Dielectric Waveguide for Composite Materials

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Abstract

The Maxwell equations have been formulated for a composite slab waveguide at x-band wave propagation. The eigenvalues of the system equations are obtained by using MATLAB program. These eigenvalues are used to obtain the wave propagation constant and a number of modes inside the slabs. A good correspondence was seen between the number of modes and the cut off thickness. The parameter that affects the performance of waveguide is the slab thickness. The propagation constant is usually adopted to characterize this type of waveguide and show how the cutoff frequency of the mode in the slab is increased dramatically by decreasing the frequency.

Our study focused on lower modes, the results for the transmission coefficient are then used to study the propagation properties of the guided modes in waveguides. Characteristic equations, solutions for TE (transverse electric) modes are presented. Numerical results for the propagation constant and field distributions of several lower-order modes are presented.

By finding the exact transmission coefficient of lower mode of a plane wave incident at a normal incidence on composite slabs, the propagation properties of guided modes in planar slab were studied.

It is important to find suitable materials for the transmitting and receiving of microwave frequencies and useful for designing a waveguide filter to separate waves of the same frequency but with different transmission modes.

Keywords
wave guide,
rectangular waveguide
transition line,
cut off frequency.

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موجه الموجة العازل للمواد المتراكبة

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الخلاصة

وضعت معادلات ماكسويل عن الدليل الموجي للوح مركب في انتشار حزمه اكس. يتم الحصول على القيم الذاتية للمعادلات النظام باستخدام برنامج ماتلاب. وتستخدم هذه القيم الذاتية للحصول على انتشار ثابت الموجه وعدد الأنماط داخل الالواح. هناك تطابق جيد بين عدد الأنماط و سمك اللوح . المعلمات التي تؤثر على أداء الدليل الموجي هو سمك اللوح. يعتمد ثابت الانتشار على خصائص هذا النوع من الدليل الموحي وتظهر كيف أن تردد قطع من النمط في اللوح يزداد بشكل كبير من خلال خفض التردد.

دراستنا تركزت على الأنماط المنخفضة، النتائج لمعامل الانتقال تم استخدامها لدراسة خصائص انتشار الأنماط الموجهة في الدليل. معادلات مميزة لحلول أنماط (المستعرضة الكهربائية) والنتائج العددية لثابت الانتشار وتوزيعات

المجال لعده أنماط منخفضة كانت موجودة من خلال إيجاد معامل انتقال مضبوط لنمط منخفض لمستوى موجه ساقطة لسقوط عمودي على لوح متراكب، خصائص الانتشار للألواح المركب للأنماط في لوح مستوى قد درست.
ومن المهم البحث عن المواد المناسبة لإرسال واستقبال للترددات الموجات الدقيقة والمفيدة لتصميم الدليل ألموجي و مرشح للموجات منفصلة من نفس التردد ولكن مع أنماط نقل مختلفة.

Introduction

An optical waveguide is a structure which confines and guides the light beam by the process of total internal reflection (TIR).

Waveguides are the backbone of modern optoelectronics and telecommunications systems. There are two major, and very distinct, types of waveguides (metallic and dielectric) that are used in two separate regime of the electromagnetic spectrum [1,2]

One of the simplest forms of optical waveguide structures is the dielectric slab waveguide. The guided modes of the slab waveguide can easily be described because of its simple geometry. The study of slab waveguide is important for the understanding of the wave-guiding properties of more complicated dielectric waveguides. Optical waves in waveguides propagate only at a discrete set of states, which are called modes. The modes are characterized by their propagation constant, which is a measure for the speed at which the phase fronts propagate along the structure [3]. It is possible to have more than one mode of electromagnetic wave propagation within a waveguide. Each mode has a cut-off frequency at which the wave number in the direction of propagation is zero.

Single-mode waveguides are known to have very low optical dispersion, high bandwidth by allowing only the zero-order mode to propagate. Single-modes are capable of transferring high amounts of optical data due to lower optical dispersion over long distances [4].

The second general type of waveguide modes, multimode has a larger core than single-mode fiber. It gets its name from the fact that numerous modes, or light rays, can be carried simultaneously through the waveguide [5].

A transverse electric mode ***(TE)*** is one in which there is no component of the electric field parallel to the direction of propagation $E_z = 0$.

The number of the guided modes that can be supported by a three layers slab waveguide depends on the thickness, **2*a***, of the wave guiding layer and on ω (angular frequency) and refractive indices. The higher order modes penetrate deeper into the cladding regions than the lower order modes. The lowest order mode has a ***β*** (propagation constant) that is nearly parallel to the ***z***- axis and the highest order mode will have a ***β*** at nearly the critical angle [6].

By calculating the cut-off thickness for certain modes, the film thickness can be determined to ensure that the waveguide is able to support the fundamental mode and to control the thickness when designing the single mode waveguides.

The energy carried by the wave is distributed between the attenuated and transmitted wave and can be characterized in terms of the incident E field amplitude of the two media (i.e. composite material and air).

The main causes of propagation losses in straight wave guide are absorption and scattering from materials inhomogeneities and boundary imperfections [7,8].

A dielectric slab waveguide is a planar dielectric sheet or thin film of some thickness, say 2a, as shown in figure 1. Wave propagation in the z-direction is by total internal reflection from the left and right walls of the slab. Such waveguides provide simple models for the confining mechanism of waves propagating in optical fibers [3].

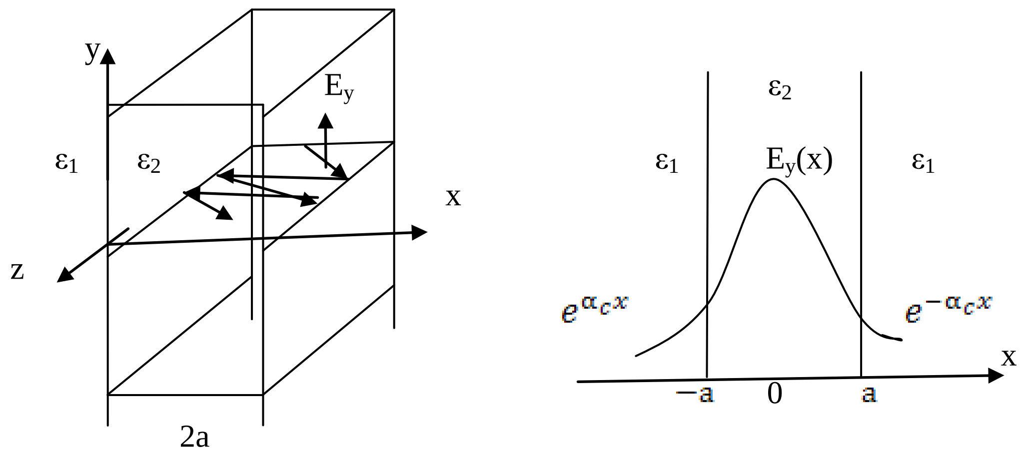

Figure 1. Dielectric slab waveguide (3).

Although the method is easy to use and capable of measuring transmission coefficient over a wide frequency range, the accuracy is moderate. Furthermore, the material sample must be sufficiently thick (so that the fringing field at the end of the coaxial line is confined within the material sample) and the surface in contact with the probe must be flat and free of air gaps or bubbles [9].

We selected Composite materials waveguide, PS/Alumina. The number of modes that have been presented in every waveguide has been analyzed and the transmission coefficient of samples for various composite materials is measured.
We have studied the effect of refractive index and thickness of composite materials on the transmission frequency and the modes in the slab . A major aim of this work was to reduce excess propagation loss of the TE mode of an optical slab waveguide. The single mode cutoff thickness can be one of the criteria to determine the thickness of a slab.

Results and Discussion

A program in MATLAB has been developed to calculate propagation constant, modes, cut-off conditions, losses and transmission coefficients from a slab of composite materials. The X-band rectangular waveguide applied in this work having the dimensions *a* = 2.4 cm, *b*=1.2 cm.

The waveguide is filled with the dielectric materials with dielectric constants 1.596 for polystyrene (PS)/Alumina.

Solving for Waveguide Modes

The results are presented using the X-band frequencies (8.0-12.4GHz), The MATLAB code has been used to analyze the number of modes presented in every waveguide and the results are compared with cut-off thickness condition results. An m-file has been created in order to calculate the parameters for each slab according to different frequencies and thicknesses, using the equations 1و 2 and 3 and equation 4 for even modes and 5 for odd modes [10,11].

$$k_c^2 = k^2 n_2^2 - \beta^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$-\alpha_c{}^2 = k^2 n_1^2 - \beta^2$$

$$\alpha_c = k_c \tan k_c a \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$f_c = \frac{mc}{4aNA}, \quad m = 0, 1, ..M \quad \ldots\ldots (3)$$

$$Ey(x) = \begin{cases} E_1 \cos k_c x, & \text{if } -a \le x \le a \\ E_1 \cos k_c a\, e^{-\alpha_c (x-a)}, & \text{if } x \ge a \text{ (even TE modes)} \\ E_1 \cos k_c a\, e^{\alpha_c (x+a)}, & \text{if } x \le -a \end{cases} \quad (4)$$

$$Ey(x) = \begin{cases} E_1 \sin k_c x, & \text{if } -a \le x \le a \\ E_1 \sin k_c a\, e^{-\alpha_c (x-a)}, & \text{if } x \ge a \text{ (odd TE modes)} \\ -E_1 \sin k_c a\, e^{\alpha_c (x+a)}, & \text{if } x \le -a \end{cases} \quad (5)$$

Where k is wave number of light in the medium , k_c is the cutoff wave number, f_c is cutoff frequency, α_c is attenuation coefficient, A is an arbitrary vector field and n_1 and n_2 the cladding and substrate refractive index respectively .

Using a waveguide optic modeling software system in MATLAB code, a number of modes can be obtained through the waveguide for different thicknesses as shown in Figs. 2,3 and 4. It has been found that for PS / Alumina waveguide, there are 1 , 2 and 3 modes for thicknesses 1.46 , 2.8 and 4.4 cm as shown in Figs. 2,3 and 4 respectively.

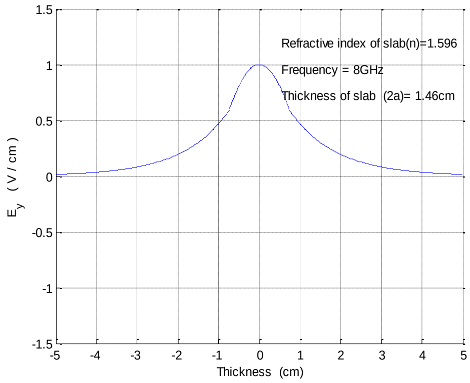

Figure 2: TE mode in waveguide with thickness 1.46 cm at 8 GHz for PS / Alumina.

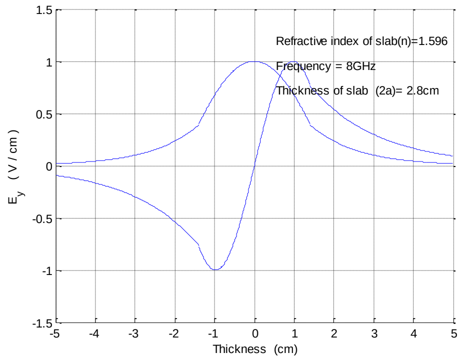

Figure 3: TE modes in waveguide with thickness 2.8 cm at 8 GHz for PS / Alumina.

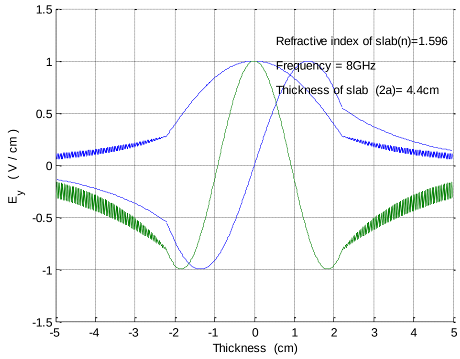

Figure 4: TE modes in waveguide with thickness 4.4 cm at 8.2 GHz for PS / Alumina.

The mode propagation parameters for TE mode results found at 8 GHz have been shown in Table 1.

Table 1: Parameters of the PS / Alumina waveguide of the three lower order modes at 8 GHz.

Thickness cm	m	β	k_c	α dB/cm	f_c GHZ
1.46	0	2.3580	1.2613	0.1442	0
2.8	0	2.5422	0.8296	0.1661	0
	1	2.1335	1.6122	0.1148	4.3068
4.4	0	2.6094	0.5847	0.1738	0
	1	2.4095	1.1598	0.1505	2.7407
	2	2.0592	1.7061	0.1040	5.4814

For thickness 1.46 cm, no higher TE modes were found and this can be attributed to the boundary condition of the cut off thickness curve for this case. As the slab thickness increases, higher order modes can be found for 2.8 and 4.4 cm thickness with lower propagation loss.

If the slab is too thin, then it will provide only a weak perturbation on the background dielectric constant and guided modes will still exist, but they will hug the edge of the light cone and be only weakly guided.

To avoid repeating graphs, we put the results of other frequencies with different thicknesses for PS / Alumina samples for TE mode, in Table2

Table 2: Mode numbers, propagation constant, modes loss at different frequencies and thickness for PS / Alumina TE polarization

F GHz	2a cm	m	β	k_c	α dB/cm	f_c GHz
9	1.3	0	2.6534	1.4177	0.1623	0
	2.6	0	2.8694	0.9039	0.1880	0
		1	2.4381	1.7623	0.1344	4.6381
	3.8	0	2.9321	0.6734	0.1952	0
		1	2.6961	1.3347	0.1675	3.1735
		2	2.2828	1.9595	0.1119	6.3469
10	1.18	0	2.9522	1.5678	0.1808	0
	2.4	0	3.1940	0.9857	0.2096	0
		1	2.7327	1.9251	0.1525	5.0246
	3.4	0	3.2570	0.7518	0.2168	0
		1	2.9923	1.4899	0.1875	3.5468
		2	2.5286	2.1862	0.1231	7.0936
11	1.04	0	3.2316	1.7540	0.1969	0
	2	0	3.4906	1.1557	0.2279	0
		1	2.9137	2.2427	0.1550	6.0296
	3.1	0	3.5832	0.8250	0.2385	0
		1	3.2934	1.6351	0.2045	3.8900
		2	2.7857	2.3999	0.1361	7.7801
12	0.94	0	3.6537	1.9573	0.2233	0
	1.6	0	3.9005	1.4022	0.2529	0
		1	3.1499	2.6941	0.1549	7.5370
	2.6	0	4.0291	0.9730	0.2677	0
		1	3.6705	1.9254	0.2254	4.6381
		2	30448	2.8123	0.1381	9.2762

The results show that the lower frequency gives fewer modes. Moreover, the dependence of modal attenuation on mode order is related to the index profile. Also, it has been noticed that as the mode number *m* increases, the quantities *α* and β decreases, while k_c increases causing the fields outside the slab to be less confined.

Increasing the frequency will increase β *and* therefore reduce the wavelength of TE mode inside the slab.

Cut off Thickness

The single mode cutoff thickness can be one of the criteria to determine the thickness of a slab. The waveguide allows guided wave propagation only if the thickness is greater than a critical cutoff thickness for each waveguide mode.

The values of the cutoff thickness, for the lowest order modes, for the composite waveguide structures at the X-band, have been calculated using equation 6 and shown in figures 5 and tables 3 (12).

$$c_{th.} = \frac{\lambda}{2\pi\sqrt{n_2^2 - n_3^2}}\left[m\pi + \tan^{-1}\left(\sqrt{\frac{n_3^2 - n_1^2}{n_2^2 - n_3^2}}\right)\right] \dots \dots \quad (6)$$

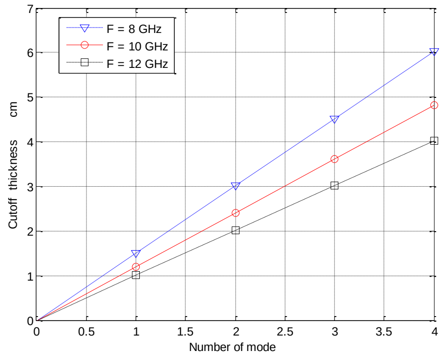

Figure 5: Relationship between critical cutoff thickness and number of modes of PS/Alumina for several propagating frequencies **.**

The cutoff thickness $c_{th.}$ decreases with the reduction of the slab refractive index and increasing microwave frequency,. Hence it is important to say that, in order to get a single mode waveguide operating with high preferable requirements with specific frequencies(as those applied in this work), the slab thickness must not exceed the cut-off thickness deduced as shown in Tables below.

Table 3: Cut off frequency of lowest order mode PS /Alumina.

Frequency GHz	Cut off thickness cm
8	1.50
9	1.33
10	1.20
11	1.09
12	1.00

Transmission Measurements

A program using Matlab has been developed to calculate transmission coefficients of a slab of a composite material at the X-band using equation (7).

$$T = \frac{1}{\left\{1 + \frac{(ka)^2}{8}\left(\frac{\lambda}{a}\right)^2 + j\frac{(ka)^2}{2(k_c a)}\left[1 - \frac{1}{2}\left(\frac{\lambda}{a}\right)^2\right]\right\} - \varepsilon\left[\frac{(ka)^2}{2} - j\frac{(ka)^2}{2(k_c a)}\right]} \dots \quad (7)$$

It should be mentioned, that the normal-incident transmission coefficients have been calculated in this work.

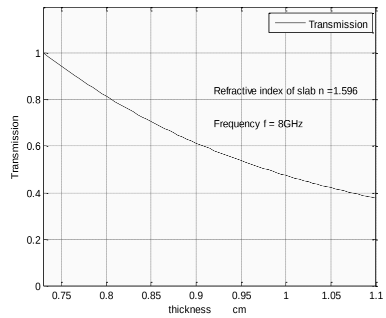

Figure.6 : Transmission of PS /Alumina at frequency 8 GHz

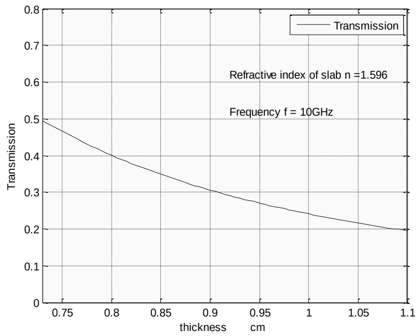

Figure 7: Transmission of PS /Alumina at frequency 10 GHz

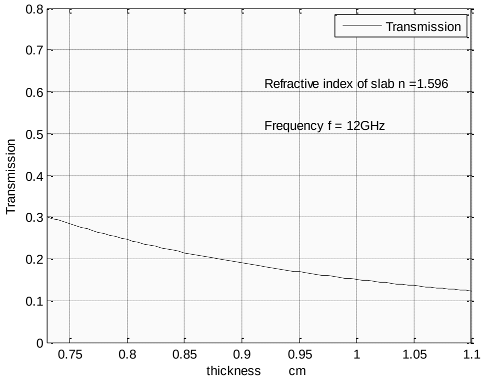

Figure 8: Transmission of PS /Alumina at frequency 12 GHz.

On the other hand, very thick slabs may cause high losses, resulting in a weak signal levels that cannot be accurately measured.

For all samples the reflectance *R* remains small compared to transmittance *T*. We assumed that all the materials in the composite, has a uniform dielectric constant.

The transitivity *T* in the slab waveguide as a function of thickness has an oscillating behavior between *T* =100% and *T* = 0%. Therefore, wave guides can be obtained with different transmitivities by changing the slab thickness range.
Figure 6 to 8 shows the transmittance for PS/ Alumina sample with same thickness and different frequencies. From these figures it has been noticed, that the transmission will vary inversely with the frequency and the lower transmission also changes according to the frequency applied.

For PS/ Alumina, at thickness 0.73 cm the transmission will reach 100% for 8 GHz, while for 10 GHz at same thickness is nearly 50%, and about 30% for 12 GHz.

In Figs. 9 and 10, the relation between the transmission coefficient and the thickness of the slab when the frequency changes have been shown.

One may conclude from the results above, that full transmission depending on the wave frequency, thickness and the refractive index of the slab. The values of *T* reduce exponentially with the thickness of composite materials, in perfect agreement with the results reported in [14].

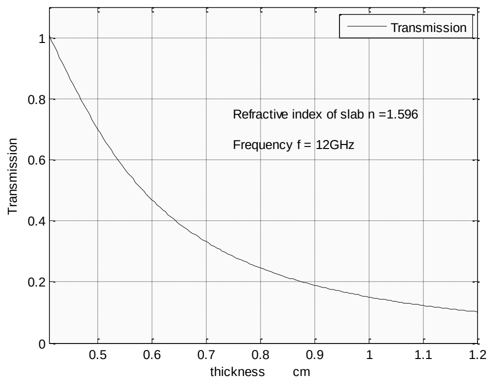

Figure 9 : Transmission of PS /Alumina at frequency 10 GHz.

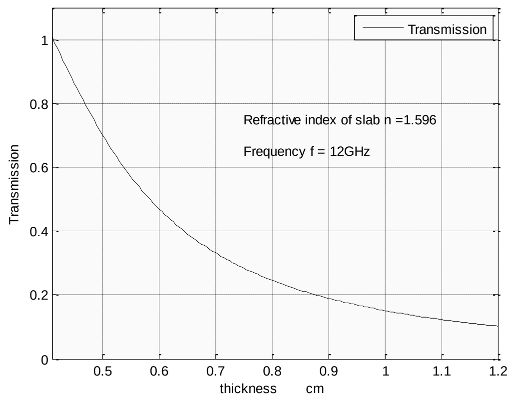

Figure 10: Transmission of PS /Alumina at frequency 12 GHz.

Conclusions

The basis of the work presented is the measurement and modeling of the characteristics of electromagnetic wave propagation inside the composites dielectric waveguide.

These eigenvalues are used to obtain the wave propagation constant and a number of modes inside the slabs. A good correspondence was seen between the number of modes and the cut off thickness. We have shown that the propagation constant in various slab waveguides depends on the declaration value of refractive index of the slab. Our studies focused on lower mode, the results for the transmission coefficient are then used to study propagation properties of guided modes in waveguides.

As it was shown, the full transmission 100% of various slab waveguides depends on the value of refractive index of the slab and its thickness. It is important to find suitable materials for the transmitting and receiving of microwave frequencies, useful for communications and data transfer. The comparison between the results of the full transmission coefficient for PS/Alumina, **(**$BaTiO_3$/ ABS, EPDM/ $BaTiO_3$, Zirconium Tin Titanate/Epoxy– not puplished) waveguides demonstrate how powerful our idea works.

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