Research Article

Factors influencing the microwave propagation performance of different types of materials

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Abstract: This paper focuses on studying and comparing specific various types of materials which are Silica glass (SiO_2), $FR-4$, Titanium oxide (TiO_2), Graphene (C), Silicon (Si), Gallium arsenide ($GaAs$), and Chromium oxide (Cr_2O_3). It deals with single layer of each previous material in dielectric slab waveguide. Moreover, it studies and compares the effects of a microwave frequency ($30GHz$) of the applied electromagnetic waves on TE-modes under assumption of using a constant value of materials thicknesses. It was clearly shown that waveguide parameters of different materials are different depending on its structure and its refractive index. Results and discussion section demonstrates overall comparing among these seven different materials.

Keywords: Microwave propagations Slab Waveguide$SiO_2$$TiO_2$ Graphene

1. Introduction

Microwaves was discovered in 1964 [1]. It pervades the whole universe; it was applied in tremendous scientific fields such as military, medical, communication, scientific instruments, radars, spaceships, satellites, domestic appliances ... etc [2]. Most impressive, modern technologies depend on the microwave frequencies.

A waveguide is a physical structure that efficiently guides a high frequency electromagnetic (EM) signals which is rated ($3\ GHz - 300\ GHz$). As a transmission medium, it used as components in integrated circuits such as light wave communications, biomedical imaging, ... etc. Waveguide can be classified according to structures, mode structure, refractive index distribution, and materials. In general, waveguide has many different parameters such as number of modes, a cut-off frequency which is a minimum frequency that will be propagated, attenuation, the effective skin depth, the propagation wave number, and cut-off wave number [3]. These parameters is depends on the type of materials, and their structures. Electromagnetic waves propagate differently at a discrete set in a specific waveguide.

This discrete set is called mode which is the mathematical description of the natural propagations of EM waves [4-6]. A number of modes differs from materials to another in dielectric slab waveguide. Each mode has specific parameters [6]. Each material majorly characterizes by it refractive index and the other indices. Actually, the refractive index varies not only with the material types and its structures but also with the other effects such as temperature [7].

Recently, Yonggang Qin, Xiaobo Feng, and Yu Liu studied the refractive index of graphene for rectangular ggraphene quantum dots in the visible region and in the infrared region. They found that graphene quantum dots dramatically performs a bitter than conventional semiconductor quantum dots [8]. Moreover, the measurement with graphene in the imaging spectroscopic ellipsometer is quicker than traditional methods [9]. [10] stated a new comprehensive approximated formula of the optical properties of silica glass which depend on the refractive and absorption indices. Also, [11] was proposed a novel approach to determine refractive index of a silicon, and its related to the geometrical thickness of this material.

In this paper, dielectric slab waveguide is used to study the electrical properties of the different types of materials in microwave propagations at frequency 30 GHz. It studies and compares different types of materials which are Silica glass (SiO_2), $FR-4$, Titanium oxide (TiO_2), Graphene (C), Silicon (Si), Gallium arsenide ($GaAs$), and Chromium oxide (Cr_2O_3). We investigate and discuss the performance of each different material separately then compare them to choice an appreciate material for a specific purpose depending on its parameters and structure. The thichness of a specific material is clearly important and affects the performance of that material. For simplicity, it is chosen a constant value for all types of materials that are employed in this paper. Otherwise, the thickness of material can be varied depending on its performance and applications.

This paper is organized as follows. Section 2 briefly describes seven different materials that is employed and its properties. Section 3 derives the mathematical expressions of TE modes and their relations to the types of materials,and the frequency of the EM wave. In section 4, simulation results state the performance of each material separatelythen compare their effects on TE modes and their parameters. Section 5concludes this paper.

2. Materials

This section describes the seven different materials that are implemented indielectric slab waveguide to study their electrical properties in microwave propagations at frequency 30 GHz. They are Silica glass (SiO_2), $FR-4$, Titanium oxide (TiO_2), Graphene (C), Silicon (Si), Gallium arsenide ($GaAs$), and Chromium oxide (Cr_2O_3).

2.1 Silica glass (SiO_2)

Silica glass is a noncrystalline form of silica which is also known as vitreous silica, amorphous silica, and glassy silica. Commercially, silica glass is classified to four types. First, electric melting of natural quartz crystal is found in vacuum. The second type quartz crystal powder while the third and fourth types are produced from SiC_{14}.

SiO_2 has a favorable characteristics in physical, chemical, and optical. Its optical and thermal radiation performances are essentially predicted and optimized [10]. Therefore, it has many different applications such as laboratory glassware, lenses or beam splitters, lighting and IR heating, fiber optics, a dielectric insulator, a waveguide, photonic crystal fibers, thermal protection systems like fibrous thermal insulation.

2.2 $FR-4$

FR-4 Epoxy is a composite material and a popularly versatile high-pressure thermoset plastic laminate grade with good strength to its weight and high value of dielectric constant. Moreover, it is stable in both conditions' humidity and drought. Therefore; it is commonly used as an electrical insulator but it has low loss tangent [12-13]. Furthermore, this material is a majority of producing the rigid printed circuit boards.

2.3 Titanium oxide (TiO_2)

Titanium dioxide (TiO_2) is a dielectric material with high relative dielectric constant and low dielectric loss. Environmentally, it has stable dielectric properties [14]. TiO_2 is importantly classified as industrial material. It is used as a main component of paint, pigment, cosmetics [15]. Due to having high dielectric constant and refractive index, it is used for optical coatings, beam splitters and anti-reflection coatings. Furthermore, it can be used as a humidity sensor and high temperature oxygen sensor [16].

However; TiO_2 is a photosensitive semiconductor through illuminating it with energy light higher than its band-gap. That leads to generate electron-hole pairs.

Basically, there are three basic crystalline phases of Titanium oxide which are anatase (tetragonal), rutile (tetragonal), brookite (orthorhombic). Anatase and rutile have excellent photocatalytic and antibacterial properties.

2.4 Graphene (C)

Graphene is comprised of a plane of carbon atoms which are arranged in honeycomb lattices. It is intensely attended because of its properties in physical and chemical characteristics [8]. Due to the structure of graphene which it is tailoring of various nanostructures, Graphene has numerous benefits such as one-dimensional nanoribbons and zero-dimensional quantum dots with desired size, edge, and shape [17]. Furthermore, these advantages making graphene material as a base of the nanostructures promising candidates to build blocks of future opto-electronic devices [18].

Additionally, it has remarkable properties, for instance, high crystal quality, its accurate charge carriers, ballistic transport of electrons on a submicron scale [9], high carrier mobility, and high electrical conductivity. Therefore; it is essentially applied in optical communication and signal-processing systems [19]. The example of using graphene material in optical applications is designing a gas sensor, and plasmatic resonators.

2.5 Silicon (Si)

Silicon is a semiconductor element which is a fundamental wafer manufacturing. The geometrical thickness of the Silicon wafer is the more important parameters in its applications which leads to undesired connections or disconnections [11]. Silicon is essentially used in the modern technologies of electronics, opticals, and photonics and photovoltaics. Particularly, its important optical properties is the sense of absorption and refraction of the incident electromagnetic radiation of different wavelength ranges which are infrared (IR), visible and ultraviolet (UV).

2.6 Gallium arsenide ($GaAs$)

In recent decades, Gallium arsenide (GaAs) is investigated to be the most technologically important. It is a type of a semiconductor materials which characterizes with its band structure parameters. The most important structure parameter is its energy gap which its value is an $1.519\ electron - voltage$. Furthermore, it characterizes with a good property such as photochemical stable, non-degradability, good thermal conductivity, high photoelectric conversion efficiency, good performance at high temperatures, fine radiation resistance, and high damage threshold [20].

Therefore; Gallium arsenide has been intensively employed in the various fields of optoelectronics applications, for instance, widespread concern as a semiconductor storable absorber applications, Nanotubes and its internally-carrier transport applications [21], and higher mobility for generating microwaves.

2.7 Chromium oxide (Cr_2O_3)

Chromium oxide (Cr_2O_3) is a magnetic dielectric material which consists of the rhombohedral primitive cell. Eight Cr atoms are coordinated with two oxygen layers. Cr_2O_3 is the more stable bulk oxide under ambient conditions with corundum structure [22]. This type of material exhibits a high hardness and a high wear with corrosion resistance. Therefore; the major application of it is to protect coatings in digital magnetic recording units and in gas-bearing applications.

However, it has been employed in optical and electronic applications such as a tunnel junction barrier [23], selectively absorbing films for solar energy conversion, electrode material for electro chromic windows, solar energy shielding films for windows, and infrared (IR)-transmitting coatings, also in industrial applications such as in catalysis and solar thermal energy collectors. Furthermore, Cr_2O_3 can be an either p-type or n-type semiconductor depending on its growth conditions.

3. Mathematicalmodels

Mathematical models of TE modes are analyzed generally to investigate and compare the performance of different types of materials and their parameters using dielectric slab waveguide [3], [24]. In general, EM fields propagate inside and outside slab waveguide. Electrical fields summarize in two forms which are odd and even TE-modes as shown in (1) and (2), respectively.

$$E_y(x) = \begin{cases} E_1 \sin k_c x\, for \quad -a \leq x \leq a \\ E_1 \sin k_c a\, e^{-\alpha_c(x-a)} forx \geq a \\ -E_1 \sin k_c a\, e^{\alpha_c(x+a)} forx \leq -a \end{cases} \quad (1)$$

$$E_y(x) = \begin{cases} E_1 \cos k_c x\, for \quad -a \leq x \leq a \\ E_1 \cos k_c a\, e^{-\alpha_c(x-a)} forx \geq a \\ E_1 \cos k_c a\, e^{\alpha_c(x+a)} forx \leq -a \end{cases} (2)$$

Where E_1 is a constant value depending on the tangential components of the magnetic and electric fields, k_c indicates the cut-off wave numbers in (3) for each angle of incidenceθ, α_c is the EM field attenuation in (4) for each angle of incidenceθ, and a indicates the thickness of material which is a constant value $a = 0.5\ cm$in this paper. Also, $1/\alpha_c$ is the skin depth distance which is occupiedby EM fields.

$$k_c = k_1 \cos\theta = k_0 n_1 \cos\theta \ (3)$$

$$\alpha_c = \sqrt[2]{\beta^2 - {k_0}^2 {n_2}^2} = k_0 \sqrt[2]{{n_1}^2 \sin\theta^2 - {n_2}^2} (4)$$

Where β indicates the propagation wave number in (5) for each angle of incidenceθ.

$$\beta = k_1 \sin\theta = k_0 n_1 \sin\theta \text{ (5)}$$

Moreover,$(M+1)$ modes alternate between odd and even, if the normalized frequency variable$R$ in (6) in the interval (7).

$$R = k_0 a N_A = \frac{2\pi f a}{c_0} N_A = \frac{2\pi a}{\lambda} N_A \qquad (6)$$

$$\frac{M\pi}{2} \leq R < \frac{(M+1)\pi}{2} \text{ (7)}$$

Where N_A indicates the numerical aperture of the slab as in (8), and λ indicates the free space wavelength.

$$N_A = \sqrt[2]{{n_1}^2 - {n_2}^2} \text{ (8)}$$

Where$n_1 and n_2$ indicates the inside and outside refractive indices where refractive index depends on the type of materials. Therefore; the maximum mode (M) number can be calculated by (9).

$$M = floor\left(\frac{2R}{\pi}\right) \text{ (9)}$$

Moreover, the cut-off frequency of each mode can be calculated in (10).

$$f_{c_m} = \frac{m c_0}{4\, a N_A} form = 0, 1, 2, \ldots, M \quad (10)$$

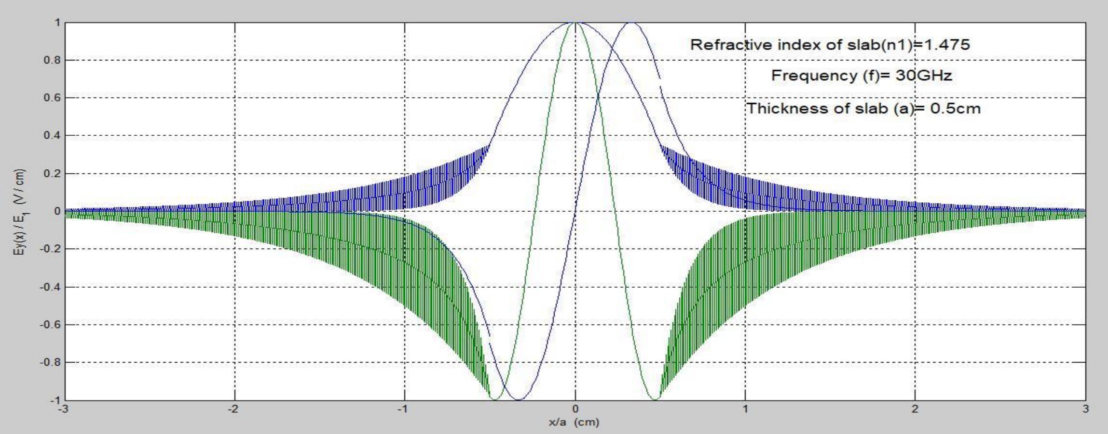
Form all the previous general equations, the performance of a specific material and its parameters depend on the refractive index of that material as shown in table 1.

Table 1.Refractive indices of various materials

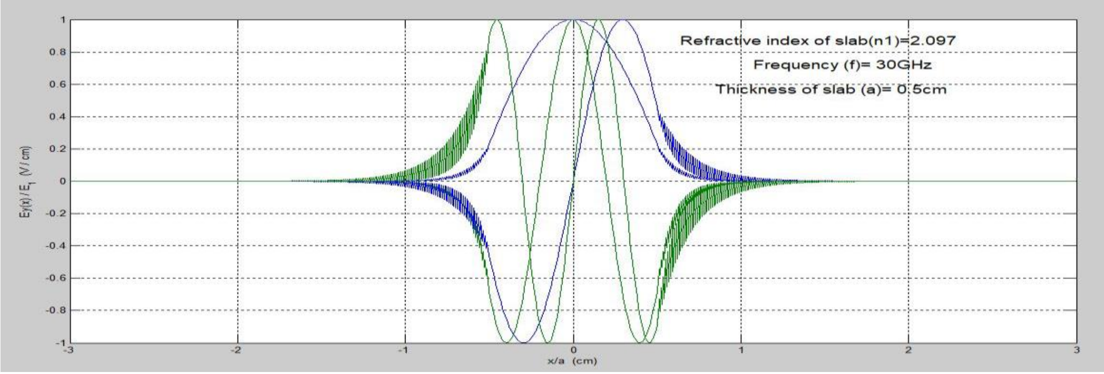
Material Name	Material Type	Formula	Refractive Index
Silica glass	semiconductor - Ceramic	SiO_2	1.475
$FR-4$	Isolator - Polymer	$FR-4$	2.097
Titanium oxide	Isolator	TiO_2	2.4
Chromium oxide	semiconductor	Cr_2O_3	2.7050
Graphene	Isolator	C	2.75
Silicon	semiconductor	Si	3.42
Gallium arsenide	semiconductor	$GaAs$	3.927

4. Resultsanddiscussion

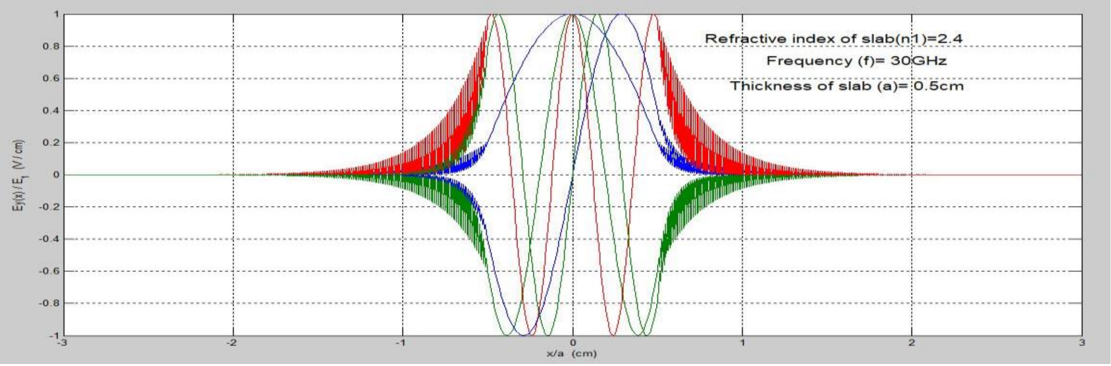
In this section, the simulation results are explained and discussed by MATLAB codes . Seven different materials were implemented in slab wave guide separately to study and compare their performance and properties. Each material has own properties and different value of waveguide parameters which are cut-off frequency, attenuation wavenumbers, and propagation wavenumbers, that leads to exploit these materials in various applications. In microwave propagations, EM wave with frequency $30GHz$ was applied separately on each material with constant value of material thickness which is $a = 0.5\ cm$. The number of modes differs from material to another as shown in electric field patterns of each materials. Fig. 1 shows electric field patterns as a function of $(x\ /\ a)\ cm$ with constant value of thickness$a = 0.5\ cm$, and with applying microwave frequency$30\ GHz$frequencies on each seven materials separately.



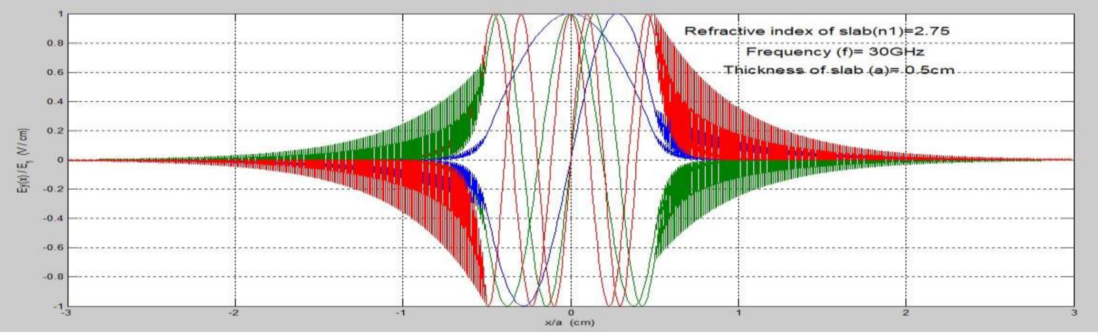
a. Silica glass (SiO_2)



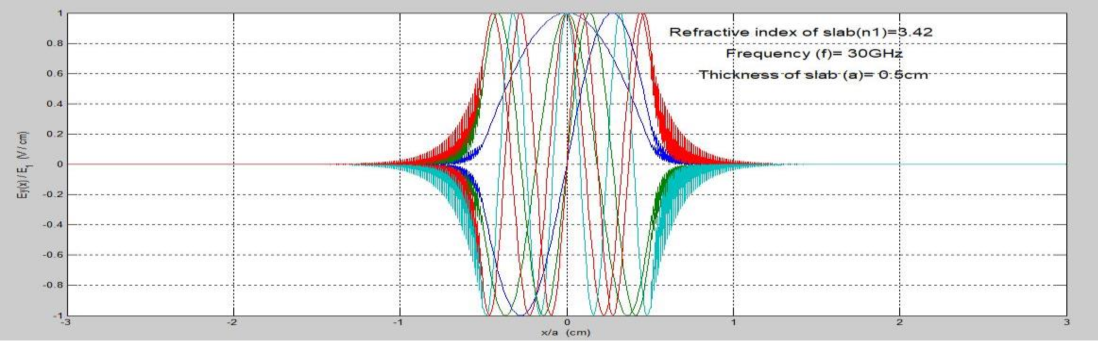
b. FR – 4



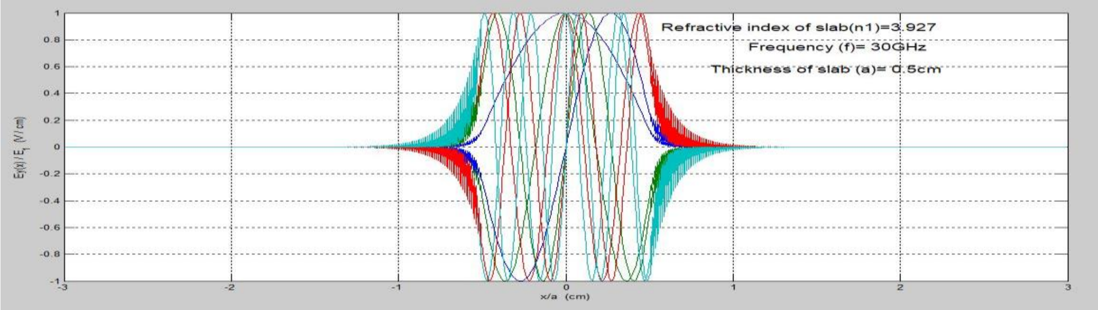
c. Titanium oxide (TiO_2)



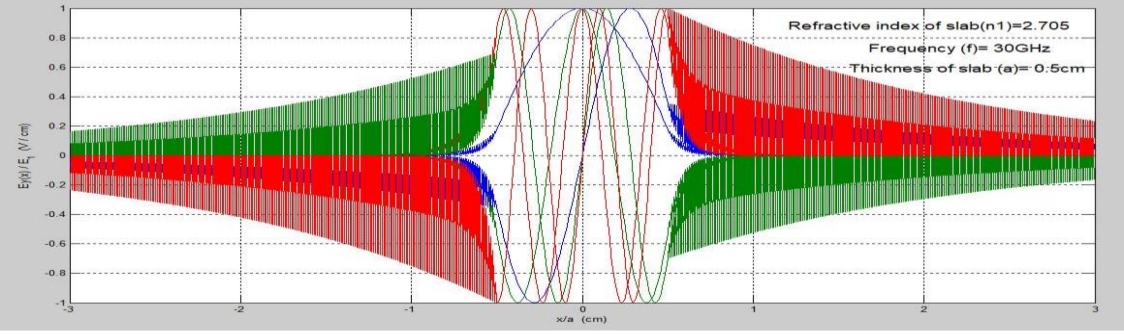
d. Graphene (C)



e. Silicon (Si)



f. Gallium arsenide (GaAs)



g. Chromium oxide ($\mathrm{Cr_2O_3}$)

Figure1. Electric field patterns

It was clearly shown from the results that each material has different microwave propagation with different number of modes depends on the structure of its material and its refractive index value, but it is notable for all materials that the EM waves could sinusoidal distributed inside each material, and exponentially distributed outside them. Furthermore, all these electric field patterns has the usual configuration. In each pattern, the electric field oscillates inside material and evanescent surrounding it with different propagation pattern for each material.

However; the TE_1 mode for all type of these seven materials distributes symmetrically because of material's properties of symmetric structure. The number of modes increases directly with increasing the value of the material's refractive index. For example, the maximum number of modes for these seven materials in this research is seven modes achieved in Gallium arsenide which has a highest refractive index as shown in table 1, then Silicon with six modes, and Silica glass has only two modes under a condition of employing a constant value of the material thickness for all these seven materials.

Depending on the number of modes for each material, the values of waveguide parameters are compared separately. Fig. 2 shows the comparison among seven different materials with their cut off frequencies respect to the number of modes.

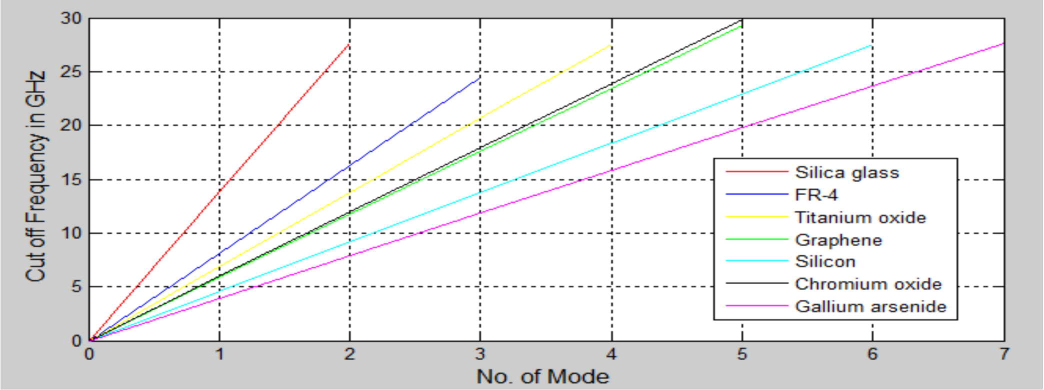


Figure2. Cut off frequency comparison.

The greatest cut off frequency is associated with Chromium oxide material, then graphene material while the lowest cut off frequency is associated with FR-4 material. Fig. 3 shows the comparison among them with attenuation wavenumbers respect to the number of modes in each material.

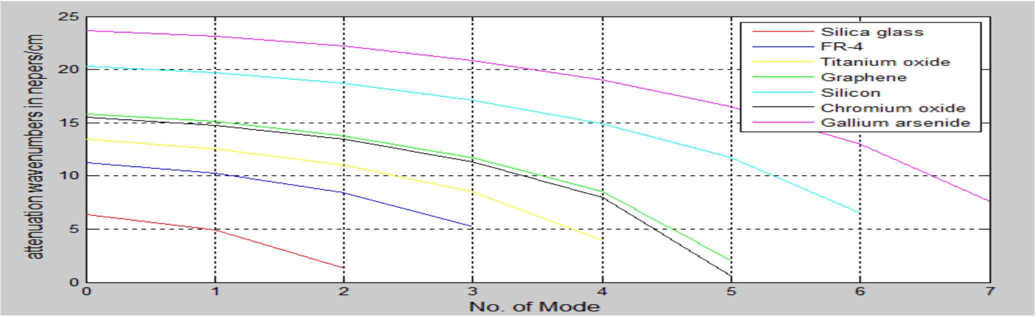


Figure3. Attenuation wavenumbers comparison.

The highest attenuation wavenumbers is associated with the maximum modes which is seven at Gallium arsenide. This implies that increasing the material refractive index leads to increasing the attenuation wavenumbers. Moreover, there is a tradeoff between number of modes and attenuation parameter.

However; in each material, the highest mode exhibit less quantity of attenuation than the other modes. This implies that the quantity of attenuation parameter reduces with a higher mode in each these seven materials. For example, Silica glass has less value of the refractive index in this paper, thus it has the less attenuation wavenumbers compared with the others. Simultaneously, the third mode of Silica glass has less quantity of attenuation wavenumbers than the other two modes of the same material.

Moreover, the propagation wavenumbers of the supported TE-mode that is associated with Gallium arsenide material is the higher compared with the other different six materials as shown in fig. 4.

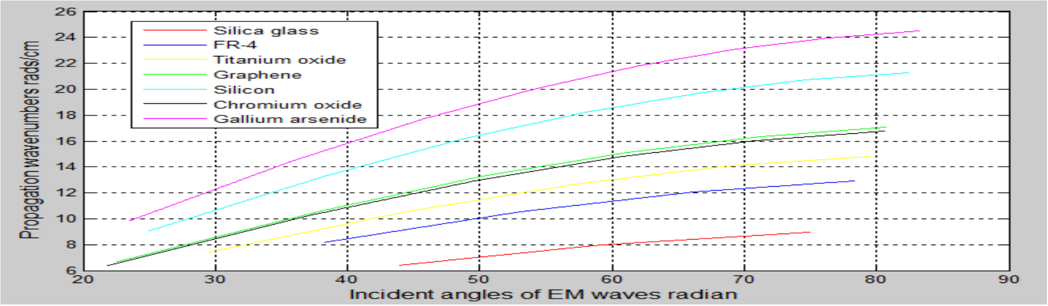


Figure4. Propagation wavenumbers respect to the incident angles.

The propagation wavenumbers of all TE modes of each material is plotted as a function to the coressponding incident angles of EM waves. The propagation wavenumbers increase directly with increasing the value of the incident angle for all these seven materials. On the other word, the propagation wavenumbers increase as the refractive index of the material increases as shown in table 1. Silica glass has the minimum value of the refractive index while Gallium arsenide has the greatest of it amonge these seven different types of materials. This process of increasing in the propagation wavenumbers indicates that the confinement of EM wave inside material is improved. Also, the evanescent of EM fields in the surrounding it is diminished.

5. Conclusion

This research paper focuses on studying, discussion, and comparing the performance of seven different materials in dielectric slab waveguide when applying EM wave with microwave frequency ($30GHz$). The seven different materials include Silica glass (SiO_2), $FR-4$, Titanium oxide (TiO_2), Graphene (C), Silicon (Si), Gallium arsenide ($GaAs$), and Chromium oxide (Cr_2O_3). To be clear, this discussion and comparing were occurred under assumption of using a constant thickness for each material. It was shown in result and discussion section that microwave propagation differs depending on the material type, then its structure, and its refractive index. The refractive index is an essential property for each material in microwave frequencies. Maximum mode, which could such material achieved, rises with a higher value of the material refractive index. Furthermore, attenuation and propagation wavenumbers are directly proportional with increasing the refractive index, on the other words, with the number of modes for each material.

However; the quantity of attenuation wavenumbers reduces with a higher mode in each material while propagation wavenumbers increase. The other waveguide parameter was discussed in this paper which is cut off frequency. It is increased directly with a higher mode in each material, and its quantity depends on the structure of each material. These results and discussion could be exploited to choose an appropriated material to a specific application.

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