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

Asmar Aming and B. M. A. Rahman, *Fellow, IEEE*

**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  $\mu\text{m}$  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  $H_{21}^y$  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  $\mu\text{m}$ . 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 ongoing. Earlier, several metallic waveguide structures for THz waveguiding were demonstrated [7, 8]. A lowest loss (0.03  $\text{cm}^{-1}$ ) 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

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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  $H_{12}^x$  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  $H_{mn}^y$  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  $\mathbf{H}$ -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  $\mathbf{H}$ -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.

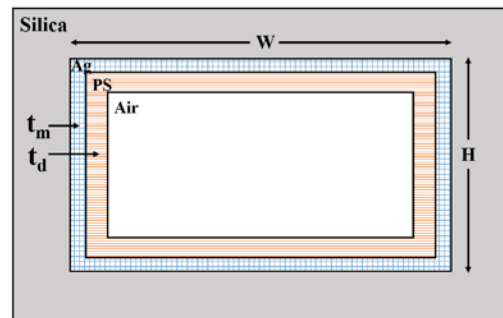


Fig. 1. Schematic diagram of a hollow-core rectangular waveguide with a dielectric coating at the inner metal surface, where  $W$  is the guide width,  $H$  is the guide height,  $t_m$  is the metal thickness and  $t_d$  is the dielectric thickness.

## 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 Polystyrene (PS) are taken as  $1 \mu\text{m}$  and  $t_d \mu\text{m}$ , respectively. As the field decays very fast inside the metal layer, even when actual metal layer can be thicker, but only  $1 \mu\text{m}$  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  $1.0 - j1.1 \times 10^{-6}$  [19] to account for the loss. The width  $W$  and height  $H$  of waveguide are considered as  $2200 \mu\text{m}$  and  $1100 \mu\text{m}$ , respectively, comparable to the circular [18, 22] and elliptical [24, 25, 30] hollow-core waveguides with the bore radius,  $a = 1100 \mu\text{m}$ . 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,  $100 \mu\text{m}$  and  $50 \mu\text{m}$ , 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,  $2200 \mu\text{m} \times 1100 \mu\text{m}$  will be highly multimoded at 2.5 THz.

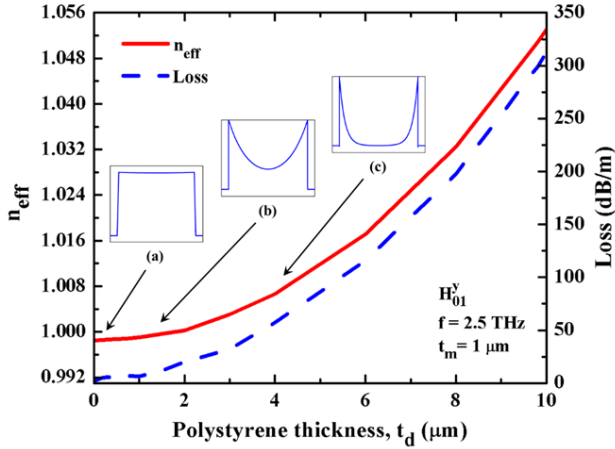


Fig. 2. Variations of  $n_{eff}$  and loss of the  $H_{01}^y$  of metal/dielectric coated hollow-core rectangular waveguide with the dielectric thickness for  $W = 2200 \mu\text{m}$ ,  $H = 1100 \mu\text{m}$ . The insets show  $H_y$  field profiles along the horizontal direction for (a)  $t_d = 0 \mu\text{m}$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

For comparison with other reported work, first, the fundamental  $H_{10}^x$  (or  $TE_{10}$ ) mode of a waveguide with a larger dimension,  $2200 \mu\text{m} \times 1100 \mu\text{m}$  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.

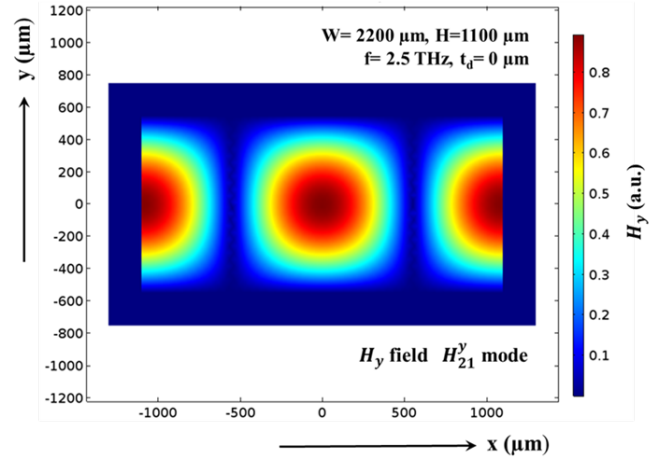


Fig. 3. The  $|H_y|$  field profile of the  $H_{21}^y$  hollow-core rectangular waveguide for  $t_d = 0 \mu\text{m}$ .

Variations of the  $H_y$  field along the  $x$ -direction are shown as insets. When  $t_d = 0 \mu\text{m}$ , shown by inset (a), the constant  $H_y$  profile shows a typical  $TE_{01}$  mode, but for  $t_d = 1 \mu\text{m}$  shown as inset (b) a dip can be observed in the middle and for  $t_d = 4 \mu\text{m}$  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.

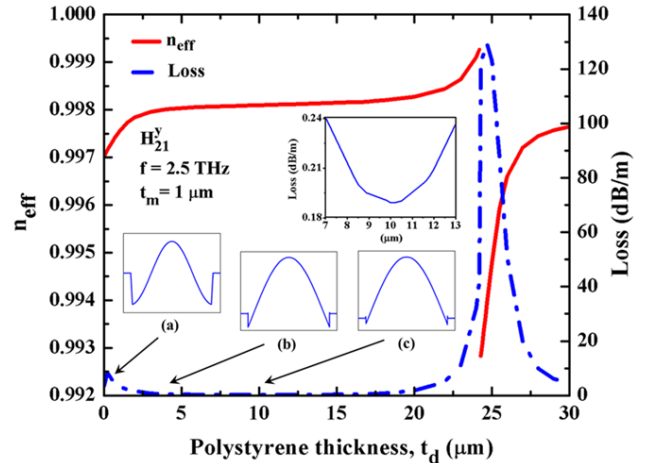


Fig. 4. Variations of  $n_{eff}$  and loss of the  $H_{21}^y$  mode of metal/dielectric coated hollow-core rectangular waveguide with the dielectric thickness for  $W = 2200 \mu\text{m}$ ,  $H = 1100 \mu\text{m}$ . The insets show  $H_y$  field profiles along the horizontal direction for (a)  $t_d =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

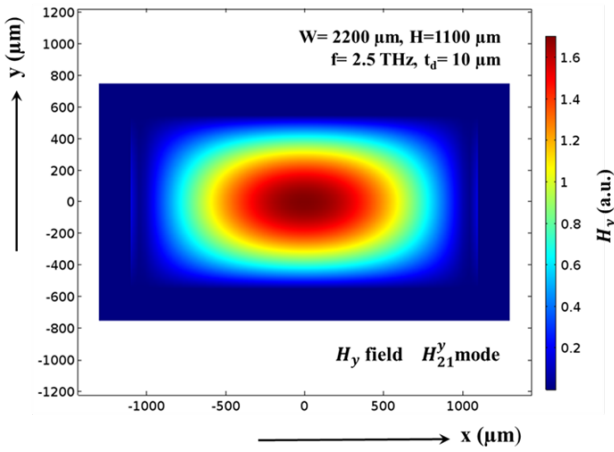


Fig. 5. The  $|H_y|$  field profile of the  $H_{21}^y$  mode hollow-core rectangular waveguide for  $t_d = 10 \mu\text{m}$ .

Following this, next, a higher order mode is examined. Figure 3 shows the absolute  $H_y$  field of the  $H_{21}^y$  mode without any PS cladding. The metallic wall on the vertical side introduces Electric wall ( $\mathbf{n} \times \mathbf{E} = 0$  or  $\mathbf{n} \cdot \mathbf{H} = 0$ ) 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  $n_{\text{eff}}$  starts to rise faster, then increases slowly until the PS thickness approaches to  $t_d = 25 \mu\text{m}$  and subsequently goes through a resonance point. Similarly, initial loss value of 1.75 dB/m for  $t_d = 0 \mu\text{m}$  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  $t_d = 10 \mu\text{m}$ , also shown as an inset. As the PS thickness approaches to  $t_d = 25 \mu\text{m}$ , 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  $t_d = 0 \mu\text{m}$ , 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  $t_d = 4 \mu\text{m}$  and  $t_d = 10 \mu\text{m}$  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  $t_d = 10 \mu\text{m}$  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  $2200 \mu\text{m} \times 1100 \mu\text{m}$  waveguide supports more than 50 modes at 2.5 THz, but modal loss value for the  $H_{21}^y$  mode, discussed above, has the lowest loss of 0.19 dB/m amongst all the modes when  $t_d = 10 \mu\text{m}$ . For this guide, with  $t_d = 10 \mu\text{m}$ , loss of the  $H_{10}^x$ ,  $H_{01}^y$ ,  $H_{12}^x$  and  $H_{11}^y$  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  $H_{21}^y$  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.

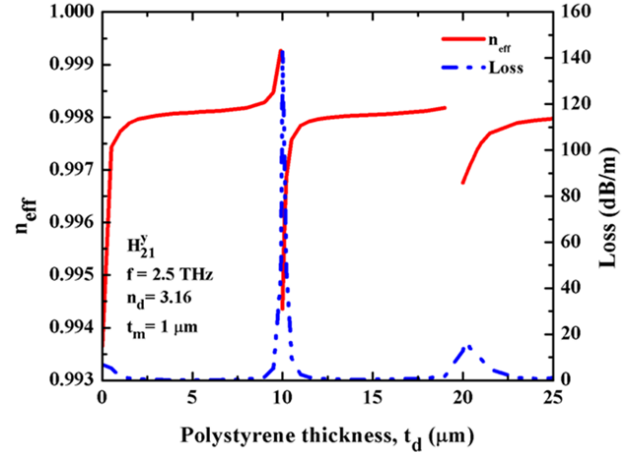


Fig. 6. Variations of  $n_{\text{eff}}$  and loss of the  $H_{21}^y$  mode of metal/dielectric coated hollow-core rectangular waveguide with the dielectric thickness when  $W = 2200 \mu\text{m}$ ,  $H = 1100 \mu\text{m}$  and  $n_d = 3.16$ .

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

Frequency (THz)	The resonant thickness ( $\mu\text{m}$ )
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]

$$d_0 = \frac{\lambda_0}{4\sqrt{n_d^2 - 1}} \quad (1)$$

where  $d_0$  is the thickness for a resonant peak,  $\lambda_0$  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  $t_d = d_0$   $\mu\text{m}$ . 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 ( $\mu\text{m}$ )
1.58	24.4
3.16	10.0
4.74	6.5

IV. CIRCULAR HOLLOW-CORE WAVEGUIDE

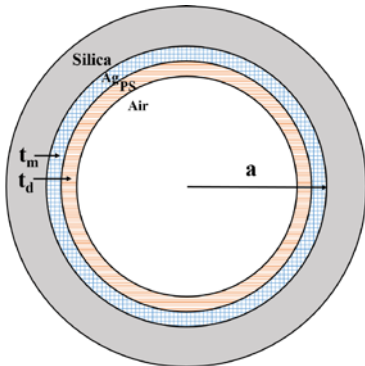


Fig. 7. Schematic diagram of the hollow-core circular waveguide with a dielectric coating at the inner of the metal surface, where  $a$  is the bore radius,  $t_m$  is the metal thickness and  $t_d$  is the dielectric thickness.

Next, a similar study is also performed with a dielectric-coated metallic circular hollow-core waveguide. The bore radius ( $a$ ) is taken as 1100  $\mu\text{m}$ . The thickness of Ag and PS

are taken as 1  $\mu\text{m}$  and  $t_d$   $\mu\text{m}$ , 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.

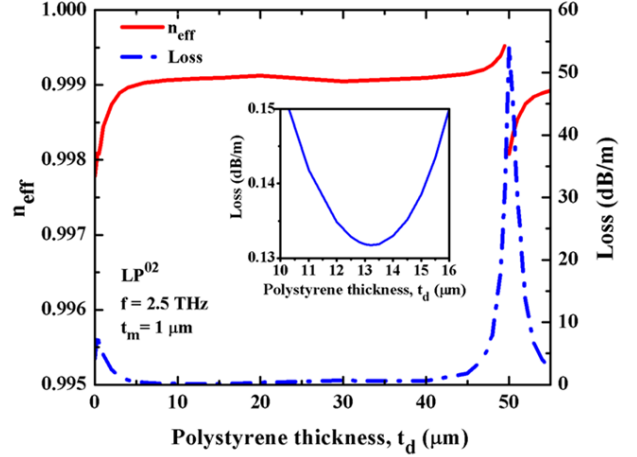


Fig. 8.  $n_{eff}$  and loss of the  $LP^{02}$  metal/dielectric coated hollow-core circular waveguide as function of dielectric thickness for  $a = 2200$   $\mu\text{m}$ .

As compared to previously reported [22], it can be observed in Fig. 8 that the loss initially increases from 4.19 dB/m for  $t_d = 0$   $\mu\text{m}$  (but not clearly visible), to 8.11 dB/m for  $t_d = 0.3$   $\mu\text{m}$  and then decreases to reach a minimum loss which is 0.132 dB/m at  $t_d = 13$   $\mu\text{m}$  (shown as an inset). Then it rapidly increases at the resonant thickness which is  $t_d = 50$   $\mu\text{m}$  in this case. The  $H_y$  field profiles of the  $LP^{02}$  mode are shown in Fig. 9. Here, when  $t_d = 0$   $\mu\text{m}$ , 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.

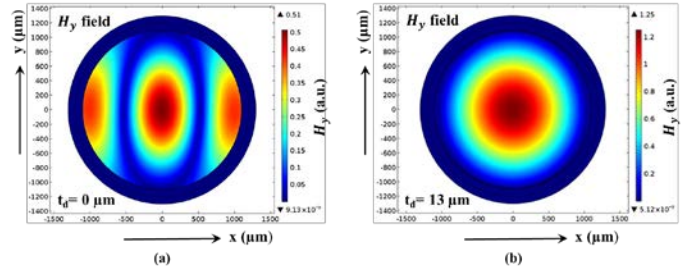


Fig. 9.  $|H_y|$  field profiles for the  $LP^{02}$  for the hollow-core circular waveguide at (a)  $t_d = 0$   $\mu\text{m}$  and (b)  $t_d = 13$   $\mu\text{m}$ .

When PS is coated, particularly at  $t_d = 13 \mu\text{m}$ , 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.

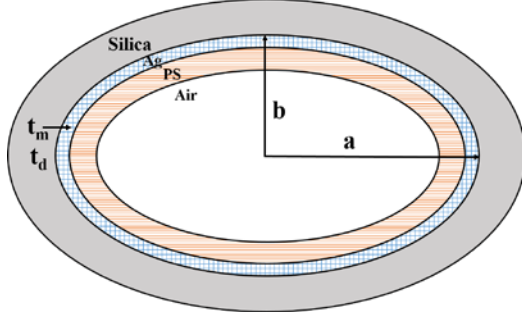


Fig. 10. Schematic diagram of the hollow-core elliptical shaped waveguide with a dielectric coating at the metal surface, where  $a$  and  $b$  are the major and minor radii,  $t_m$  is the metal thickness and  $t_d$  is the dielectric thickness.

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  $1100 \mu\text{m}$  and  $550 \mu\text{m}$ , respectively. The metal and dielectric thicknesses are taken as  $t_m = 1 \mu\text{m}$  and  $t_d \mu\text{m}$ , respectively. The PS thickness is varied to study loss at the operating frequency of  $2.5 \text{ THz}$ . A minimum loss of  $0.18 \text{ dB/m}$  for the  $LP^{02}$  mode, with dominant  $H_y$  field at  $t_d = 10 \mu\text{m}$  is achieved compared to previous study [25] which had reported  $3 \text{ dB/m}$  for  $x$ -polarization and  $6 \text{ dB/m}$  for  $y$ -polarization but with the different major and minor thicknesses of dielectric layer of  $d_1 = 15 \mu\text{m}$  and  $d_2 = 1 \mu\text{m}$ , respectively. Loss value then starts increasing again and at the resonant thickness,  $t_d = 25 \mu\text{m}$  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)  $t_d = 0 \mu\text{m}$  and (b)  $t_d = 10 \mu\text{m}$ . 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  $t_d = 10 \mu\text{m}$ , 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  $0.93 \text{ dB/m}$  at  $t_d = 17.5 \mu\text{m}$ , but

this is more than 5 times higher than that of the optimized  $LP^{02}$  mode with the dominant  $H_y$  field.

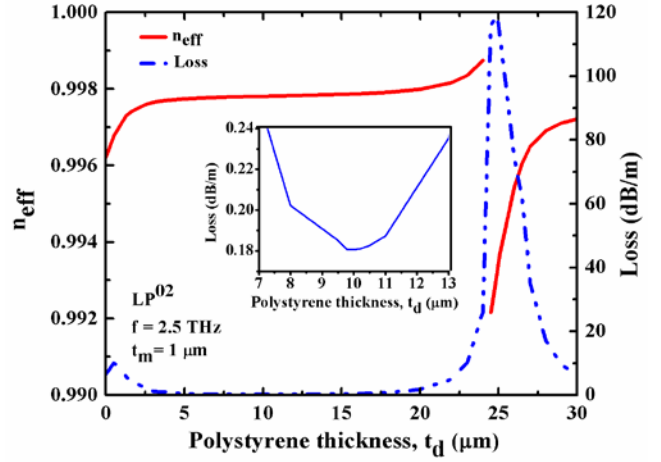


Fig. 11. Variation of the  $n_{eff}$  and loss of the  $H_y$  dominant,  $LP^{02}$  mode of metal/dielectric coated hollow-core elliptical shaped waveguide with the dielectric thickness for  $a = 2200 \mu\text{m}$  and  $b = 1100 \mu\text{m}$ .

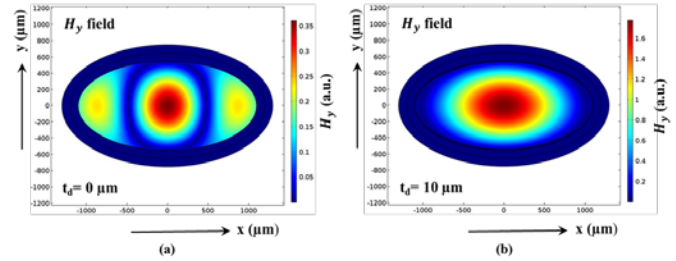


Fig. 12.  $|H_y|$  field profiles for the  $LP^{02}$  for the hollow-core elliptical waveguide at (a)  $t_d = 2.5 \mu\text{m}$  and (b)  $t_d = 10 \mu\text{m}$ .

VI. COMPARATIVE LOSS VALUES

All the structures studied here, the  $LP^{02}$  mode in a dielectric-coated circular hollow-core waveguide with  $2200 \mu\text{m}$  diameter, has shown the lowest loss of  $0.132 \text{ dB/m}$  at  $t_d = 13 \mu\text{m}$ . The lowest loss in a rectangular waveguide was  $0.19 \text{ dB/m}$  and that of an elliptical core guide was  $0.18 \text{ dB/m}$ . In all these cases, their horizontal widths were taken as the same value, equal to  $2200 \mu\text{m}$ . 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  $2756 \mu\text{m} \times 1378 \mu\text{m}$  and for an elliptical waveguide of  $3112 \mu\text{m} \times 1556 \mu\text{m}$  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  $0.09 \text{ dB/m}$  at  $t_d = 10 \mu\text{m}$  and for elliptical one, the achievable lowest loss of the

$LP^{02}$  mode is 0.06 dB/m at  $t_d = 9.5 \mu\text{m}$ . 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  $f = 2.5 \text{ THz}$

Structure	Dimension width ( $\mu\text{m}$ ) $\times$ height ( $\mu\text{m}$ )	Minimum loss (dB/m) (at PS thickness ( $\mu\text{m}$ ))	
		$H_x$	$H_y$
Rectangular	2200 $\times$ 1100	3.47 dB/m ( $T_d = 0 \mu\text{m}$ ) for $H_{10}^x$	1.75 dB/m ( $T_d = 0 \mu\text{m}$ ) for $H_{01}^y$
		0.81 dB/m ( $T_d = 16.5 \mu\text{m}$ ) for $H_{12}^x$	0.19 dB/m ( $T_d = 10 \mu\text{m}$ ) for $H_{21}^y$
	2756 $\times$ 1378	0.38 dB/m ( $T_d = 16.5 \mu\text{m}$ ) for $H_{12}^x$	0.09 dB/m ( $T_d = 10 \mu\text{m}$ ) for $H_{21}^y$
Circular	2200	0.13 dB/m ( $T_d = 13 \mu\text{m}$ ) for $LP^{02}$	
Elliptical	2200 $\times$ 1100	0.93 dB/m ( $T_d = 17.5 \mu\text{m}$ ) for $LP^{02}$	0.18 dB/m ( $T_d = 10 \mu\text{m}$ ) for $LP^{02}$
	3112 $\times$ 1556	0.31 dB/m ( $T_d = 17 \mu\text{m}$ ) for $LP^{02}$	0.06 dB/m ( $T_d = 9.5 \mu\text{m}$ ) 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  $\mu\text{m} \times 1100 \mu\text{m}$  rectangular hollow-core waveguide, was 1.75 dB/m at  $t_d = 0 \mu\text{m}$ . 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  $t_d = 10 \mu\text{m}$  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  $\mu\text{m}$  bore diameter offers the lowest loss of 0.13 dB/m when the PS thickness,  $t_d = 13 \mu\text{m}$  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  $t_d = 10 \mu\text{m}$  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  $\mu\text{m} \times 1378 \mu\text{m}$  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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