiation does not penetrate the Ag film.

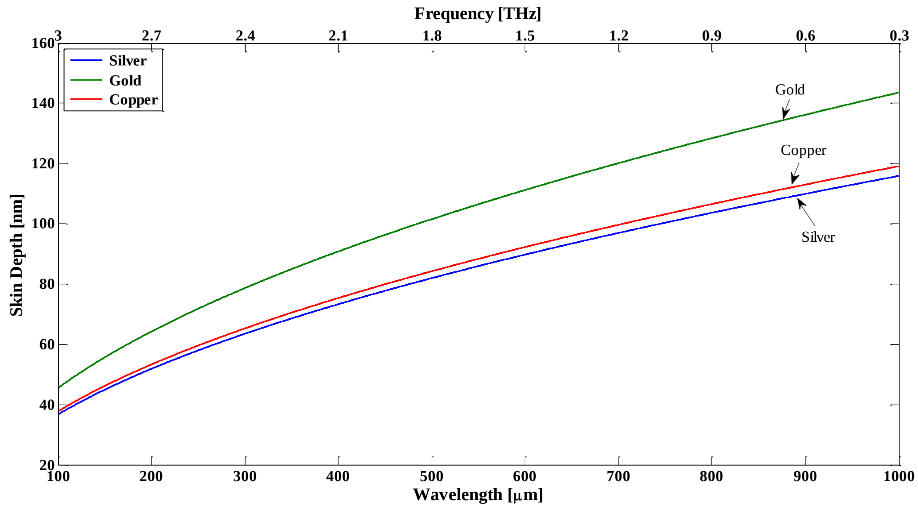

Figure 2. The variation in skin depth for different metals at terahertz wavelengths. The resistivities of the metals are $\rho = 1.59 \times 10^{-8}\ \Omega \cdot m$ for silver, $\rho = 1.68 \times 10^{-8}\ \Omega \cdot m$ for copper, and $\rho = 2.44 \times 10^{-8}\ \Omega \cdot m$ for gold.

A significant consideration in visible and IR HGWs is the surface roughness of the silver film, but is not nearly as important in THz waveguides for two major reasons. Firstly, the surface roughness related scattering losses are inversely proportional to the square of the wavelength. Therefore, going from a wavelength of 3 microns in the IR to 300 microns in the THz range results in a 10,000 fold reduction in theoretical roughness related losses. This relationship can be seen in Eq. 2, relating the attenuation coefficient resulting from scattering due to roughness, α_r, to the wavelength of operation of the waveguide.

$$\alpha_R \sim \left(\frac{4\pi\sigma_{RMS}\sin\theta}{\lambda}\right)^2 \tag{2}$$

where σ_{RMS} is the root-mean-square (RMS) surface roughness of the film; θ is the incidence angle with respect to the waveguide wall; and λ is the wavelength of use.[4] The second reason is that the RMS roughness parameter in Eq. 2 does not correspond to the exposed surface of the silver film, but rather to the interface between the Teflon tube and the silver film. Rabii et. all have shown that in the case of visible and IR HGWs, $\sigma_{RMS} \sim t^{1/2}$, where t is the silvering time.[5] In the case of the THz waveguide, however, the roughness value is entirely independent of the silvering time as the roughness at the Teflon / silver interface does not change. This is beneficial in the sense that a thicker silver film can be deposited without concern regarding roughness related losses due to the extended deposition times. With respect to the surface roughness value of interest at the Teflon / silver interface, a large RMS roughness value is not expected. RMS roughness values obtained with atomic force microscopy yielded 34.5 nanometers for the Teflon surface and 61.8 nanometers for the etched surface. These values are too small to contribute significantly to overall losses at large operating wavelengths in the THz region.

2.2 The dielectric film

The use of a metal / dielectric film structure compared to a metal-only film leads to the enhancement of the reflection of the structure at a target wavelength due to the constructive interference of the reflected rays. Furthermore, the addition of a dielectric film reduces the suppression of TM modes encountered in a metal-only waveguide, making the HE_{11} hybrid mode the dominant propagating mode in comparison to the dominant TE_{11} mode in metallic THz guides. The attenuation coefficient calculated through a wave optics approach for a metal / dielectric waveguide for the hybrid modes is given as,

$$\alpha_{lm} = \left(\frac{\mu_{lm}}{2\pi}\right)^2 \frac{\lambda^2}{a^3}\left(\frac{n}{n^2+k^2}\right)\frac{1}{2}\left(1+\frac{n_F^2}{\sqrt{n_F^2-1}}\right)^2 \tag{3}$$

where α_{lm} is the attenuation coefficient of the HE_{lm} mode; μ_{lm} is the mode parameter of the specific HE_{lm} mode; λ is the design wavelength of the waveguide; a is the bore radius of the waveguide; $n - ik$ is the complex refractive index of the metallic film; and n_F is the refractive index of the dielectric.[6] Equation 3 assumes a straight waveguide and a lossless dielectric film. For the lowest loss HE_{11} mode, the mode parameter is given as μ_{11} = 2.4048. Figure 3 shows the attenuation as a function of wavelength for waveguides of different bore sizes. Since the loss is directly proportional to the square of the operating wavelength and inversely proportional to the cube of the waveguide bore radius, it is necessary to use sufficiently large diameter waveguides to minimize the higher losses incurred at these wavelengths compared to IR and visible waveguides. However, too large of a diameter results in a reduction of waveguide flexibility and the propagation of potentially undesirable higher-order modes, and thus a compromise must be made.

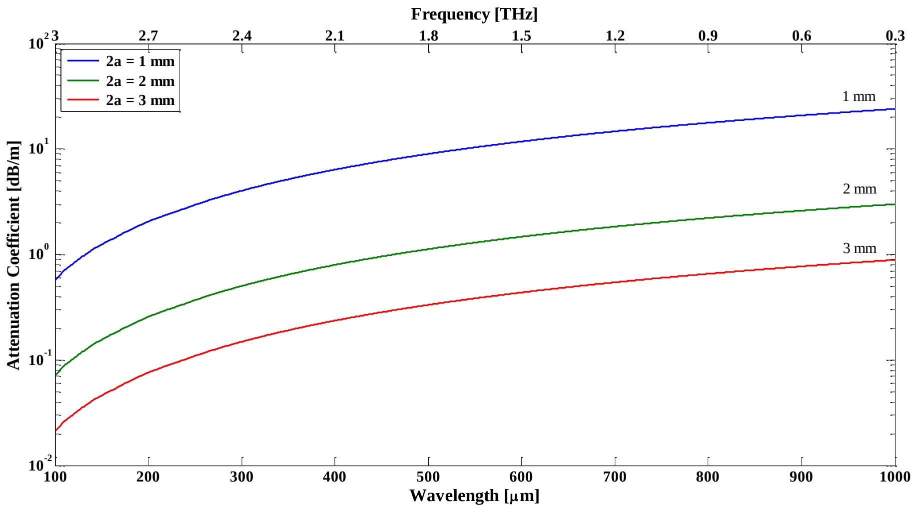

Figure 3. Theoretical attenuation coefficients of silver / PTFE waveguides in the THz region with differing inner diameters of 1, 2, and 3 millimeters. The calculation is done with gold rather than silver as data is available concerning its optical constants in the THz region.

The calculated attenuations in Fig. 3 use the optical constants of gold rather than silver as those for gold are available in the literature.[7] As the two metals behave similarly in the IR region, it is expected that their behavior is similar in the THz frequency region as well. The refractive index of Teflon is assumed to be 1.43 throughout the region.

The thickness of the dielectric material directly determines the functional wavelength(s) of a metal / dielectric waveguide due to the interference effect. In determining the optimal thickness, d_o, of a single dielectric film for a target wavelength of operation, the following equation is used:

$$d_o = \frac{\lambda_d}{2\pi\sqrt{n_F^2 - 1}} \tan^{-1}\left(\frac{n_F}{(n_F^2 - 1)^{1/4}}\right) \tag{4}$$

where n_F is the refractive index of the dielectric film.[4] This study focuses on the coating of a Teflon tube with a wall thickness of approximately 120 microns, corresponding to a target wavelength of 750 microns, or a frequency of 0.4 THz.

3. FABRICATION OF SILVER / TEFLON THZ WAVEGUIDES

3.1 Etching and sensitization

To overcome Teflon's extremely low coefficient of friction it is necessary to modify the surface to allow for subsequent adhesion of a silver film. This is done through an etching procedure in which the fluorocarbon bonds are broken in the presence of a reactive alkali metal. Specifically, a commercial etchant produced by Acton Technologies (FluoroEtch) comprised of sodium naphthalene complex dissolved in 2-methoxyethyl ether was used. The Teflon tube to be coated is submerged in a test tube containing the etching solution, resulting in the visible darkening of the etched outer surface of the tube. Although not a precise science, longer etching times and higher etchant temperatures tend to correspond to a greater degree of darkening of the Teflon surface. The etching procedure in this study was done for two minutes at room temperature. Following the etching process, the tube is immersed in a solution of isopropyl alcohol which serves to deactivate the sodium naphthalene complex thereby halting any further etching from residual etchant solution remaining on the dielectric tube.

In addition to the etching process, the waveguide is sensitized prior to the silvering procedure. This is done to ensure that the initial stages of silver nucleation and growth are localized on the Teflon surface as opposed to the deposition apparatus. The sensitization solution consists of palladium chloride and excess stannous chloride with added hydrochloric acid. A stable colloidal suspension of elemental palladium particles in formed in the following chemical reaction,

$$Pd^{2+} + Sn^{2+} \xrightarrow{HCl} Pd^{0} + Sn^{4+} \tag{5}$$

in which the stannous ions reduce the palladium to its elemental form and the resulting stannic ions combined with the excess stannous ions stabilize the colloidal solution through the formation of a tin-ion shell around the particle, preventing agglomeration.[8] The Teflon tube is placed in the sensitizing solution followed by a 5 wt% NaOH solution to neutralize the acidity of the previous solution.

3.2 Silvering

The waveguide is silvered via the DLPD method using the same procedure employed in visible and IR HGWs for the inner capillary silver coating.[4] In this case, the outer surface of the Teflon tube is coated with silver. To be able to perform such a procedure, the Teflon tube is placed in the center of a plastic tube to allow the solutions to flow between the inside of the encasing tube and the outside of the Teflon tube, consequently depositing on the Teflon outer surface. A 14.36 mM ammonia-complexed silver (I) ion solution and reducing 3.10 mM dextrose solution are mixed and using a peristaltic pump, they are pumped through the plastic tube where they react to deposit a silver layer. The setup for this procedure is illustrated in Fig. 4 below. The Teflon tubing used in this study had a inner diameter of 2 mm and silvered samples ranged in length from as short as 8 cm to as long as 20 cm.

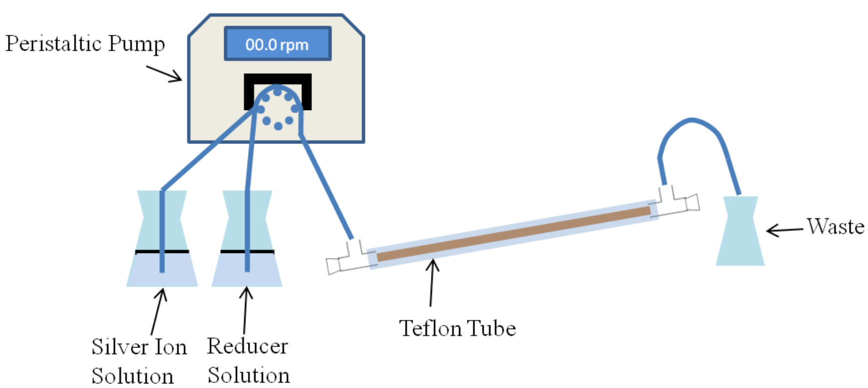

Figure 4. Representation of the setup utilized during the silvering procedure for the silver / Teflon THz waveguide.

Typical coating times for THz waveguides are approximately 30 – 40 minutes. Though such a long silvering time would contribute significantly to roughness related losses in visible and IR HGWs, long deposition times are inconsequential in Thz waveguides, as discussed earlier, since the roughness of interest is independent of silvering time. One parameter of interest during the deposition is the flow rate of solution through the encasing tubing. A flow rate too slow results in a less uniform coating, with a greater degree of silver deposition occurring on the portion of the waveguide closer to the pump due to solution depletion along the waveguide length. To combat this, the pump rate may be increased to a sufficiently fast speed, or the solution temperatures may be decreased to retard the nucleation and growth process.

4. DISCUSSION OF RESULTS

4.1 IR spectral analysis

The infrared spectrum of the silver / Teflon fiber was obtained to determine the quality and uniformity of the starting Teflon tube and as a means to measure the film thickness. Due to the interference effect, peaks and troughs appear in the absorbance spectrum corresponding to destructive and constructive interference of light. A clean spectrum with well defined peaks implies that the dielectric film, in this case the Teflon wall, is of good quality with minimal variation in thickness. Figure 5 shows the IR spectrum of the THz waveguide from 1 to 4 μm.

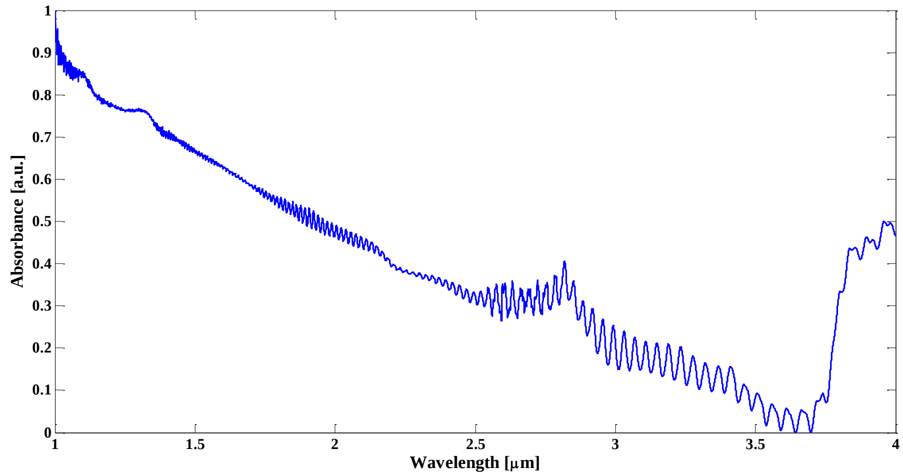

Figure 5. An IR spectrum obtained with a Bruker Tensor 37 FTIR spectrometer and cryogenic indium antimonide detector.

The spectrum was taken with a Fourier Transform Infrared (FTIR) spectrometer using an external beam and a parabolic mirror to focus light into the waveguide. A liquid nitrogen cooled indium antimonide (InSb) detector was used to obtain a spectrum in the 1-4 micron range. The spectrum indicates that the dielectric tube is in fact of high quality as a result of the clarity of peaks in the spectrum and the overall lack of noise. The gradual increase in absorbance with decreasing wavelength occurs due to both decreasing detector sensitivity and the contribution of increased scattering related losses. From the spectrum, the thickness of the dielectric film, or in this case the dielectric tube wall thickness, can be calculated based on the locations of successive interference peaks. The portion of the spectrum ranging from 2.8 microns to 3.5 microns is expanding in Fig. 6 with dotted lines corresponding to the peak locations. From this spectrum, the following equation is used to determine the film thickness, d:

$$d = \frac{\sum_{n=2}^{N}(\lambda_{n-1}^{-1} - \lambda_{n}^{-1})^{-1}}{4(N-1)\sqrt{n_F^2 - 1}} \tag{6}$$

where λ_n is the wavelength of the nth interference peak; N is the total number of peaks used in the calculation; and n_F is the refractive index of the dielectric.

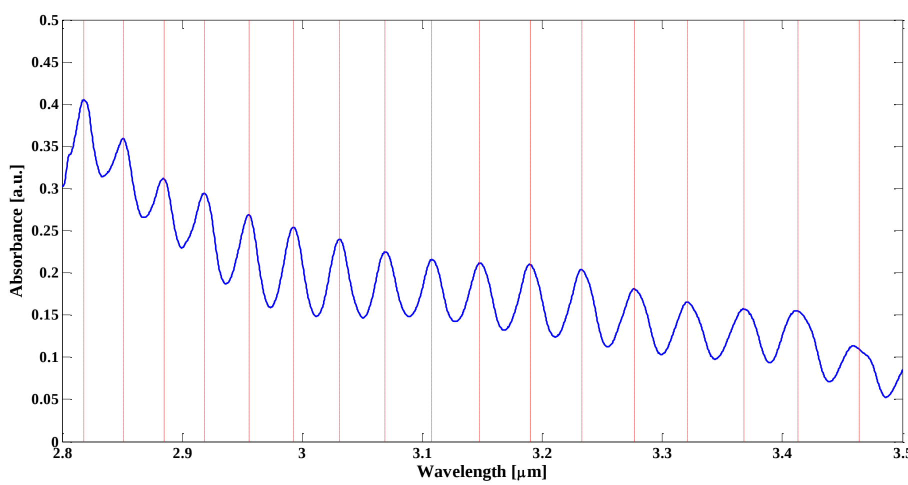

Figure 6. Expanded view of the IR spectrum from 2.8 to 3.5 microns, with interference peak locations emphasized.

The Teflon wall thickness calculation using Eq. 6 for the waveguide used in this study resulted in a value of 67 microns ± 2 microns. The standard deviation of 2 microns is very low and further confirms a high degree of uniformity of the tubing. However, a physical measurement of the tubing yields a wall thickness of around 120 to 130 microns. This disparity has been attributed to the high absorption of Teflon in the 1 to 4 μm range, resulting in a preferential absorption of TM modes over TE modes, causing only the presence of TM peaks in the experimental absorption spectrum. Figures 7a through 7c demonstrate the simulated IR spectrum with increasing values of extinction coefficient for the Teflon tube. The graphs on the left distinguish between the peaks originating from the TE and the TM polarized components, while those on the right show the resulting total absorbance spectrum combining both polarizations.

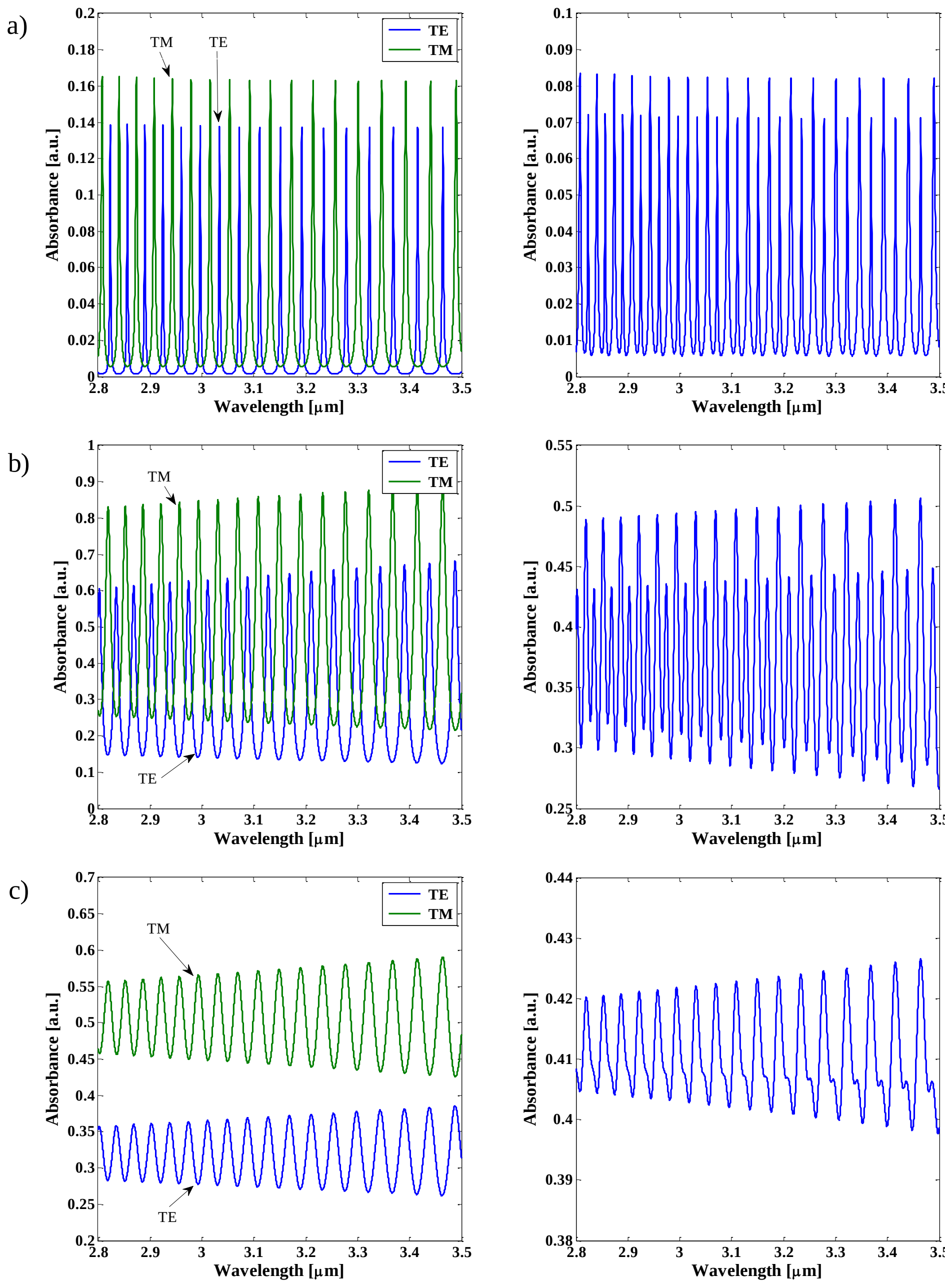

Figure 7. Simulations of the silver-coated Teflon tube with increasing extinction coefficient of a) k = 0, b) k = 0.001, and c) k = 0.003.

The spectra are simulated with a ray optics approach using a transfer matrix method analysis with a dielectric tube wall thickness of 130 microns with a refractive index of 1.35 in the region. The constants used for silver in the calculation are those reported by Palik.[9] Figure 7a shows the spectrum assuming a lossless dielectric. Figures 7b and 7c show the spectrum simulated with extinction coefficient values of k = 0.001 and k = 0.003, respectively. As the extinction coefficient increases, it can be seen that the TM modes are absorbed to a greater degree than the TE modes. In Fig. 7c, the TE absorption peaks are almost entirely suppressed in the absorption spectrum and solely the TM peaks are visible in the combined spectrum on the right. It is expected that large dielectric absorption in the region accounts for the calculated Teflon wall thickness of approximately half of the actual value.

4.2 Far-IR spectroscopy

Spectroscopy of the silver / Teflon waveguide was performed in the far infrared as an additional means of determining waveguide quality and dielectric wall thickness. The spectrum shown in Fig. 8 was obtained using a Bruker VERTEX spectrometer with a helium-cooled silicon bolometer.

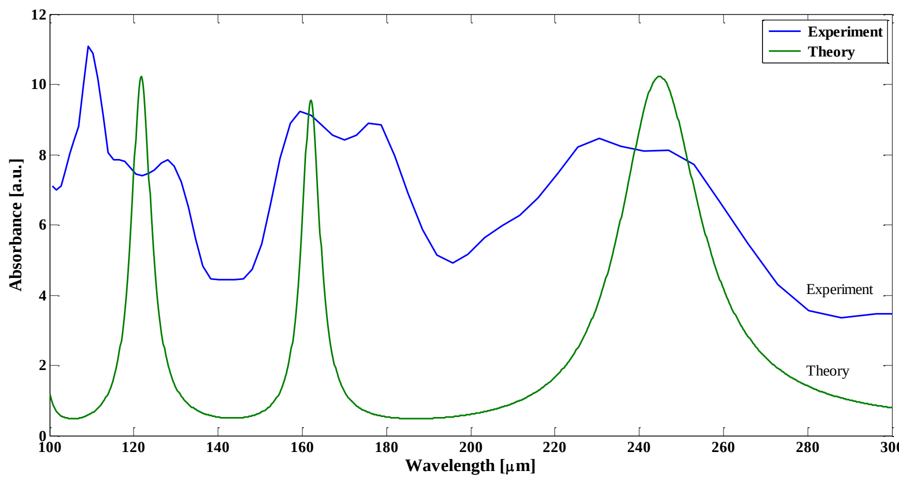

Figure 8. The far IR spectrum of the silver / Teflon waveguide taken with a Bruker spectrometer with silicon bolometer.

The experimental peaks can be seen to match up with the theoretically predicted peak locations for a 126 μm Teflon dielectric film. The theoretical calculation was performed in the same method as those in Fig. 7 and under the assumption of a lossless dielectric. However, the experimental peaks do appear to be broader than expected. Such broadness generally implies a lack of uniformity in the film, contrasting the well-defined peaks encountered in the 1-4 μm spectrum.

4.3 THz time-domain spectroscopy

The spectrum of the hollow waveguide was taken in the terahertz frequency range using a near-field time-domain spectrometer (TDS) to determine the optical response of the waveguide in the desired region of operation. The details of the experimental setup and procedure are similar to those described in Reference [10]. The overlaying simulated spectra for the lowest loss HE_{11} mode and for the TE_{12} mode are shown to illustrate the origination of losses in the experimental data in Fig. 9 below. The experimental data confirms that the silver film exceeds the skin depth of THz radiation due to the presence of interference peaks in the spectrum. The numerical simulations were carried out in CST Microwave Studio assuming a bulk conductivity of silver of $\sigma_{Ag} = 6.3012 \times 10^7$ S/m and using optical constants for Teflon obtained from Reference [11].

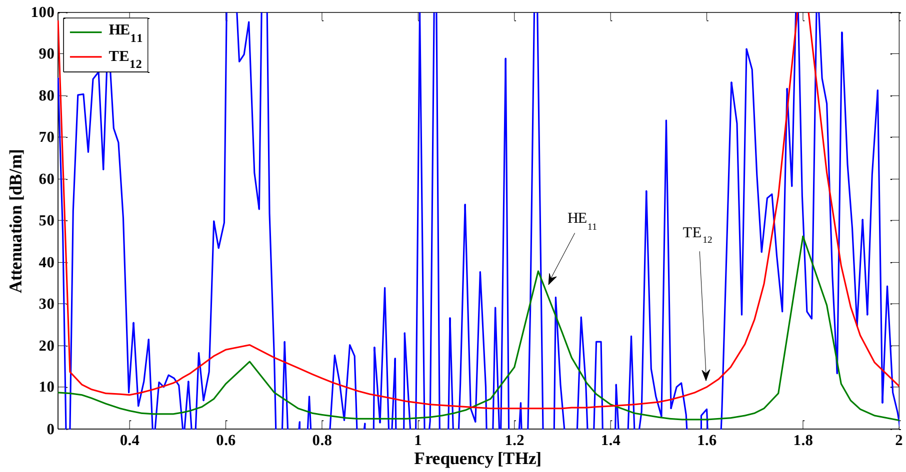

Figure 9. The experimental terahertz spectrum for the silver / Teflon waveguide with overlaying simulated spectra for the HE_{11} and TE_{12} modes.

It is believed that the ripples in the spectrum occur as a result of multi-mode propagation in the guide, and thus mode interference. While a simulation of the TE_{11} mode of a silver-only waveguide predicts a loss of approximately 1.7 dB/m, the simulated HE_{11} mode in a silver / Teflon waveguide leads to an attenuation value of about 3.5 dB/m at the optimal frequency. Thus, it appears that at low frequencies, the addition of a dielectric film is not in fact advantageous in the case of Teflon. However, at higher frequencies a silver / Teflon waveguide is predicted to produce improved losses over a metal-only guide, and therefore further research must be conducted using dielectric tubes of reduced wall thickness compared to the ~120 μm guide analyzed in this study.

5. CONCLUSION

A method for the successful fabrication of a silver / Teflon waveguide for utilization at THz frequencies has been established. This method includes depositing a silver coating on the outer surface of a Teflon tube of predetermined thickness, forming a metal / dielectric structure analogous to that implemented effectively in infrared waveguides. The use of a dielectric tube as a starting material allows for the realization of large dielectric film thicknesses not attainable by the conventional DLPD methods used in IR HGWs. Future research will focus on silver / Teflon THz waveguides optimized for higher frequencies where predicted losses for the dominant HE_{11} mode in the waveguide will be lower than those predicted for the propagating TE_{11} mode in a metal-only guide. Continued development of this technology would provide a low-loss waveguide for THz radiation delivery in applications such as nondestructive evaluation, endoscopy, and standoff detection.

6. ACKNOWLEDGMENTS

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