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Research Article

A Comparative Analysis of Graphene Cladding Rectangular Waveguides Filled with Various Materials for 1.65 THz Ablation System

Hilal Koç Polat[*],[1], Miraç Dilruba Geyikoğlu[2], Bülent Çavuşoğlu[2] Mehmet Ertuğrul[3] ,Emine Parlak[4]

[1]Electrical and Electronics Engineering, Erzurum Technical University, Erzurum, Türkiye
[2]Electrical and Electronics Engineering, Atatürk University, Erzurum, Türkiye
[3]Metallurgical and Materials Engineering Department, Karadeniz Technical University, Trabzon, Türkiye
[4]Internal Medicine Department, Atatürk University, Erzurum, Türkiye.

Keywords

Graphene,
Teflon,
THz dielectric waveguide,
THz wave ablation,
Zeonex.

Abstract

Today, cancer diagnosis and treatment with the THz radiation model (THz wave ablation) is a subject of interest to researchers. The design performance of THz ablation systems depends on the design of a waveguide that will provide low-loss transmission of radiation from the antenna to the tissue. In this study, first of all, the superiority of graphene over noble metal is demonstrated. Then, the performance of THz rectangular waveguides which use graphene cladding and different core materials such as Silicon (Si), Silica (SiO2), Zeonex, Teflon, and PMMA (Polymethyl methacrylate) are comparatively investigated. The electromagnetic field distribution, transmission coefficients (S21), attenuation constant (dB/mm), and effective refractive index (neff) are analyzed in Computer Simulation Technology Studio Suit software to see the effect of various core materials on the characteristic of rectangular waveguides. Obtained simulation results show that Si, Teflon, and Zeonex have high transmission performance with ≈-0.5 dB. In addition, in the wavelength range where the operating performance of the waveguide is examined, Teflon and Zeonex perform well with an attenuation constant of less than 0.096 dB/mm. Electric field distributions of Teflon and Zeonex confirm that the transmission performance is better than others. In conclusion, Teflon and Zeonex materials are handy and promising for the 1.65 THz ablation system.

1. Introduction

0.1-10 THz frequency range, which is not yet in use and is of critical importance in terms of spectral bandwidth, has been the focus of attention of researchers in different fields of technology [1]. In particular, since THz radiation does not ionize biological molecules, they do not cause damage such as fragmentation of biological tissues. Therefore, if appropriate systems can be designed, THz radiation will be reliable for cancer treatment (THz ablation system). According to studies, methylated DNA, an abnormal DNA type found in early-stage cancers, has been found to have a distinct molecular resonance at 1.65 THz [2][3]. In this context, studies targeting 1.65 THz in the literature [4][5]. The performance and reliability of the THz system depend on the design of a waveguide that will provide low-loss transmission of radiation from the antenna to the tissue. However, the fact that antenna structure systems operating in this frequency range are almost nano-sized is one of the technological challenges in waveguide design.

A general waveguide is a structure of various cross-sections with low refractive index, filled with high refractive index material [6]. The material used in waveguide design and the geometry of the structure changes the performance of the waveguide by affecting its propagation loss. The losses can be caused by metals (conductors) or dielectrics in the homogeneous waveguide. Although transmission lines such as microstrip and CPW perform well at microwave frequencies, their performance decreases at mm-wave due to increased ohmic losses and surface roughness [1]. Ohmic losses are critical due to shorter wavelengths in the THz range. Therefore, much research has focused on reducing the high losses caused by metal-based structures [7][8]. These conductor losses can inherently be eliminated by using dielectric waveguides. However, dielectric waveguides exhibit loss due to increased dielectric absorption at THz frequencies [9]. In recent years, modulating propagation loss by adjusting applied chemical potential to graphene material in waveguides has been a focus of researchers' attention [10]. Graphene's tunable electrical properties provide a considerable advantage in developing micro- and nano-sized devices [11]. Under the static potential, graphene's electrons can behave like electromagnetic waves in dielectrics. Thus, a graphene-based barrier can be considered an electron waveguide [12]. When graphene is used with dielectrics, surface plasmon polaritons occur at the graphene-dielectric interface, and surface electromagnetic waves propagate parallel to the interface. This, too, shows that the graphene-dielectric waveguides perform well in loss or confinement. Waveguides with ultra-high refractive index have been achieved thanks to the multi-layered structures in which graphene is used [13]. When the THz region is examined, it has been seen that low-loss ultra-long propagation length waveguides are provided with hybrid designs created by using dielectric materials and graphene [14].

This study aims to design a waveguide that provides radiation transmission with low loss from the SiO2-based antenna in the 1.65 THz band [5] designed for the THz ablation system to the tissue. Rectangular waveguides and coaxial cable lines are waveguides developed so far in the literature and have come up with different types, such as dielectric-filled or air-filled structures in applications. Although these waveguide structures have challenging designs at high microwave frequencies and THz frequencies, the rectangular waveguide, in particular, is still considered the highest quality

*Corresponding Author: hilal.koc@erzurum.edu.tr
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structure due to its lowest transmission loss and unique electrical performance [15]. This paper explores the characteristic performances of graphene cladding rectangular waveguides filled with dielectric materials such as Si [16], SiO2 [17], Zeonex [18], Teflon, and PMMA [19] which are pretty preferred for use in dielectric waveguides. When the studies carried out to date are examined, a study has yet to be encountered that looks at the effect of these materials on waveguide performance for the same structure and discusses the suitability of the materials for use in THz waves. Therefore, in this study, the electromagnetic field profile on the graphene cladding rectangular waveguides filled with various materials is evaluated. In addition, the primary parameters that determine the performance of the waveguide, such as transmission coefficients (S21), attenuation constant (dB/mm), and effective refractive index (n_{eff}) have been comparatively analyzed.

2. Materials and methods

2.1. Rectangular waveguide design

The formula used to determine the dimensions of the hollow metallic rectangular waveguides configured for the microwave frequency region may be extended to design waveguides for the THz frequency region. In these waveguides with a 2:1 aspect ratio, the cut-off frequency 'fc' is calculated using Equation 1.

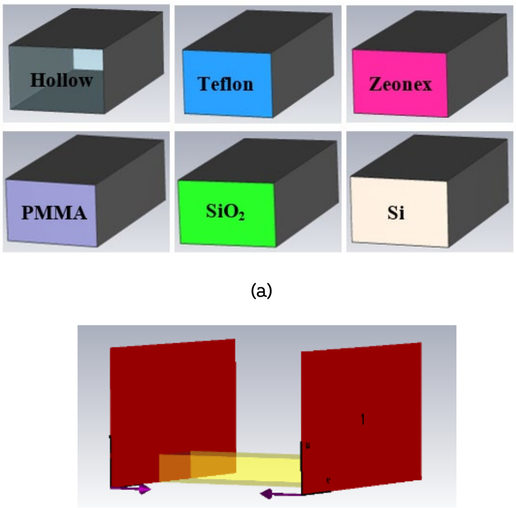
$$f_c = \frac{c}{\sqrt{\varepsilon_r}} x \frac{1}{2a} \qquad (1)$$

where c is the speed of light in a vacuum with a value of approximately $3x10^8$ m/s, ε_r is the relative permittivity assumed to be 1, and a is the width of the rectangular given in m [20].

In this study, first of all, hollow graphene and gold rectangular waveguides were designed to give superiority of graphene over the noble metal. Gold was preferred in this study because it is widely used in THz region designs due to its good metallic properties and low absorption [21]. Figure 1(a) demonstrates rectangular waveguides whose dimensions are given in Table 1 and transmitting at around 1.65 THz frequency band, designed in the CST Microwave Studio program.

Table 1. The physical dimensions of rectangular waveguide

Parameter	Definition	Value (μm)
a	waveguide broad wall dimension	135
b	height of waveguide	67.5
L	length of waveguide	500
t	thickness of wall	0.5



(a)

(b)

Figure 1. a) The designed rectangular waveguide structures, b) location of ports

The hollow waveguide has been designed for gold and graphene, respectively (for separate chemical potentials at 293 Kelvin and $6x10^{-12}$ s). Frequency Domain (FD) solver has been used in CST to calculate losses, which is an important parameter when evaluating the performance of the waveguide.

The complex permittivity of rectangular hollow graphene and gold waveguides is demonstrated in Figure 2. It is seen that graphene has a higher permittivity than gold in the operated frequency range. It is preferred to use materials with high permittivity in waveguides to prevent radiation from spreading in space. Therefore, in this study, the graphene-coated waveguide will be examined.

Generally, waveguides are designed to be hollow, that is, their core has a refractive constant of 1. The performance of the waveguide can be enhanced using core materials with a higher refractive index instead of a vacuum. Moreover, if we consider the production of simulated almost nano-sized waveguides, the dielectric filling will facilitate fabrication compared to the vacuum. Therefore, the hollow rectangular waveguide is investigated in this paper by filling it with various dielectric materials. The dielectric materials were created in the material library of the CST program by entering their properties [22]. The structures of graphene rectangular waveguides, which are hollow and filled, are shown in Figure 1(a).

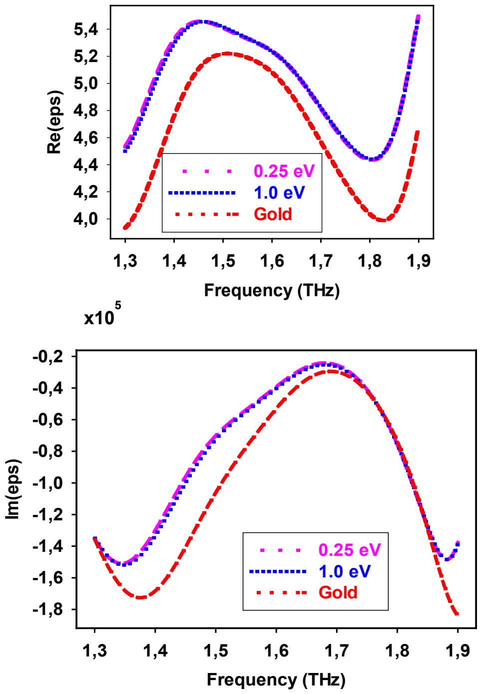


Figure 2. The complex permittivity of graphene and gold

3. Results and discussion

Electric field (and therefore associated magnetic field) intensities can say something about the information transmission performance of waveguides. Higher electric field strength means better information transfer or more reliable information transfer. Electric field distributions of waveguides at 1.65 THz are given in Figure 3. When electric field profiles are examined, Teflon and Zeonex show the best propagation.

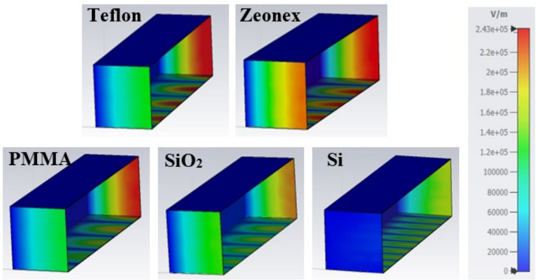


Figure 3. The electric fields in the waveguides at 1.65 THz

Similarly, in Figure 4, the simulated transmission coefficients (S21) of the designed waveguides between 1.10-2.10 THz prove that Teflon and Zeonex perform well around -0.5dB.

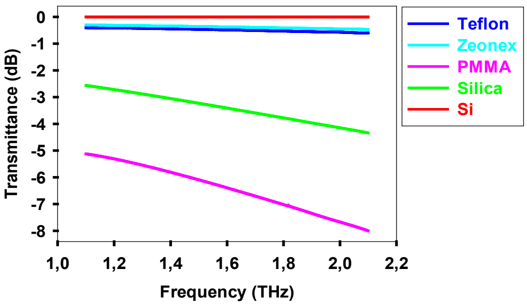


Figure 4. Transmittance (S21) parameter of different core materials

The real part of effective refractive indices plotted between 1.1-2.1 THz (1.4x10^5-2.7x10^5 nm wavelength) is depicted in Figure 5. The effective refractive index affects the propagation length along the propagation direction.

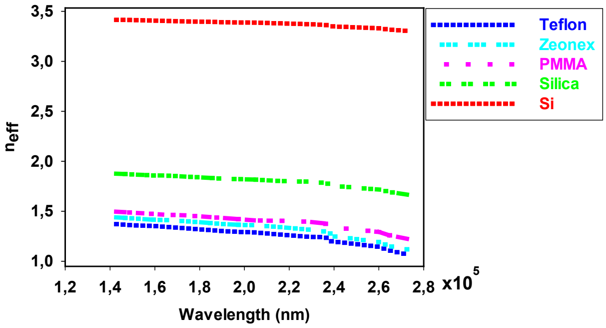


Figure 5. The real effective refractive indices of waveguide structures

As electromagnetic waves can be absorbed or scattered as they transmit through the waveguides, their intensity decreases. This reduction is observed in the imaginary component of the propagation constant, known as the attenuation constant. Figure 6 depicts the attenuation constant at the wavelengths at which the waveguides are examined. When the graph is reviewed, it can be seen that even lower propagation losses can be achieved by changing the core material. The obtained results support the electric field results. Attenuation (loss) is seen at least in Teflon, followed by Zeonex, with approximately 0.093 dB/mm loss observed at 1.8x10^5 nm wavelength.

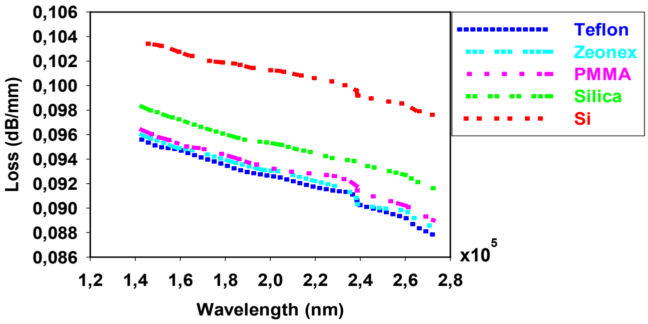


Figure 6. The attenuation constant of waveguide structures

4. Conclusion

In this study, graphene-based rectangular waveguide design and performance analysis are presented to ensure focusing efficiency in THz ablation systems, which have recently come to the fore in cancer treatment research. Various filling materials such as Si, SiO2, Zeonex, Teflon, and PMMA were preferred for performance analysis. According to the obtained transmission coefficient results, Si, Teflon, and Zeonex showed an outstanding transmission performance with ≈-0.5 dB. The high performance of Teflon and Zeonex has been confirmed by the electric field distributions formed in the waveguide. According to the analysis results, graphene-based waveguides prepared with Teflon and Zeonex fillers can increase focusing efficiency in THz ablation applications.

Declaration of Conflict of Interests

There is no conflict of interest between the article authors.

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