ABSTRACT

In recent times, terahertz (THz) or the far-infrared region of the electromagnetic spectrum has gained critical significance due to many potential applications including medical diagnostics, nondestructive evaluation of material parameters, chemical sensing, remote sensing and security screening. However with the development of various applications, the need of guided systems for the transmission of THz radiation have posed a challenge, as a flexible waveguide could simplify the propagation and detection of THz waves in remote locations without atmospheric absorption. Different structures, such as, rigid hollow metallic waveguides, solid wires, or short lengths of solid-core transparent dielectrics such as sapphire and plastic have already been explored for THz guiding to characterize their individual loss and dispersion profile. Recently, it has been reported that copper coated flexible, hollow polycarbonate waveguide has low loss of less than 4 dB/m with single mode operation at 1.89 THz. In the present study, using a broadband THz source of photoconductive antennae, we characterize the loss and dispersion profile of hollow core polycarbonate metal waveguides in the frequency range of 0.2 to 1.2 THz.

Keywords: Terahertz time domain spectroscopy, Hollow waveguides, Waveguide characterization, Propagation consideration, Coupling efficiency

1. INTRODUCTION

With the advent of semiconductor optoelectronics technology\(^1\), generation and detection of coherent THz radiation has become possible and associated with the development of THz technology and techniques; a search for flexible guiding systems for THz transmission has become crucial. Guided propagation of THz waves is advantageous as the THz beam can be directed into obscure places without employing any bulk optics and as most of the radiation energy is trapped inside the small cross-section of the core of the waveguide structure during its propagation, spectroscopic measurements can be done with enhanced sensitivity\(^2\).

From mid 1960’s the research effort had been directed to develop a variety of materials for transmitting wavelengths greater than 2 µm\(^3\),\(^4\). However, air-core guiding of CO\(_2\) laser through simple metallic structure was shown much later\(^5\) and use of flexible, circular hollow waveguides became common, especially in medical diagnostic later on\(^6\). Recently with the advent of photonic crystal fibers which exhibit omnidirectional behavior\(^7\),\(^8\) and with low loss and dispersion of THz transmission through metal wires\(^9\), various applications like bio-medical imaging and diagnostics, nondestructive evaluation of material parameters, chemical and gas sensing, remote sensing and security screening are expected to improve their performance through guided THz transmission. In most of these applications, THz waveguides would play the crucial role of a short-haul energy transmitter from a broadband source to remote sensors.

Hollow waveguides present an attractive alternative to other forms of THz guiding structures owing to their ability to transmit THz wavelengths with low loss and their relatively simple structure and potential low cost\(^10\). The utility of transport of THz pulses in such waveguides, especially in circular structures, are recently being inspected and characterization of their attenuation profile, dispersion and bending losses are in progress\(^11\). In the present study, we attempt to characterize a straight, circular Cu coated hollow core waveguide of bore size 2 mm in terms of its attenuation and dispersion profile. We calculate the attenuation coefficient of the lowest loss mode and the group velocity dispersion and waveguide dispersion of the waveguide under study.
2. EXPERIMENTAL TECHNIQUES

2.1 Experimental Arrangement

The experimental set-up consists of a Ti:Sapphire laser emitting 125 fs pulses at 800 nm, part of which pumps an Auston switch consisting of a semi insulating GaAs wafer with a gold transmission line structure microlithographically imprinted on it. The structure acts as a coplanar stripline (CPS) antenna when an AC bias is applied to it and becomes the source of THz radiation with a center frequency of about 0.5 THz. A silicon ball lens mounted above the antenna collects the emitted THz beam and guides it through a set of gold plated off axis parabolic mirrors to the detector. The detection scheme is just the reverse of the generation process, where the incoming THz electric field provides the bias for the antenna which is optically gated by the other part of the laser pulse.

The Cu coated hollow core waveguide was placed at the focus of the plano convex lens at the THz source side and the guided pulse was collected by the second plano convex lens to direct the collimated beam to the parabolic mirror. The pair of lens had a focal length of 50 mm with diameter 38 mm. Metal foils were placed at the entrance and exit faces of the waveguide to ensure no stray THz radiation gets directed onto the detector.

The experimental layout for waveguide characterization using THz time domain spectroscopy (THz-TDS) is shown in Figure 1.

2.2 Fabrication of the Hollow Core Waveguide (HCW)

The hollow waveguide technology used involves coating the inside of either silica or polymer tubing with metallic and metallic/dielectric coatings using liquid-phase chemistry methods. For this study, Copper was chosen as the metallic layer because it is one of the best reflectors at THz frequencies, having a measured reflectivity of 0.997 at 513.02 µm\textsuperscript{1}\textsuperscript{2}. The reason for polycarbonate tubing was because it has a very smooth inner surface nearly equal in roughness to silica glass and secondly the use of the same allows the guides to be quite flexible even with relatively large bore sizes. The polycarbonate tubing used for this study has bore sizes of 2 mm. In contrast, glass tubing with similar bore size would be inflexible.

During the fabrication, Copper films were deposited inside polycarbonate tubing using an electrode less, liquid-phase chemistry process\textsuperscript{13}. The first step involves sensitizing the polycarbonate using an aqueous solution of PdCl\textsubscript{2} and SnCl\textsubscript{2}. Next a copper bath solution was prepared consisting of copper sulfate, formaldehyde, Rochelle salt, and sodium hydroxide with a pH of 12.5. This solution was pumped through the plastic tubing at a flow rate of 5 ml/min. The formaldehyde reduces the Cu ions and Cu metal plated out on the tubing. The duration of the deposition process is 30 to
45 min and the estimated thickness of the Cu layer formed is 0.5 to 0.7 µm. This thickness is much greater than the skin depth of about 0.05 µm for Cu at THz frequencies. A schematic of the prepared hollow core waveguide and the diagram of the coating process are shown in Figures 2(a) and (b) respectively.

![Figure 2: (Color Online) (a) Transverse section through a hollow core waveguide showing the profile of the structure, and (b) Schematic of the waveguide fabrication procedure](image)

### 3. THz PROPAGATION CONSIDERATIONS THROUGH HCW

#### 3.1 Attenuation

Attenuation, or power loss, as light travels a distance L, through a material, can be measured in terms of the fractional power lost in transit. In particular for metal coated hollow core fibers, the attenuation is principally caused by surface impedance at the air-metal interface which is accentuated by the fact that at present range of frequencies, the attenuation coefficient \( K \approx 10^2 \). This is the reason why, in general, the circular electric modes \( TE_{nm} \) have the lowest loss in metallic hollow core waveguides while the circular magnetic \( TM_{nm} \) and hybrid modes \( HE_{nm} \) are rapidly attenuated for even the shortest wavelengths. In fact, the lowest loss mode is the \( TE_{01} \) mode which travels parallel to the walls of the guide and has a very tight energy spread centered round the axis of the hollow core waveguide.

Other sources signal attenuation during guided propagation comes purely from experimental considerations such as atmospheric losses in the air core, coupling losses due to launching misalignment, scattering glosses due to surface roughness of the waveguide wall and other effects.

Theoretically, the attenuation in hollow metallic and dielectric waveguides for long wavelengths was calculated by Marcatilli and Schmeltzer in 1964 where they show that a metal coated circular cylindrical hollow straight guide will have the lowest loss for \( TE_{01} \) mode given by,

\[
\alpha_{lm} = \left( \frac{u_{lm}}{2\pi} \right)^2 \frac{\lambda^2}{a^3} \frac{\text{Re}\left( \frac{1}{\sqrt{n^2 - 1}} \right)}
\]

where \( u_{lm} \) is the \( m^{th} \) root of the Bessel function, \( a \) is the bore radius. \( \tilde{n} \) is the complex refractive index of the metal.

#### 3.2 Dispersion

An optical signal becomes increasingly distorted as it travels along a waveguide due to the mechanisms of intermodal and intramodal dispersion caused by different group velocities of different modes and due to explicit dependence of the core-cladding refractive indices on wavelength. Essentially, the dispersion causes different wavelengths to propagate along the fiber with different travel time which causes broadening of the pulse at output end. Therefore, for all practical applications, dispersion characteristics of waveguide propagation is extremely important from design perspective and
these phenomena can be explained by considering the group velocity of the propagating waves inside a waveguide of particular geometry and material.

3.2.1 Intermodal Dispersion
Intermodal dispersion is present whenever more than one mode is excited in a waveguide. In that case, the different modes travel along different paths with different reflection angles at the core/cladding boundary resulting in broadening of the pulse. This is measured as the difference in travel time between the longest ($L_1$) and shortest ($L_2$) paths and for hollow core waveguide is given by:

$$\tau_m = \frac{n_1}{c} \left( L_1 - L_2 \right)$$

where the refractive index of the core $n_1=1$ for hollow core metallic waveguides. However, for the waveguide under study (straight 2mm bore Copper coated hollow polycarbonate waveguide), this dispersion can be neglected as the principal mode that is excited in the waveguide in our launch conditions is the TE$_{01}$ mode which incidentally, is the lowest loss mode.

3.2.2 Intramodal Dispersion
Even in single mode operation, as an optical signal propagates along the guide, each spectral component (the incident pulse is centered about a mean wavelength), undergoes a time delay $t_g$ per length $L$ of the waveguide and is given by:

$$t_g = \frac{L}{c} \left( \frac{d\beta}{dk} \right) = -\left( \frac{\lambda^2 L}{2\pi c} \right) \left( \frac{d\beta}{d\lambda} \right)$$

where $k=2\pi/\lambda$ is the free space wave vector and $\beta$ is the propagation constant. Correspondingly, assuming that the THz source has a finite spectral width, the factor,

$$D = \frac{1}{L} \left( \frac{dt_g}{d\lambda} \right)$$

is then defined as intramodal dispersion and is usually measured in units of ps/mm.cm.

In general, $D$ consists of contributions from both the core material referred to as material dispersion (involving $dn_1/d\lambda$) and from the guiding aspects of internal reflection referred to as waveguide dispersion (involving $d\theta/d\lambda$).

3.2.2.1 Material Dispersion
This is obtained by assuming that there is no waveguide dispersion and it occurs whenever the refractive index of the core composition is a nonlinear function of $\lambda$. It thereby follows that for a hollow core waveguide, there is no material dispersion at any wavelength since the core material is air with refractive index $n = 1$.

3.2.2.2 Waveguide Dispersion
For a specific mode propagating within the waveguide, the angle of reflection $\theta$ is a function of wavelength; this variation produces a wavelength dependent time delay $\tau_{wg}$ along a waveguide length $L$ as the wavelength spans the spectral width $\Delta\lambda$ of the source. The resulting ratio,

$$D_{wg} = \frac{\tau_{wg}}{L\Delta\lambda}$$

is a measure of the waveguide dispersion. For a hollow core waveguide with single mode operation, this is the principal dispersion mechanism that would cause group velocity dispersion causing the broadening of the guided THz pulse.
4. EXPERIMENTAL ANALYSIS

4.1 Calculation of Waveguide Attenuation

Time resolved THz spectroscopy measurements provide simultaneous information about the amplitude and phase of the samples under study. One reference waveform \( E_{\text{ref}}(t) \) is measured without the waveguide and the lenses moved to their confocal position, and a second measurement \( E_{\text{sample}}(t) \) is performed, in which the THz radiation propagates through the waveguide. The amplitude transmittance is calculated by performing a Discrete Fourier Transform (DFT) of the sample and reference measurements. Subsequently, the attenuation coefficient is given by,

\[
\alpha \left( \frac{dB}{m} \right) = 10 \log_{10} \left( \frac{P(0)}{P(L)} \right)
\]

The coupling loss was estimated by using cutback method where a long waveguide was “cut back” to smaller lengths and the data points for specific losses were extrapolated for zero length of the waveguide to obtain the coupling loss in dB. However, since this coupling loss is a function of frequency and the THz source used was broadband, coupling losses at different frequency points was measured for a better adjustment in the final value of the attenuation coefficient of the waveguide arising out of modal loss due to surface impedance.

4.2 Calculation of Waveguide Dispersion

As mentioned earlier, in waveguide dispersion we are interested in the dispersion of the propagation constant \( \beta \) of the guided pulse traveling through the waveguide with the frequency \( \nu \). Since \( \beta \) is a function of launching angle which is again dependent on the frequency, the propagation constant therefore, is also a function of frequency \( \nu \). Therefore the waveguide dispersion coefficient is given by,

\[
D_{\text{wg}} = -\frac{\Delta \tau}{cL} v^2 = \frac{d \tau}{dv} \frac{v^2}{cL} = -\frac{v^2 \Delta \phi''(v)}{cL}
\]

where \( L \) is in cm and \( c \), the speed of light is taken in mm/s to obtain an appropriate unit of ps/cm.mm for the dispersion coefficient for hollow core waveguides in the present spectral range. This quantity thus, in other words, gives the amount of the pulse broadening in the units of picosecond per cm (length of the fiber) per millimeter (spectral width of the THz source).

5. RESULT

5.1 Time domain data and amplitude spectrum for HCW

THz electric fields of the reference pulse and the HCW of different lengths have been shown in Figure 3. It is seen from Figure 3(a), that an input pulse of FWHM (full width at half maximum) 1.4 ps broadens to a pulse of FWHM 6.5 ps after traveling through the waveguide. Hence, the group velocity dispersion (GVD) for the 48.80 mm length waveguide is approximately 2.1 ps/THz.cm at a center frequency of 0.5 THz.
Figure 3: (Color Online) (a), (c) and (e) show the time domain reference THz pulses and the propagated pulses through Copper coated polycarbonate hollow waveguide of lengths 4.882 mm, 6.076 mm and 6.828 mm respectively. (b), (d) and (f) show their corresponding relative amplitude transmittance. It should be noted that the phase of the guided pulse through the HCW have been temporally shifted to overlap with the reference pulses for easy comparison in (a), (c), (e). It is also observed that as the length of the HCW was increased, the propagated pulses were attenuated to larger extent.

5.2 Attenuation coefficient for HCW
The experimentally obtained attenuation coefficient from Equation (6) and the theoretically expected attenuation for $TE_{01}$ mode are compared in Figure 4 where the total loss is in dB/m and is corrected for losses associated with coupling. However, the losses due to atmospheric absorption is not corrected for and the undulation of the attenuation coefficient near 0.56 THz, 0.78 THz, 1.13 THz and 1.19 THz are suspected due to water vapor absorption in the unpurged experimental set up for waveguide characterization.

Figure 4: (Color Online) Comparison of the experimental and theoretical attenuation coefficients in dB/m
5.3 Dispersion characterization for HCW
The unwrapped phase of the reference pulse and the guided pulse through fiber length of 4.882 cm are shown in Figure 5(a) as a function of frequency and the corresponding phase difference is plotted in Figure 5(b). The pulse dispersion, which is proportional to the derivative of the phase difference, is plotted in Figure 5(c). It can be seen that the pulse broadening is around 2 ps at 0.5 THz, a fact that has already been reflected from the GVD calculation obtained from the time domain data.

![Figure 5: (Color Online) (a) shows the phase of the reference THz pulse and the guided pulse through the hollow core waveguide of length 4.882 cm; (b) shows the corresponding phase difference and (c) shows the pulse broadening in picosecond](image)

6. DISCUSSIONS

In the present study, we could characterize the straight Cu coated hollow core cylindrical waveguide through its attenuation and dispersion profile. However, for a more practical approach, the scope of the present study has to be broadened to include the characterization of different bore sizes, different coating materials and outer layers and at the same time, the losses and mode profile are to be characterized for bent fibers. At present, these are some of the few aspects that are being studied and this work is an attempt to establish a general technique for characterization of such fibers with a broadband far infrared source.

REFERENCES


