Low-Loss Metallic Waveguide for Terahertz Applications

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Abstract: In the present work, we have proposed a hybrid-cladding hollow-core metallic waveguide for low loss THz propagation. Two interface layers have been added between the hollow core and the metal cladding. The thicknesses of the interface layers have been optimized considering the limitation of actual fabrication of such guided structures. The modal analysis for the proposed 2D structure has been done using the RF module in COMSOL and hence we have obtained the operating frequency range for which the structure produces core-confined mode. For the core-confined mode, the loss has been investigated for the operating frequency range. Also the effect of thickness optimization on the loss of core-confined mode has been investigated at 1 THz.

Keywords: Terahertz, waveguides, Mode-propagation

Introduction

Terahertz (THz) waves, also known as T-rays, are electromagnetic (EM) waves with frequency range from 0.3 THz to 10 THz and corresponding wavelength range from 1000 µm to 30 µm. On the EM wave spectrum, T-rays are located in between Microwaves and Infrared radiation. This portion of EM spectrum was unexplored till early 1980s as suitable THz sources and detectors were not available until then. This is the reason why THz region was referred to, as the THz gap [1]. In recent years, THz waves have gained much attention of research due to their distinct properties. Some of the properties of T-rays are: (i) Unlike X-rays, THz waves do not photo-ionise biological tissues because it has low photon energy (1.2 meV to 41.36 meV), (ii) T-rays are transparent to most dry dielectrics as it is less affected by Mie scattering and (iii) this frequency range allows molecule specific vibrational and rotational transition. These distinctive properties make T-rays eligible for many applications such as spectroscopy, medical imaging, security screening, remote sensing, etc [2-4]. However, there are some limitations which restrict extensive use of THz region in different fields. One of such limitation is that THz waves suffer extreme water absorption and hence, propagate in free space with very high loss. Hence, the study of low-loss propagation of THz waves, using waveguides is highly pertinent [2].

Metallic hollow-core circular waveguides can be a suitable candidate for THz propagation as it offers many advantages over other propagating media [5]. One of the advantages of the above waveguide structure is that it suffers only ohmic losses, and hence, allows for low attenuation (α = 0.7 cm^{-1} at 1 THz) THz propagation; whereas, coplanar waveguides and transmission lines result in much higher attenuation (α = 14 cm^{-1} and α = 18 cm^{-1} respectively) as a result of dielectric losses, radiative losses and ohmic losses [6]. In addition to this, hollow-core metallic waveguides have simpler structure and their fabrication cost is low. The main drawback, however, of metallic waveguides are that metals have high reflectivity because of large value of complex refractive index in THz region and hence result in high ohmic losses. In order to overcome this problem in metallic waveguides, researchers proposed hybrid-cladding waveguides. A hybrid-cladding metallic waveguide is one with at least one interface layer between the hollow core and the metal cladding. The interface layer can be of any material such as dielectric material, composites or metamaterials [6].

In this work, we have proposed a structure of hybrid-cladding metallic waveguide with two interface layers between core and cladding for low-loss THz propagation. The 2D structure has been simulated in COMSOL multiphysics using RF module and the thickness of the layers have been optimized. The frequency range for which the waveguide provides with core confinement mode has been investigated. Attenuation (α) for the core confined mode has been calculated over the operating frequency range.

Theory

A circular metallic hollow-core waveguide mostly supports three types of modes – the transverse electric (TE) mode, transverse magnetic (TM) mode and the Hybrid mode. A waveguide behaves as a high pass filter and hence supports all possible modes above the cut-off frequency. However, the losses are minimum in the lower order modes (TE_{nm} modes). In higher order modes, attenuation is very large even for small distance propagation. Indeed, the TE_{01} mode travels parallel to the axis of waveguide and produces core-confined mode [7]. Related to the above, Marcatelli and Schmeltzer [8] showed that the attenuation constant (α) of a metallic waveguide is mode specific and for TE_{01} mode the attenuation is given by:

$$\alpha = \left(\frac{u_{nm}}{2\pi}\right)^2 \left(\frac{\lambda^2}{a^3}\right) Re\left(\frac{1}{\sqrt{n^2-1}}\right) \tag{1}$$

where, u_{nm} is the m^{th} root of nth order Bessel function, λ is operating wavelength, a is radius of core and n is the complex effective mode index. From the equation it is quite clear that to lower the attenuation, the core radius should be sufficiently larger than the wavelength. All other loss sources, such as scattering losses, coupling losses and atmospheric losses can be analyzed only experimentally [7].

In the proposed structure, materials chosen for the hybrid-cladding circular waveguide are copper as outer cladding; Indium Tin Oxide (ITO) and Gallium doped Zinc Oxide (GZO) as interface layers. This set of materials is chosen as the optical properties of these materials are well known in the THz region [9]. Addition of the interface layers increases the reflectivity by means of interference effect and reduces the ohmic losses. The 2D structure of the model is shown in figure 1. The waveguide has a hollow-core with radius 1 mm which is large relative to the wavelength so as to obtain lower loss. Also the thicknesses of the interface layers are optimized in order to get core-confined mode of propagation. Polycarbonate tube is used as the jacket since it has very smooth inner surface and at the same time it is very flexible [7].

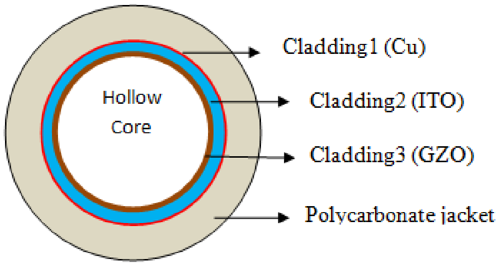

Fig.1 2D structure of proposed metallic hollow-core waveguide

Simulation Method

COMSOL multiphysics is a simulation software that allows a physics-based user interface platform to solve various scientific and engineering problems. It enables low-cost, reliable and high speed model analysis considering the limitation of actual fabrication of such guided structures. It also facilitates with ease ways to optimize the model for a specific target range of frequencies to be guided. The steps involved in the simulation are following –

Step 1: Selecting physics and study. For this model, physics used is Electromagnetic waves, Frequency Domain as the problem is related to high frequency Electromagnetic wave propagation and study selected is Modal Analysis.

Step 2: Defining parameters such as radius of core, thicknesses of claddings, operating wavelength and proper value of refractive index (n) and absorption coefficient (k) for each layer; creating geometry of the model using the defined parameters and assigning material to domains of created geometry with proper value of n and k.

Step 3: Creating mesh to divide the model into discrete and simple elements. Here we choose the extremely fine element size for creating mesh. The reason to do so is that we are using dimension as small as a few micrometers and it is needed that mesh is created for the entire structure.

Step 4: Computation of the model in order to find the effective mode index of the core confined mode.

The model has been simulated for different operating wavelength in order to find the upper and lower limit of operating wavelength. For each operating wavelength the corresponding values of n and k are used. The computation result gives the value of complex effective mode index which is further used to calculate the core-confined mode loss.

Results and Discussion

The modal analysis for the structure has been done for operating frequency starting from 0.5 THz and the upper limit is found to be 2.25 THz. Beyond this frequency, the structure is not producing core-confined mode, hence the electric field is leaking out from the core. The surface plot of the 2D model showing the core-confined modes at 0.5 THz, 1 THz, 2 THz and 2.5 THz is given in figure 2.

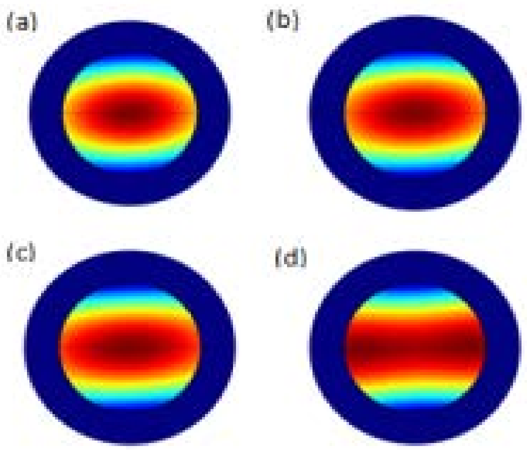

Fig.2 2D surface plot of low loss mode in THz waveguide at (a) 0.5 THz (b) 1 THz (c) 2 THz and (d) 2.5 THz

It can be observed from the above figure that the core-confinement mode exists upto 2.25 THz. From the modal analysis we obtained the value of effective mode index for different frequencies. The real and imaginary parts of these complex effective mode indexes have been plotted with respect to the operating frequency. From figure 3, it is clear that both the values increase as the frequency increases.

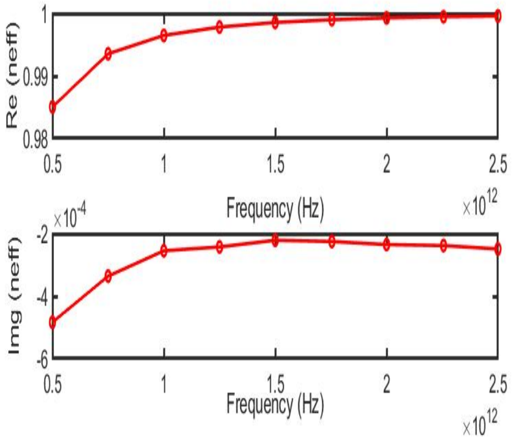

Fig. 3 Variation in real and imaginary part of effective mode index with respect to operating frequency

The value of effective mode index of the waveguide has been further utilized to calculate the attenuation for the core-confined mode using equation (1). From the equation it is evident that the loss not only depends on wavelength and core radius but also on the value of complex refractive index. The plot for loss against frequency is given in figure 4. It shows agreement with the surface plot obtained from the COMSOL simulation. For 2.5 THz, the loss is observed to be maximum which can be confirmed from the surface plot at the same frequency which shows that the electric field is not core-confined. Here we have considered the core-confined mode loss, so higher the confinement; lower should be the loss and vice-versa.

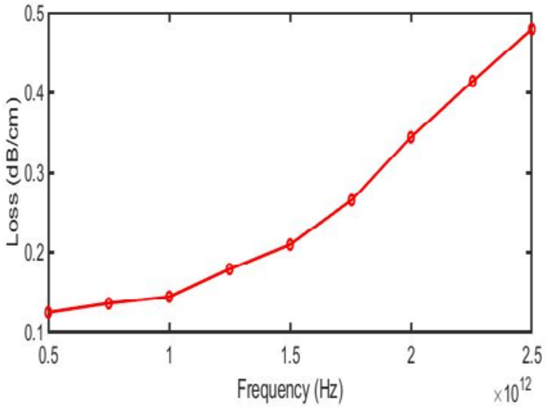

Fig. 4 Plot of core-confined mode loss with respect to frequency

The thickness of the interface layer is optimized so that the hollow-core waveguide is feasible for fabrication. The optimization was done keeping in mind the following factors - the thicknesses of the layers should be more than that of depth of penetration and the thicknesses are small enough to allow flexibility of the waveguide. The thickness of copper layer is kept at 1 µm because this is much larger than its skin depth that is 62 nm at 1 THz [10]. Similarly the GZO layer thickness has been optimized to 5 µm.

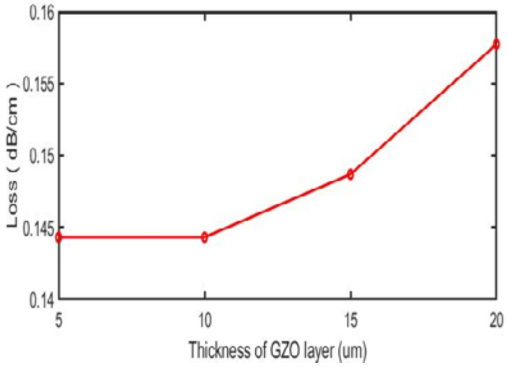

Fig. 5 plot of loss for different thickness of GZO layer at 1 THz

The loss for the core-confined mode has been plotted at a constant operating frequency of 1 THz while varying the thickness, which is shown in figure 5. The plot demonstrates that loss is higher for 20 µm and it decreases as the thickness reduces and gradually saturates after 10 µm.

Conclusion and Future Scope

The COMSOL simulation was very well utilized for the modal analysis of the proposed structure and calculation of core-confined mode loss. The structure simulated has been found to be a good candidate for THz propagation with low loss up to 2.25 THz. The THz waveguide demonstrated here has minimal fabrication complexity and can be utilized as sensing and imaging probe for application such as security screening. The operating frequency range of the waveguide can be improved by either increasing the number of interface layers or by using other materials as the interface layers. In future we plan to fabricate this structure, and hence characterize it by determining all other losses including the scattering loss, dispersion and coupling loss using THz time domain spectroscopy.

References

1. Lewis, Terahertz Physics, pp. 205-230, Cambridge University Press, (2012).
2. Zhang and Xu, Introduction to THz Wave Photonics, pp. 1-9, Springer, New York (2010).
3. Leahy – Hoppa et al. ‘Wideband terahertz spectroscopy of explosives’, Chemical Physics Letters, vol. 434, pp. 227-230 (2007).
4. Xin et al. ‘Terahertz imaging system for remote sensing and security applications’, 3rd Asia Pacific conference on Antenna and Propagation, pp. 1335-1338 (2014).
5. Mitrofanov et al., Terahertz waveguide for low transmission losses: characterization and applications, Terahertz Emitter, Receiver and Applications, vol. 9199 (2014).
6. Atakaramians et al., Terahertz dielectric waveguide, Advances in Optics and Photonics, vol. 5, pp. 169-215 (2013).
7. Bandyopadhyay et al., Characterization of Hollow Polycarbonate Metal waveguides using Terahertz time domain spectroscopy, Terahertz and Gigahertz Electronics and Photonics, vol. 6120 (2006).
8. Marcatili and Schmeltzer, Hollow metallic and dielectric waveguides for long distance optical transmission and losses, The Bell System Technical Journal, pp. 1784-1809 (1964).
9. Wang et al., Ultra broadband terahertz characterization of highly doped ZnO and ITO, Optical Material Express, vol. 5, Issue 3, pp. 566-575 (2015).
10. Hagemann et al., Optical constants from the far infrared to the x-ray region: Mg, Al, Cu, Ag, Au, Bi, C, and Al_2O_3, J. Optical Society of America, vol. 65, pp. 742-744 (1975).