Design and Characterization Low-loss modes in Dielectric-Coated Hollow-core waveguides at THz Frequency

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***Abstract*— Designs of hollow-core rectangular, circular, and elliptical waveguides with inner coating of silver and polystyrene (PS) are presented for low-loss terahertz guidance. The PS thickness deposited over silver is optimized to achieve the lowest possible loss for each waveguide at the frequency of 2.5 THz. The mode also tends to be a near-Gaussian in shape, easy for coupling to transmitter and receiver. The lowest propagation loss of 0.13 dB/m is obtained for the LP^{02} mode in a circular waveguide with 2200 µm bore diameter by using a full-vectorial finite element method. It is also shown here that rectangular and elliptical waveguides with a similar core area offer a lower loss value for the H^{y}_{21} mode and the LP^{02} mode, respectively, compared to a circular waveguide. Besides this optimized rectangular waveguide not only shows a minimum loss of 0.09 dB/m but with 4 times higher loss for the other polarization, hence the polarization state of the signal can also be maintained in this waveguide.**

***Index Terms*— Finite element method (FEM), Terahertz (THz) waveguide, Dielectric-coated hollow core waveguide, metal-clad dielectric waveguides, modal solutions**

I. Introduction

'THz waves or T-waves' is a window of electromagnetic spectrum located between the microwaves and infrared band, covering 0.1 THz to 10 THz or in terms of wavelength from 3 mm to 30 µm. It is also known as the sub-millimetre or extreme far-infrared band [1, 2]. One of the outstanding problems THz system facing is the very large attenuation through atmospheric transmission and compounded by the lack of a suitable low-loss guided interconnect. These limit the potential of the THz system. So, low-loss waveguide is required to development of viable THz systems. Recently, the development of low-loss THz waveguide have drawn considerable attentions for different applications, such as sensing [3], security screening [4], imaging and spectroscopy [5, 6]. Low-loss THz waveguide will not only be useful in guiding electromagnetic radiation away from a THz source with greater efficiency, but also in developing more compact devices in the future.

The efforts to develop low-loss THz waveguide are still on-going. Earlier, several metallic waveguide structures for THz waveguiding were demonstrated [7, 8]. A lowest loss (0.03 cm^{-1}) was reported through a bare metal wire by Wang and Mittleman [9], but unfortunately these modes spread into the surrounding medium and were less confined in the core.

As THz wave suffers negligible loss through the dry air, a variety of structures with air-core become another possible option to design low-loss THz waveguide, such as pipe waveguide [10], hollow Bragg fiber [11], porous core fiber [12-14], porous core photonic crystal fiber [15, 16] and hollow-core waveguide [17-19]. In these waveguides, a significant portion of the modal power is guided through the low-loss air. Among the various waveguides suggested, the metal-clad waveguide which can tightly confine power in the core and supports surface plasmon modes (SPMs), which is the electromagnetic wave located at the interface of a metal and a dielectric medium. Such structures could be used for many applications if loss can be reduced.

Harrington *et al.* [19] reported less than 4 dB/m losses from a hollow polycarbonate tubing with inner Cu coating and such waveguide can preserve a single mode guidance when bore diameter is small. Ito *et al.* [20] reported losses 7.5-8 dB/m for hollow metallic waveguide with inner Ag coating. It can be noted that the losses from hollow metallic waveguide are limited to a several dB/m because the field penetrates into the metallic wall where the power is absorbed. It was reported that, the loss from metal hollow waveguide can be further reduced by coating a thin dielectric layer on the inner metal wall surface of the waveguide [21]. The effort to fabricate hollow metallic waveguide with inner dielectric of polystyrene, Ag/PS, waveguide were also reported by Bowden *et al.* [18, 22]. Here, it was identified that the losses depend on the thickness of the PS film which can be controlled by the concentration of PS in the coating solution and the coating rate. A lower loss value of 0.95 dB/m for HE_{11} at 2.5 THz was reported [22]. It was also shown that with PS coating can exhibit the lowest loss for the TE_{01} as well [18]. Themistos *et al.* [17] investigated an Ag/PS clad hollow glass waveguide

Manuscript received …….; revised …………….; accepted………………….

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(HGW) supporting SPMs. This design was optimized to minimize the attenuation of the RP^{02} mode by controlling the thickness of the PS inner coating of HGW. A very low-loss value with a Gaussian shaped profile for the RP^{02} mode was reported.

Dielectric-coated hollow-core rectangular waveguide by Rahman *et al.* [23] was proposed as one of the low-loss and also polarization maintaining waveguide in the THz region. The optimum configuration was studied to obtain a low-loss THz propagation. As a result, the H^x_{12} mode was found to have the lowest loss of 2.07 dB/m amongst all the modes with Ag and Teflon coatings for a waveguide with width, W = 1.0 mm and height, H = 0.6 mm at 2.5 THz. However, by increasing the width and height, the loss can be further reduced. More recently, Tang *et al.* [24] reported an elliptical dielectric-coated metallic hollow waveguide. A desirable ellipticity and the optimization of the fiber geometry were studied to reduce the attenuation loss. Subsequently, an elliptical hollow fiber with Ag layer and dielectric coated was fabricated and measured for polarization maintaining and low-loss transmission of THz wave [25]. They reported that the dielectric layer can significantly reduce transmission loss and enhance its polarization maintenance. Such an elliptical shaped hollow fiber has potential applications as polarization-maintaining THz fiber, THz filter, and THz sensor.

In this paper, design and optimization of dielectric-coated hollow-core rectangular, circular and elliptical shaped waveguides are presented. The waveguide modes are present in terms of the H^y_{mn} mode where m and n subscripts denote the field maxima along the $x-$ and $y-$axes, respectively. A novel design approach is proposed where the thickness of dielectric layer is optimized to support the low-loss propagation for these structures in THz region. A larger guide size of rectangular and elliptical waveguides are also studied to compare the loss to a circular guide with a similar area.

II. Numerical Solutions

To study loss and dispersion characteristics of the dielectric-coated hollow-core waveguide, a full-vectorial finite element method (FEM) is considered. An accurate, versatile and numerically efficient FEM based on full-vectorial **H**-field formulation developed earlier [26] which has been widely used in the analyses of microwave and optical guided-wave devices including the intermediate terahertz waveguide. In this study, the **H**-field formulation is utilized to obtain the modal solutions of dielectric-coated hollow-core waveguides: rectangular, circular and elliptical waveguides. The cross-section of waveguides can be represented by using many triangles of different shapes and sizes. The flexibility of unequal size elements in the FEM is a preferable choice which can also represent the curved interfaces of circular and elliptical waveguides more accurately. Here, this method is used to find the different modes, their propagation constants and their corresponding full-vectorial field profiles. Additionally, in this cases, not only the real part of the propagation constant but the attenuation constant is also calculated to obtain the loss value.

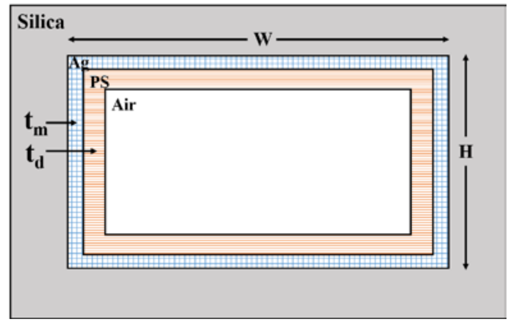

Fig. 1. Schematic diagram of a hollow-core rectangular waveguide with a dielectric coating at the inner metal surface, where W is the guide width, H is the guide height, t_m is the metal thickness and t_d is the dielectric thickness.

III. Rectangular Hollow-Core Waveguide

The structure considered here, as shown in Fig. 1, a thin metal-clad dielectric rectangular waveguide with an air-core and additionally a layer of dielectric deposited at the inner surface of the metal cladding. The thickness of Ag is denoted by t_m and the thickness of PS identified as t_d. In this case the outer dielectric can be any suitable materials and the mode guided inside the core will not be affected by the dielectric property of this material, but for numerical simulation, in this work, it is taken as silica. The thickness of the silver (Ag) cladding and Polysterene (PS) are taken as 1 μm and t_d μm, respectively. As the field decays very fast inside the metal layer, even when actual metal layer can be thicker, but only 1 μm thick metal layer is considered in the numerical simulations, to improve the field representation in this region. The complex refractive indices used of PS inner coating layer, Ag metal cladding and Silica outer cladding are considered to be n_d = 1.58 – j0.0036 [27], n_m = 308 – j532 [28] and n_s = 1.96 – j0.0061 [29], respectively, at 2.5 THz. At this frequency, the complex refractive index of air is taken as 1.0 – j1.1 × 10^{-6} [19] to account for the loss. The width W and height H of waveguide are considered as 2200 μm and 1100 μm, respectively, comparable to the circular [18, 22] and elliptical [24, 25, 30] hollow-core waveguides with the bore radius, a = 1100 μm. The PS thickness is varied to achieve the minimum modal loss.

Traditionally, rectangular metal waveguides are used for guidance of microwave signals. In this case they are designed with its width double of its height to support only TE_{10} mode, as a single-mode waveguide over the broadest possible frequency range. Circular waveguides are less commonly used as they cannot maintain the polarization state, besides for special cases, such as to connect to a rotating antenna.

A waveguide with its width and height, 100 μm and 50 μm, respectively can guide a single mode at an operating frequency of 2.5 THz. However, modal loss of the fundamental TE_{10} mode is calculated to be as high as 100 dB/m. This mode with dominant H_x and E_y can also be identified as H_{10}^x or E_{10}^y mode, similar as notation used for optical waveguides. Although modal loss in a larger waveguide is significantly reduced due to increased metal area but the number of guided modes will also increase, and as example a waveguide with dimension, 2200 μm × 1100 μm will be highly mutimoded at 2.5 THz.

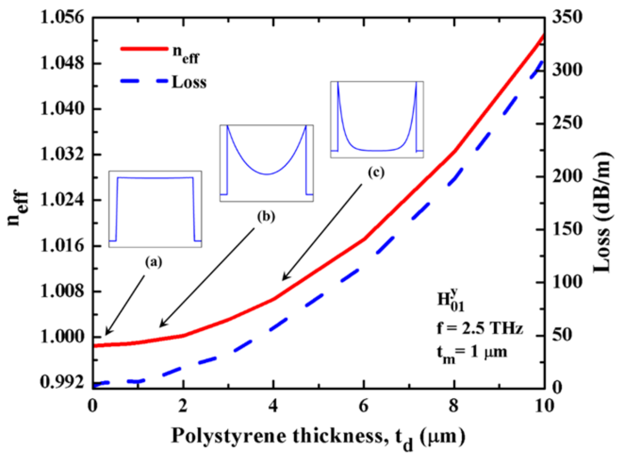

Fig. 2. Variations of n_{eff} and loss of the H_{01}^y of metal/dielectric coated hollow-core rectangular waveguide with the dielectric thickness for W = 2200 μm, H = 1100 μm. The insets show H_y field profiles along the horizontal direction for (a) t_d = 0 μm, (b) t_d = 1 μm, and (c) t_d = 4 μm.

For comparison with other reported work, first, the fundamental H_{10}^x (or TE_{10}) mode of a waveguide with a larger dimension, 2200 μm × 1100 μm is considered. We have calculated the loss value of the H_{10}^x mode in this guide as 3.47 dB/m without any PS coating. The second guided mode, TE_{01} or H_{01}^y has also been observed and its loss value is lower than that of H_{10}^x mode, as its width is larger than its height.

As the H_{01}^y mode had a lower loss of 1.75 dB/m, next, effect of introducing a dielectric cladding on this mode is studied. The real part of effective index (n_{eff}) and propagation loss of this mode are shown in Fig. 2. It can be observed that both the effective index and loss of the H_{01}^y mode increase monotonically with the PS thickness. We have observed that as the PS thickness increases field gets more localized near the metal/PS layer, and becomes less confined in the air-core.

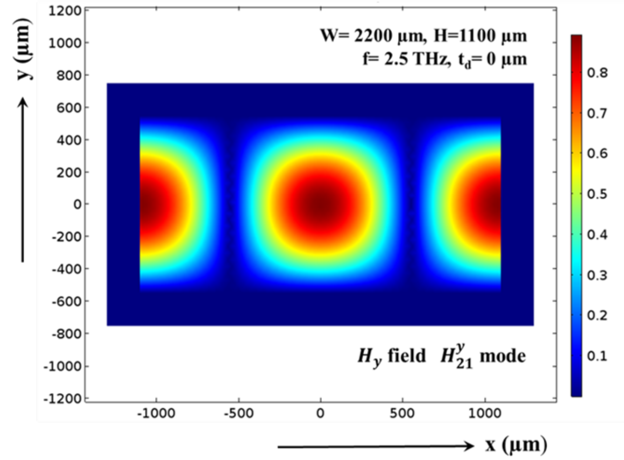

Fig. 3. The $|H_y|$ field profile of the H_{21}^y hollow-core rectangular waveguide for t_d = 0 μm.

Variations of the H_y field along the $x-$direction are shown as insets. When t_d = 0 μm, shown by inset (a), the constant H_y profile shows a typical TE_{01} mode, but for t_d = 1 μm shown as inset (b) a dip can be observed in the middle and for t_d = 4 μm shown as inset (c), a very large dip can be observed which pushes more fields in the metal and thus increasing the loss. As a result, the modal loss of the fundamental mode of the waveguide increases with the dielectric layer thickness, similar as reported earlier [23] and so this additional dielectric-clad will not provide any advantage for this particular mode. However, earlier studies [17, 18, 23] have reported that for some specific modes the waveguide loss can be reduced by using a dielectric-coating inside of metallic surface.

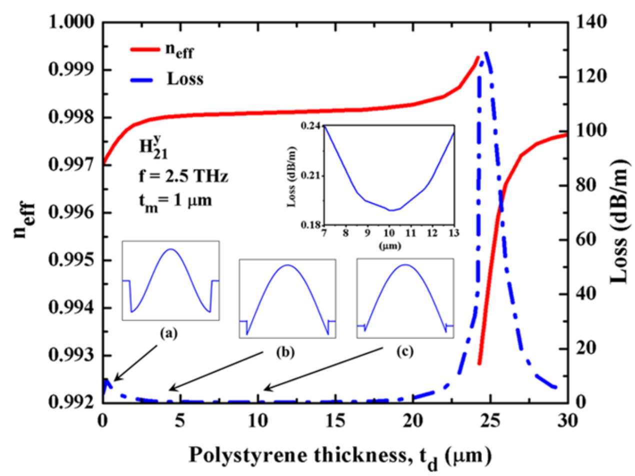

Fig. 4. Variations of n_{eff} and loss of the H_{21}^y mode of metal/dielectric coated hollow-core rectangular waveguide with the dielectric thickness for W = 2200 μm, H = 1100 μm. The insets show H_y field profiles along the horizontal direction for (a) t_d = 0 μm, (b) t_d = 4 μm, and (c) t_d = 10 μm.

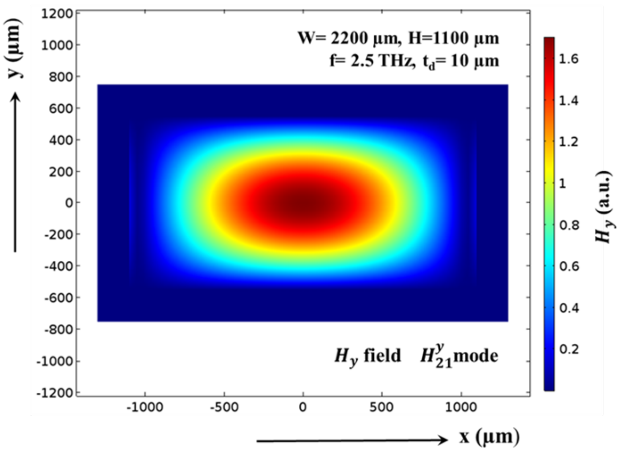

Fig. 5. The $|H_y|$ field profile of the H^y_{21} mode hollow-core rectangular waveguide for t_d = 10 μm.

Following this, next, a higher order mode is examined. Figure 3 shows the absolute H_y field of the H^y_{21} mode without any PS cladding. The metallic wall on the vertical side introduces Electric wall ($\mathbf{n} \times \mathbf{E} = 0$ or $\mathbf{n} \bullet \mathbf{H} = 0$) boundary condition on the electromagnetic field. This forces H_x to be zero (Dirichlet) on the two vertical side walls and H_y to have Neumann boundary condition. The same Electric wall boundary condition forces H_y to be zero on the two horizontal side walls. Variations of the attenuation characteristic and effective index of this mode with the PS thickness are presented in Fig. 4. It can be observed that initially n_{eff} starts to rise faster, then increases slowly until the PS thickness approaches to t_d = 25 μm and subsequently goes through a resonance point. Similarly, initial loss value of 1.75 dB/m for t_d = 0 μm increases rapidly with a very thin dielectric coating (not clearly visible here), but then loss reduces and reaches a minimum value of 0.19 dB/m at t_d = 10 μm, also shown as an inset. As the PS thickness approaches to t_d = 25 μm, loss increases, reaches a peak value and then decreases rapidly. The existence of this resonance will be discussed later on.

The H_y field profiles along the horizontal direction are also shown as insets in Fig. 4. When t_d = 0 μm, that is PS is absent, the H_y profile is shown as inset (a), where it can be observed that the field follows a typical cosine curve, as expected for a mode in a rectangular metal waveguide. However, when t_d = 4 μm and t_d = 10 μm shown as insets (b) and (c), respectively, peaks at the sides reduce. It can be noted that when the PS thickness increases, the field moves more into the air-core and the field sidelobes at the metal interface reduce. The lowest loss value of 0.19 dB/m can be achieved when t_d = 10 μm and in this case the power is more confined at the center of the air-core, so the mode field becomes near-Gaussian in shape, as shown in Fig. 5. It would be a good option for guiding this THz mode through such a waveguide.

Although, such a large 2200 μm × 1100 μm waveguide supports more than 50 modes at 2.5 THz, but modal loss value for the H^y_{21} mode, discussed above, has the lowest loss of 0.19 dB/m amongst all the modes when t_d = 10 μm. For this guide, with t_d = 10 μm, loss of the H^x_{10}, H^y_{01}, H^x_{12} and H^y_{11} modes are calculated as 311.30, 312.68, 1.23 and 0.58 dB/m, respectively. So this guide will effectively be a single-moded guide as the other modes will dissipate quickly. Besides, this mode being near-Gaussian in shape, would be easy to couple to transmitter and receiver.

Next, the existence of a resonance peak is studied in more details. We have noticed that, this resonant peak of the loss does not depend on a waveguide dimension but it depends on the n_d and the operating frequency. Both the effective index and propagation loss of the H^y_{21} mode as function of the variation of PS thickness but with a higher refractive index, n_d = 3.16 is considered and presented in Fig. 6. It can be noted that these resonant points repeat regularly. The resonant characteristic at the PS thickness obtained through numerical simulations are given in Tables I and II.

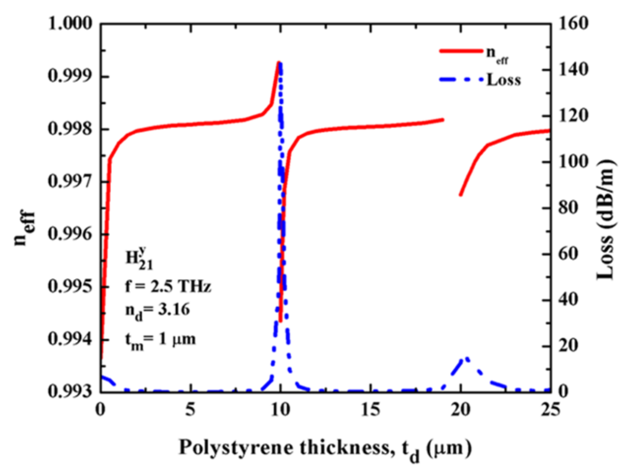

Fig. 6. Variations of n_{eff} and loss of the H^y_{21} mode of metal/dielectric coated hollow-core rectangular waveguide with the dielectric thickness when W = 2200 μm, H = 1100 μm and n_d = 3.16.

TABLE I
THE RESONANT THICKNESS WITH n_d = 1.58 at DIFFERENT OPERATING FREQUENCIES

Frequency (THz)	The resonant thickness (μm)
1.5	40.8
2.0	30.6
2.5	24.4

The resonant thickness values for a constructive interference is given by [21, 31]

$$d_0 = \frac{\lambda_0}{4\sqrt{n_d^{\,2} - 1}} \tag{1}$$

where d_0 is the thickness for a resonant peak, λ_0 is the given wavelength and n_d is the refractive index of the dielectric layer. The values given in these tables agree very well with the values from Equation (1). However, in our simulations, this thickness yields a resonant point when loss value increases rapidly. We have noticed that a larger number modes co-exist when $t_d = d_0$ µm. We have also noted that some of these modes appear to show boundary condition that do not obey the electric walls on the 4 sides. However, for closer observation, as we expand the field in the dielectric region, it appeared that, this layer behaves like a $\frac{\lambda}{4}$ long section where electric wall at metal/dielectric wall transforms to a magnetic wall at dielectric/air interface at $\frac{\lambda}{4}$ distance away. Thus it allows a large number of modes to co-exist and their effective index values cross the effective index value of the H_{21}^{y} mode and this degeneration cause mode mixing and higher losses.

TABLE II
THE RESONANT THICKNESS WITH DIFFERENT REFRACTIVE INDICES OF DIELECTRIC AT f = 2.5 THz

Refractive index of the dielectric layer	The resonant thickness (µm)
1.58	24.4
3.16	10.0
4.74	6.5

IV. CIRCULAR HOLLOW-CORE WAVEGUIDE

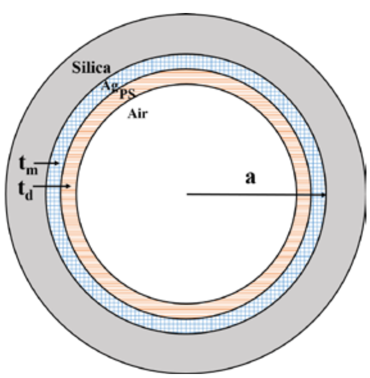

Fig. 7. Schematic diagram of the hollow-core circular waveguide with a dielectric coating at the inner of the metal surface, where a is the bore radius, t_m is the metal thickness and t_d is the dielectric thickness.

Next, a similar study is also performed with a dielectric-coated metallic circular hollow-core waveguide. The bore radius (a) is taken as 1100 µm. The thickness of Ag and PS are taken as 1 µm and t_d µm, respectively as shown in Fig. 7. At the same operating frequency, the propagation loss of the LP^{02} mode is considered. It should be noted that this particular mode transforms to a low-loss mode with the PS thickness and other modes have significantly higher loss values. Figure 8 shows the effective index and loss values of this waveguide as a function of the PS thickness. Both the real part of effective index and loss show a similar trend as that of the H_{21}^{y} mode in a rectangular waveguide.

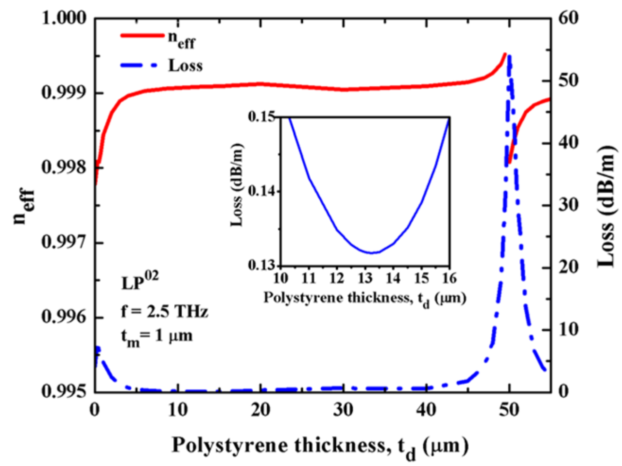

Fig. 8. n_{eff} and loss of the LP^{02} metal/dielectric coated hollow-core circular waveguide as function of dielectric thickness for a = 2200 µm.

As compared to previously reported [22], it can be observed in Fig. 8 that the loss initially increases from 4.19 dB/m for t_d = 0 µm (but not clearly visible), to 8.11 dB/m for t_d = 0.3 µm and then decreases to reach a minimum loss which is 0.132 dB/m at t_d = 13 µm (shown as an inset). Then it rapidly increases at the resonant thickness which is t_d = 50 µm in this case. The H_y field profiles of the LP^{02} mode are shown in Fig. 9. Here, when t_d = 0 µm, the H_y field is shown in Fig. 9 (a), the Electric wall boundary condition enforces Neumann and Dirichlet boundary conditions for the H_y field at the vertical and horizontal side walls, respectively. The field profile shown here can be considered as the H_{21}^{y} mode in a rectangular waveguide but transformed due to curved metal wall.

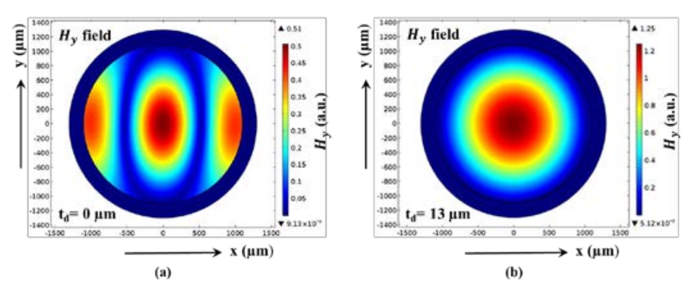

Fig. 9. $|H_y|$ field profiles for the LP^{02} for the hollow-core circular waveguide at (a) t_d = 0 µm and (b) t_d = 13 µm.

When PS is coated, particularly at t_d = 13 μm, the field moves towards the center of the air-core yielding the lowest loss value. The mode tends to be Gaussian in shape, as shown in Fig. 9 (b). It should be noted that a similar mode with dominant H_x field (this can also be called LP^{02} mode) can also be formed which is a degenerate mode with the mode shown here. As both these polarized modes exist in a circular hollow-core waveguide with the same loss values, so polarization state would be difficult to control.

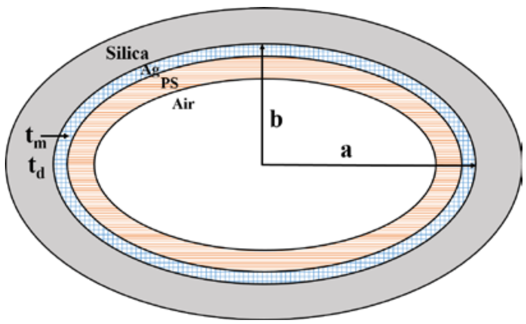

Fig. 10. Schematic diagram of the hollow-core elliptical shaped waveguide with a dielectric coating at the metal surface, where a and b are the major and minor radii, t_m is the metal thickness and t_d is the dielectric thickness.

V. Elliptical Hollow-Core Waveguide

A further study of an elliptical shaped hollow-core waveguide is also carried out as it will have different loss values for two polarizations. First, the LP^{02} mode, with dominant H_y field is closely investigated. Figure 10 shows schematics of an elliptical shaped waveguide with the major and minor radii, a and b are 1100 μm and 550 μm, respectively. The metal and dielectric thicknesses are taken as t_m = 1 μm and t_d μm, respectively. The PS thickness is varied to study loss at the operating frequency of 2.5 THz. A minimum loss of 0.18 dB/m for the LP^{02} mode, with dominant H_y field at t_d = 10 μm is achieved compared to previous study [25] which had reported 3 dB/m for $x-$polarization and 6 dB/m for $y-$polarization but with the different major and minor thicknesses of dielectric layer of d_1 = 15 μm and d_2 = 1 μm, respectively. Loss value then starts increasing again and at the resonant thickness, t_d = 25 μm rapidly goes through the mode mixing, as shown in Fig. 11. Figure 12 shows H_y field profiles of the LP^{02} mode at (a) t_d = 0 μm and (b) t_d = 10 μm. Without PS cladding, the field profile is similar as the H_{21}^{y} mode in a rectangular waveguide but modified due to the curved metal boundary. For t_d = 10 μm, as shown in Fig. 12 (b), field is confined inside the air-core. It can be noticed that the field profile shows near-Gaussian in shape when the PS thickness increases. Another LP^{02} mode with dominant H_x field is also studied and this yields a minimum loss value of 0.93 dB/m at t_d = 17.5 μm, but this is more than 5 times higher than that of the optimized LP^{02} mode with the dominant H_y field.

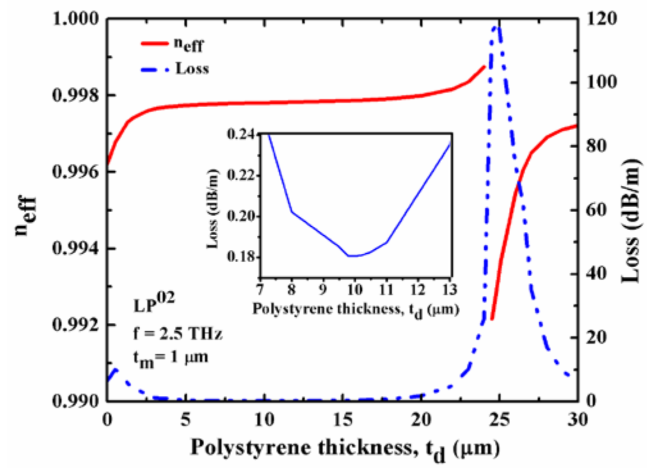

Fig. 11. Variation of the n_{eff} and loss of the H_y dominant, LP^{02} mode of metal/dielectric coated hollow-core elliptical shaped waveguide with the dielectric thickness for a = 2200 μm and b = 1100 μm.

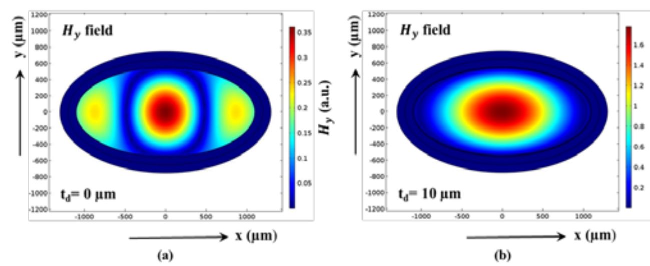

Fig. 12. $|H_y|$ field profiles for the LP^{02} for the hollow-core elliptical waveguide at (a) t_d = 2.5 μm and (b) t_d = 10 μm.

VI. Comparative Loss Values

All the structures studied here, the LP^{02} mode in a dielectric-coated circular hollow-core waveguide with 2200 μm diameter, has shown the lowest loss of 0.132 dB/m at t_d = 13 μm. The lowest loss in a rectangular waveguide was 0.19 dB/m and that of an elliptical core guide was 0.18 dB/m. In all these cases, their horizontal widths were taken as the same value, equal to 2200 μm. But as the non-circular guide has a smaller cross-sectional area, so their minimum loss values were also a bit higher. So, to have a fairer comparison, next both the rectangular and elliptical waveguides are examined which have an equal core area as that of the circular one. So, a rectangular waveguide with dimension of 2756 μm × 1378 μm and for an elliptical waveguide of 3112 μm × 1556 μm are studied. The simulated result found that the high order mode with dominant H_y field has a lower loss value than the H_x field in both structures. For the rectangular waveguide, the H_{21}^{y} mode reached the lowest loss which is 0.09 dB/m at t_d = 10 μm and for elliptical one, the achievable lowest loss of the

LP^{02} mode is 0.06 dB/m at t_d = 9.5 μm. Table III summarizes the calculated loss values at optimum PS thickness for the different structures and dimensions. The analyses carried out have revealed that a large waveguide can minimize the propagation loss significantly and transforms the mode shape to a Gaussian-like.

TABLE III
THE MINIMUM LOSS VALUES AT f = 2.5 THz

Structure	Dimension width (μm) × height (μm)	Minimum loss (dB/m) (at PS thickness (μm))	
		$\boldsymbol{H_x}$	$\boldsymbol{H_y}$
Rectangular	2200 × 1100	3.47 dB/m (T_d = 0 μm) for H_{10}^x	1.75 dB/m (T_d = 0 μm) for H_{01}^y
		0.81 dB/m (T_d = 16.5 μm) for H_{12}^x	0.19 dB/m (T_d = 10 μm) for H_{21}^y
	2756 × 1378	0.38 dB/m (T_d = 16.5 μm) for H_{12}^x	0.09 dB/m (T_d = 10 μm) for H_{21}^y
Circular	2200	0.13 dB/m (T_d = 13 μm) for LP^{02}	
Elliptical	2200 × 1100	0.93 dB/m (T_d = 17.5 μm) for LP^{02}	0.18 dB/m (T_d = 10 μm) for LP^{02}
	3112 × 1556	0.31 dB/m (T_d = 17 μm) for LP^{02}	0.06 dB/m (T_d = 9.5 μm) for LP^{02}

VII. CONCLUSION

A rigorous finite element approach has been used to design a low-loss dielectric-coated metallic hollow-core waveguide for THz guidance. The evolution of mode field profiles and propagation losses, with the variation of the dielectric thickness have been thoroughly studied. It is shown here that the minimum modal loss of the fundamental H_{01}^y mode in a 2200 μm × 1100 μm rectangular hollow-core waveguide, was 1.75 dB/m at t_d = 0 μm. This modal loss monotonically increases with increasing thickness of the dielectric layer. Although other higher-order modes have higher losses, without an additional dielectric layer, however, it was observed that by adding a PS layer, loss values of the H_{21}^y mode can be significantly reduced. So, the PS thickness was optimized to achieve the minimum loss value of such a waveguide. Although, this waveguide supports many modes but the lowest loss of 0.19 dB/m at t_d = 10 μm for the H_{21}^y mode with a near-Gaussian mode fields was observed. It would also be easy to couple this mode to input and output components. The resonant peak and mode degeneration in such dielectric-clad waveguides were also studied. The analyse carried out revealed that resonant thickness does not depend on waveguide dimension but it depends on the frequency and refractive index of the dielectric layer. The circular hollow-core waveguide with a 2200 μm bore diameter offers the lowest loss of 0.13 dB/m when the PS thickness, t_d = 13 μm for the LP^{02} mode. This structure can be suggested as a low-loss waveguide in THz region. For elliptical shaped waveguide, the LP^{02} mode, with dominant H_y field shows a minimum loss of 0.18 dB/m at t_d = 10 μm with a near-Gaussian in shape. However, larger rectangular and elliptical waveguides even have a lower loss value, compared to a circular guide of same core area. It is also shown here that a 2756 μm × 1378 μm rectangular guide with the same area as that of the circular guide, not only have a lower loss (0.09 dB/m) for the H_{21}^y mode but also can maintain its polarization state as the other polarized mode have much higher loss values.

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