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Wave Propagation in Dielectric Slab Waveguide with two Different Cladding Materials.

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ABSTRACT

In this study the Ku– band microwave with a frequencies of (12- 18) GHz propagation in dielectric materials InGaAsP (refractive index n1=3.39) with two different claddings, air(n2=1) and polyacrylate (n2=1.5), was investigated. Using the cladding polyacrylate gives better results. The graphical and numerical results of the behavior of electromagnetic wave propagation along Z - direction in dielectric slab waveguide in the two cases of cladding were investigated with the aid of MATLAB program. The graphical and numerical results coincide. The modes of propagation have been analyzed and all parameters have been given. The values of different parameters as cutoff wave number, cutoff frequency, cutoff thickness, propagation constant, and transmission of electromagnetic wave have been calculated. The transmission of the microwave depends on the slab thickness and the frequencies applied and it has been found to varied from 75% to 100%. The reflection amplitude inside the slab is not effected when the angle of the incident wave is less than the critical angle, while it increased rapidly as the angle increased higher than the critical angle.

Introduction

The study of electromagnetic waves properties of dielectric materials is an important element in which electromagnetic waves are used to transport energy from place to another, such as Television or broad casting station.The efficient transfer of information or energy from one point to another in a chosen direction is performed by specially designed electromagnetic structures or media called, electromagnetic waveguides.

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There are two major, and very distinct, types of waveguides (metallic and dielectric) that are used in two separate regimes of the electromagnetic spectrum [1,2]. The waveguide is a structure which confines and guides the wave beam by the process of total internal reflection (TIR). These electromagnetic waveguides are very important devices as regards carrying electromagnetic energy or signals in a certain direction, and as a basic part of the microwave since waveguides allow the waves from optoelectronic devices to travel for a large distance without being obstructed and to be directed in small areas of the microwave integrated circuit(MIC), where the (MIC) is a thin-film type of microwave circuit designed to perform a certain function. Waves in waveguides propagate only at a discrete set of states, which are called modes. The mode is the mathematical concept of describing the nature of propagation of electromagnetic waves in a waveguide[3]. The modes are characterized by their propagation constant, which is a measure for the speed at which the phase fronts propagate along the structure [4]. 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. There are two general categories of waveguides in use today, single mode and multi-mode waveguides [5-7]. Single-mode waveguides are known to have very low wave dispersion and high bandwidth by allowing only the zero-order mode to propagate[8]. The second general type of waveguide modes is the multimode which has a larger core than the single-mode fiber. It gets its name from the fact that numerous modes, or light rays, can be carried simultaneously through the waveguide [9].

The mathematical plane electromagnetic waves have transverse electric(TE) and magnetic(TM) components that are perpendicular to each other and aimed in a propagation direction also perpendicular to their transverse electric and magnetic components where for the transverse electromagnetic waves TEM: ($E_z=0$ & $H_z=0$), Transverse magnetic waves TM: ($E_z\neq0$ & $H_z=0$) and Transverse electric waves TE: ($E_z = 0$ & $H_z\neq0$).

The number of the guided modes that can be supported by a three layer slab waveguide depends on the thickness, 2a, of the wave guiding layer and the frequency of the wave and refractive indices. The thickness of the film can be determined by calculating the cutoff thickness for certain modes to ensure that the waveguide is able to support the fundamental mode and to control the thickness when designing the single mode waveguides. The single mode cutoff thickness can be one of the criteria to determine the thickness of a slab.

A study of slab waveguide often leads to graphical and analytical solutions and thus provides a much clearer physical insight into the understanding of transmission of electromagnetic waves in these materials.

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 [4].

In this work the number of modes and the transmission coefficient are measured. Also the effect of the different cladding materials, the thickness of dielectric material and the modes in the slab, on the propagation loss of the TE mode of a microwave slab waveguide have been studied. For this purpose, InGaAsP (ε = 11.4921) as dielectric materials waveguide with different surrounding media, air and polyacrylate, has been selected.

Theory:

For TE solution that depends only the

x- coordinate, the cutoff wave number k_c takes different values inside and outside the guide, so

$$k_c^2 = k^2 n_2^2 - \beta 2 \text{ outside} \ldots\ldots\ldots (1)$$

$$k_c = -\alpha_c{}^2 = k^2 n_1^2 - \beta^2 \text{ inside} \ldots (2)$$

Where β is the propagation constant. Thus, the electric field $E_y(x)$ will have the form:

$$E_y(x) = \begin{cases} E_1 \, cosk_c x \; if -a \leq x \leq a \\ E_2 \, e^{-\alpha_c x} \; if \; x \geq a \\ E_3 e^{\alpha_c x} \; if \; x \leq -a \end{cases} \quad \text{(even TE modes)} \ldots\ldots (3)$$

$$E_y(x) = \begin{cases} E_1 sink_c x, if -a \leq x \leq a \\ E_1 \, sink_c a \, e^{-\alpha_c (x-a)}, if \; x \geq a \\ -E_1 \sin k_c a \, e^{\alpha_c (x+a)} \; , if \; x \leq -a \end{cases}$$

(odd TE modes)……(4)

The boundary conditions state that the tangential components of the electric field $E_y(x)$, are continuous across the dielectric interfaces at x= - a and x= a. This continuity leads to the conditions;

For even TE mode

$$\alpha_c = k_c tank_c a \ldots \ldots \ldots \ldots \ldots (5)$$

and, for odd TE mode

$$\alpha_c = -k_c cotk_c a \ldots \ldots . \ldots \ldots (6)$$

The cutoff frequency as defined by

$$f_c = \frac{mc}{4aNA}, m = 0, 1, M \ldots .. (7)$$

Where $NA = \sqrt{n_1^2 - n_2^2}$ is the numerical aperture of the slab, c is the speed of light in free space and m is the number of mode.

The value of cutoff thickness for m=0 mode can be calculated by using equation[10]:

$$t_{co} = \frac{\lambda}{2\pi\sqrt{n_1^2 - n_3^2}} \left[m\pi + tan^{-1}\left(\frac{\sqrt{n_3^2 - n_2^2}}{\sqrt{n_1^2 - n_3^2}} \right) \right] ..(8)$$

In order to confine the wave in the slab waveguide, the incident angle (θ),

$$\theta = \text{asin}\left(\frac{\beta}{k_1}\right) \ldots \ldots \ldots .. (9)$$

should be greater than the critical angle **(θ_{cr}),**

$$\theta_{cr} = \text{asin}\left(\frac{n_2}{n_1}\right) \ldots \ldots \ldots (10)$$

In this case, the total internal reflections will increase as the incident angle (θ) increases. The transmission coefficients from a slab of a dielectric material have been calculated by using equation [11].

$$T = 1/\{\{1 + \frac{(ka)^2}{8}\left(\frac{\lambda}{a}\right)^2 + \frac{j(ka)^2}{[\,2(k_c a)]}\left[\left[1 - \frac{1}{2}\left(\frac{\lambda}{a}\right)^2\right]\right\} - \varepsilon\left[\frac{(ka)^2}{2} - j\frac{(ka)^2}{2(k_c\, a)}\right]\}\ldots\ldots(11)$$

Results and Discussion:

In this work, a MATLAB program has been developed to calculate most of the parameters representing the wave propagations in dielectric materials such as InGaAsP (ε = 11.4921) with different surrounding media, air and polyacrylate. For graphical solutions, equations(5&6) have been used.

Only one example for this solution has been given at 12 GHz for InGaAsP with n_1=3.39, n_2=1 (air) as shown in figure (2).

This figure shows the number of modes one can get in different frequencies, thickness and consequently radius. Hence, for 2a=0.38 cm, there is only one intersection between the circle and the $tank_c a$ curve which means there is only one even mode (m=0). For 2a=0.76cm, there are two intersections points, one gives even mode (m=0) and one odd mode(m=1) , and so on. The number of modes found from this method should be consistent with that for analytical solutions.

To obtain the TE field distribution by analyzing the propagation constant of the waveguides, a numerical analysis has been used. The results are presented using the K_u-band frequencies (12-18 GHz). A dielectric sample, InGaAsP, and two different cladding refractive indices, one with air and the other with polyacrylate material have been used. A MATLAB code has been used for this purpose to calculate modes, circle radius of mode, cutoff frequencies, cutoff thickness, propagation constant, cutoff wave number of each mode, attenuation, transmission and total internal reflection coefficients.

The number of modes presented in the waveguide and the parameters for each slab according to different frequencies and thickness was calculated and compared with cutoff thickness condition results. The number of modes that can propagate through the waveguide for different thickness is shown in figures (3-6). The TE_0 mode is the fundamental mode of dielectric slab waveguide. It has been found that for InGaAsP waveguide, there are one, two, three and four modes for thickness of 0.38, 0.76, 1.14, 1.54 cm respectively. It should be mentioned that the above values have represented the maximum thickness which gives the number of modes. For instance, there will be two modes for thickness in the range between 0.39 – 0.76 cm. The mode propagation results for TE mode results found at 12 GHz with n_1=3.39, n_2=1 have been shown in table 1. . For thickness 0.38 cm no higher TE modes were found and this can be attributed to the boundary condition of the cutoff thickness curve for this case. If the slab thickness increases, then a higher mode can be found, as shown in figures(4-6) with lower propagation loss. Moreover, the number of modes found in this method for each thickness is consistent with the results of the graphical method shown in figure(1).The TE mode propagation results when different cladding materials are used (n_2= 1.5) for frequency 12 GHz has been shown in table 2.The results of the InGaAsP sample with different cladding, one air(n_2=1) and the other with polyacrylate (n_2=1.5), with different frequencies and thicknesses are presented in tables 3 and 4. The results show that the lower thickness gives fewer modes. Moreover, the attenuation is depend on the mode order. Also it has been noticed that as the mode number m increases , the propagation constant β and attenuation coefficient α decreases, while k_c increases causing the fields outside the slab to be less confined. The cutoff frequency f_c is related with the mode order which increases with the No. of modes and operating frequency. The propagation constant increases with the increase in refractive index (n). Furthermore, the analysis with n_2=1.5 cladding gives better results, as shown in tables(2&4) above.

The values of the cutoff thickness, for m=0 mode, at the K_u – band frequency, have been calculated by using equation(8).

The TE modes are in the conventional dielectric slab, where the single mode cutoff thickness can be one of the criteria to determine the thickness of slab as the waveguide allows guided wave propagation only if the thickness is greater than a critical cutoff thickness for each waveguide mode. The cutoff thickness calculated is shown in figures(7 and 8). 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.

No significant variation is found in the reflection amplitude when the incident wave angle is less than the critical angle, which as a result, will also have no effect on the propagation constant (β) inside the waveguide slab. This case can be shown in figure (11). As the incident angle (θ) increases greater than the critical angle (θ_{cr}), the reflection amplitude will increase and also the propagation constant(β) inside the waveguide slab will increase.

Figures (10&11), show the relationship between the reflection amplitude and the wave incident angle, where the reflection amplitude values depend on the refractive index and on the propagation constant (β). The transmission coefficients from a slab of a dielectric material at the K_u-band have been calculated by using equation (11).

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

In figure (12), the transmissions are measured for a slab with a thickness from 0.1 to 0.19 cm for different frequencies(12-18 GHz) in InGaAsP sample with refractive index n_1=3.39. It can be seen that the transmission decreases as the slab thickness increases and the transmission increases as the frequency increases for the same thickness since the thickness will cause more modes to appear. The transmission varies from 0.75 % to 0.98 %. This is desirable in a number of applications, such as filter applications. Full transmission 100 % can be obtained when the thickness of the slab is reduced as shown in figure (13).

We conclude that a good correspondence was seen between the number of modes and the cutoff thickness. The propagation constant in various slab waveguides depends on the declaration value of refractive index of the slab. The full transmission 100% of various slab waveguides depends on the value of refractive index of the slab and its thickness.

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Table (1): Parameters of the waveguide at three lower order modes at(12) GHz for InGaAsP. With n1=3.39 ,n2=1(air)

2a (cm)	m	$\beta(cm^{-1})$	$k_c(cm^{-1})$	α (dB/cm)	f_c(GHz)
0.38	0	6.9824	4.8823	0.5661	0
0.76	0	7.9344	3.1042	0.6540	0
	1	5.9904	6.0585	0.4725	6.0932
1.14	0	8.2143	2.2618	0.6796	0
	1	7.2425	4.4873	0.5903	4.0621
	2	5.3801	6.6064	0.4134	8.1243

1.54	0	8.3368	1.7574	0.6908	0
	1	7.7668	3.5024	0.6386	3.0070
	2	6.7362	5.2167	0.5431	6.0141
	3	5.0545	6.8588	0.3811	9.0211

Table (2): Parameters of the waveguide at three lower order modes at 12 GHz for InGaAsP with n1=3.39, n2=1.5

2a (cm)	m	$\beta(cm^{-1})$	$k_c(cm^{-1})$	α (dB/cm)	(GHz) f_c
0.4	0	7.1613	4.6130	0.5293	0
0.82	0	8.0162	2.8864	0.6148	0
	1	6.3877	5.6381	0.4481	6.0172
1.22	0	8.2533	2.1152	0.6380	0
	1	7.4146	4.1969	0.5548	4.0443
	2	5.8645	6.1805	0.3904	8.0887
1.64	0	8.3587	1.6501	0.6483	0
	1	7.8597	3.2886	0.5993	3.0086
	2	6.9713	4.8982	0.5096	6.0172

	m	$\beta(cm^{-1})$	$k_c(cm^{-1})$	α (dB/cm)	f_c (GHz)
	3	5.5785	6.4398	0.3573	9.0258

Table(3): Mode numbers, propagation constant, modes loss at different frequencies and thickness for InGaAsP TE polarization for n1=3.39, n2=1

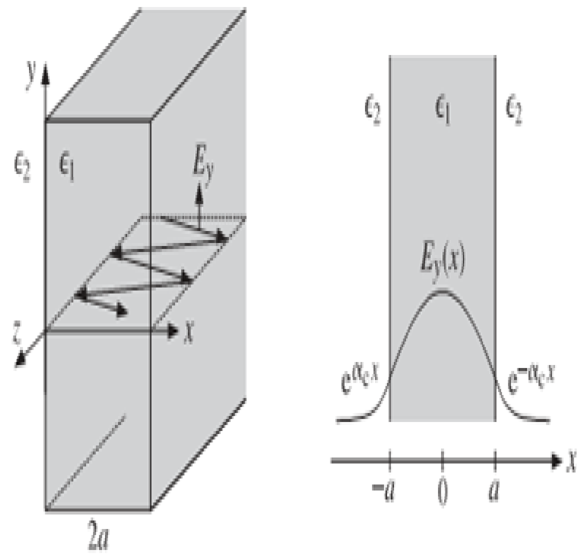
f (GHz)	2a(cm)	m	$\beta(cm^{-1})$	$k_c(cm^{-1})$	α (dB/cm)	f_c (GHz)
14	0.32	0	8.1068	5.7518	0.6568	0
	0.66	0	9.2704	3.5866	0.7642	0
		1	7.0512	7.0061	0.5573	7.0164
	0.98	0	9.5851	2.6325	0.7930	0
		1	8.4571	5.2231	0.6893	4.7253
		2	6.2969	7.6910	0.4843	9.4507
	1.32	0	9.7262	2.0503	0.8059	0
		1	9.0613	4.0861	0.7451	3.5082
		2	7.8589	6.0861	0.6336	7.0164
		3	5.8969	8.0019	0.4446	10.5246
16	0.28	0	9.2650	6.5734	0.7506	0
	0.56	0	10.5577	4.1934	0.8700	0
		1	7.8885	8.1744	0.6206	8.2694
	0.86	0	10.956 3	3.0015	0.9065	0
		1	9.6738	5.9554	0.7886	5.3847
		2	7.2193	8.7710	0.5557	10.7694
	1.14	0	11.1101	2.3697	0.9205	0
		1	10.3321	4.7220	0.8493	4.0621
		2	8.9226	7.0311	0.7186	8.1243
		3	6.6122	9.2373	0.4953	12.1864
18	0.24	0	10.3172	7.5422	0.8346	0
	0.50	0	11.8835	4.7021	0.9793	0
		1	8.9027	9.1689	0.7009	9.2617
	0.76	0	12.3214	3.3928	1.0194	0
		1	10.8638	6.7310	0.8854	6.0932
		2	8.0702	9.9096	0.6201	12.1864

f (GHz)	2a (cm)	m	$\beta(cm^{-1})$	$k_c(cm^{-1})$	α (dB/cm)	f_c (GHz)
	1.02	0	12.5020	2.6509	1.0359	0
		1	11.6370	5.2828	0.9567	4.5400
		2	10.0714	7.8673	0.8116	9.0801
		3	7.5110	10.3399	0.5645	13.6201

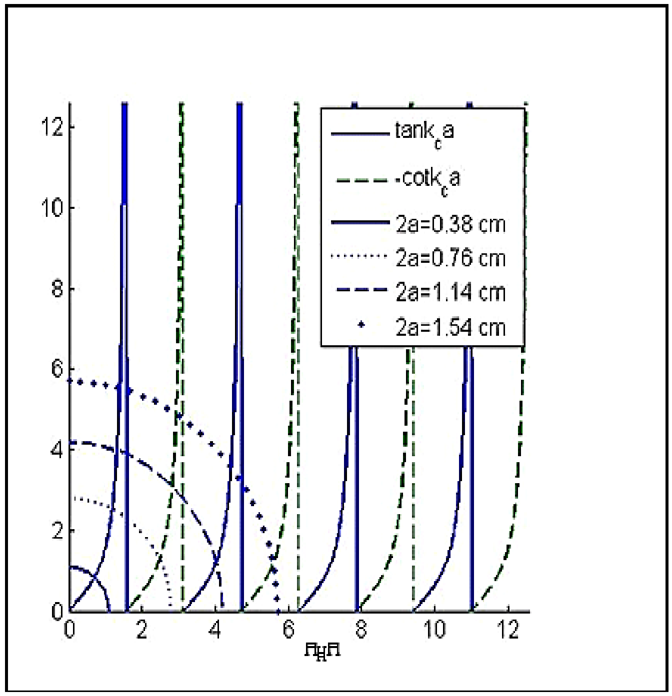
Table(4): Mode numbers, propagation constant, modes loss at different frequencies and thickness for InGaAsP TE polarization for n1=3.39,n2=1.5

f (GHz)	2a (cm)	m	$\beta(cm^{-1})$	$k_c(cm^{-1})$	α (dB/cm)	f_c (GHz)
14	0.34	0	8.3410	5.4066	0.6159	0
	0.70	0	9.3485	3.3776	0.7169	0
		1	7.4362	6.5960	0.5211	7.0487
	1.04	0	9.6260	2.4788	0.7441	0
		1	8.6383	4.9177	0.6461	4.7443
		2	6.8112	7.2395	0.4520	9.4886
16	1.4	0	9.7505	1.9319	0.7562	0
		1	9.1641	3.8500	0.6986	3.5243
		2	8.1195	5.7338	0.5931	7.0487
		3	6.4809	7.5367	0.4136	10.5730
	0.3	0	9.5509	6.1507	0.7057	0
	0.6	0	10.6624	3.9196	0.8171	0
		1	8.4039	7.6436	0.5853	8.2235
	0.92	0	11.0075	2.8078	0.8510	0
		1	9.8999	5.5716	0.7412	5.3631
		2	7.8538	8.3078	0.5244	10.7263
	1.22	0	11.1418	2.2157	0.8641	0
		1	10.4668	4.4153	0.7978	4.0443
		2	9.2638	6.5751	0.6762	8.0887

18										
1.08				0.82			0.54		0.26	
3	2	1	0	2	1	0	1	0	0	3
8.2609	10.4039	11.7679	12.5328	8.8547	11.1449	12.3853	9.5188	12.0099	10.6822	7.3751
9.7512	7.4221	4.9845	2.5014	9.2153	6.2545	3.1517	8.5276	4.3692	7.0156	8.6405
0.5233	0.7589	0.8968	0.9719	0.5921	0.8346	0.9575	0.6654	0.9207	0.7875	0.4690
13.7058	9.1372	4.5686	0	12.0343	6.0172	0	9.1372	0	0	12.1330



Figure(1):Dielectric slab waveguide[3].



Figure(2): Number of modes for different values of thickness in graphical solution.

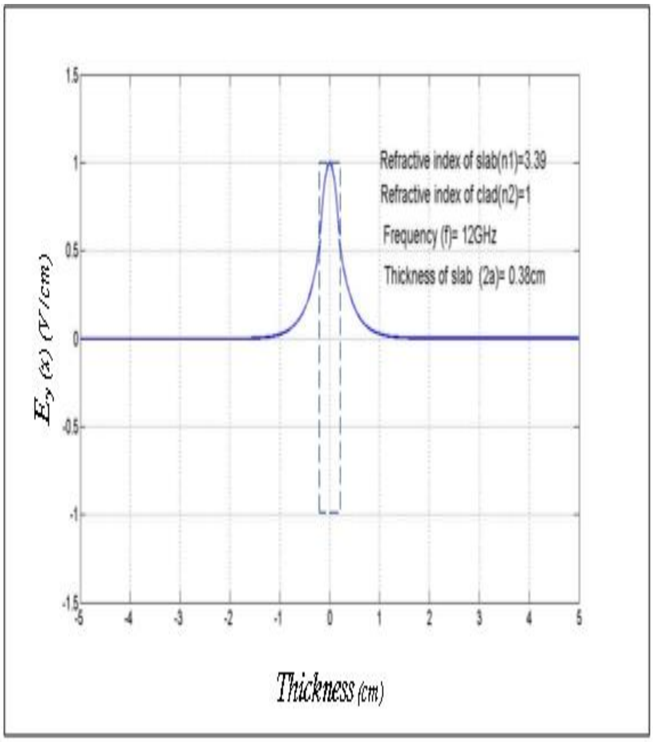


Figure (3): TE(m=0) mode in InGaAsP waveguide with thickness 0.38cm at 12 GHz for n1=3.39, n2=1.

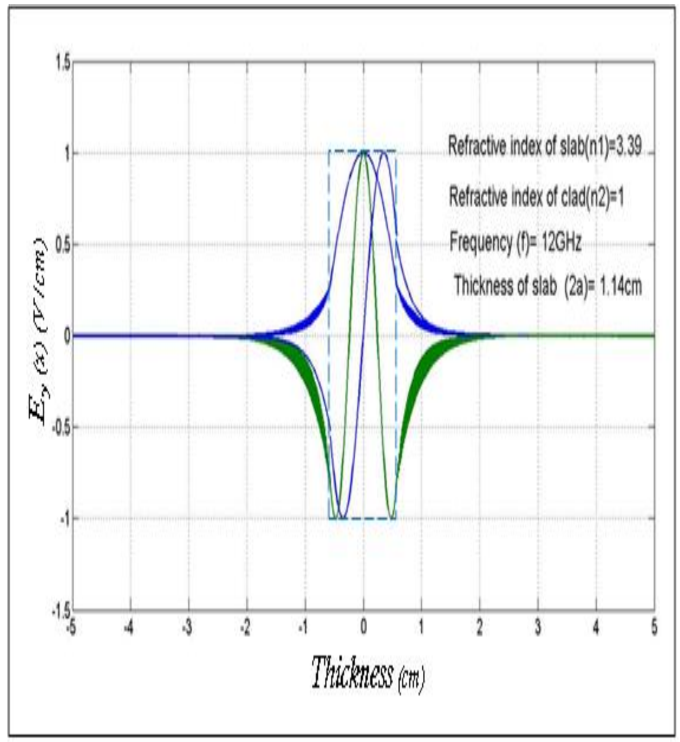


Figure (5): TE(m=0,1,2) mode in InGaAsP waveguide with thickness 1.14 cm at 12 GHz n1=3.39for , n2=1 .

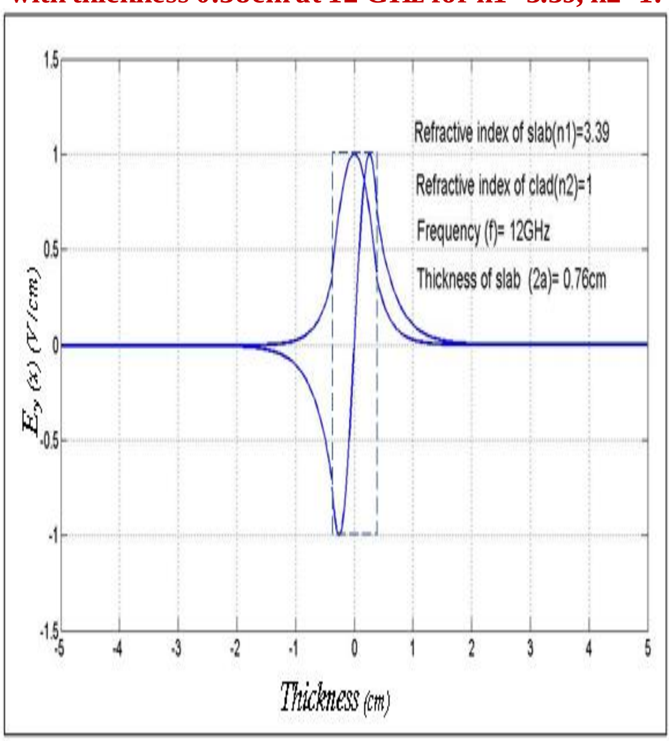


Figure (4): TE(m=0,1) mode InGaAsP waveguide with thickness 0.76 cm at 12 GHz for n1=3.39, n2=1.

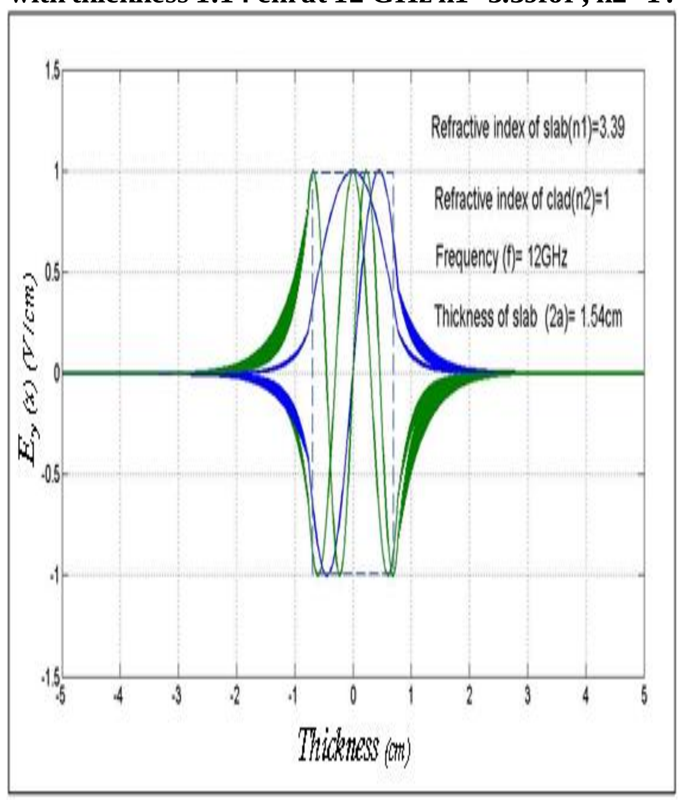


Figure (6): TE(m=0,1,2,3) mode in InGaAsP waveguide with thickness 1.54 cm at 12 GHz for n1=3.39, n2=1 .

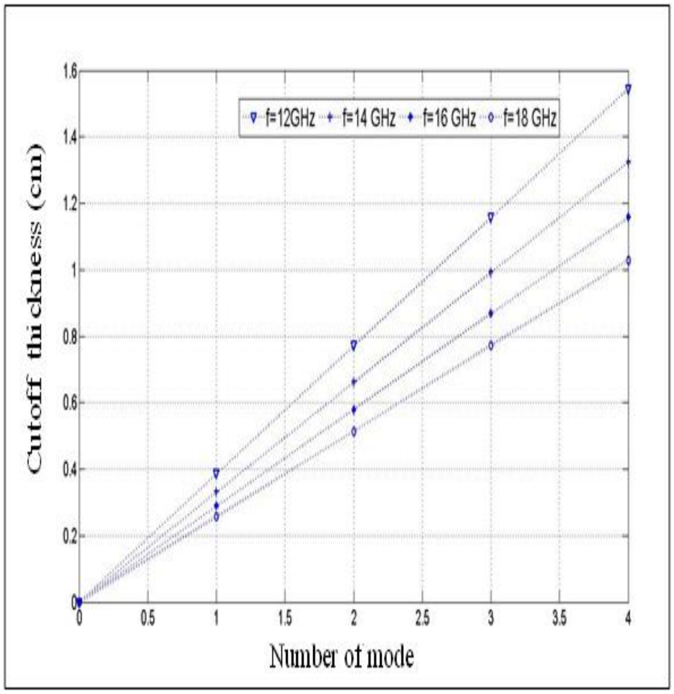


Figure (7): Critical cutoff thickness as function to the number of modes for InGaAsP with n2=1.

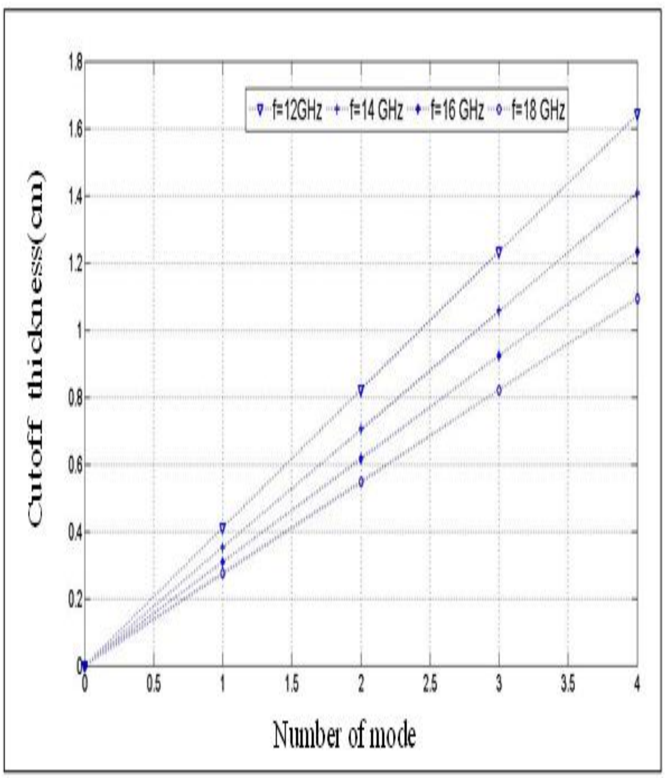


Figure (8) : Critical cutoff thickness as function to the number of modes for InGaAsP with n2=1.5.

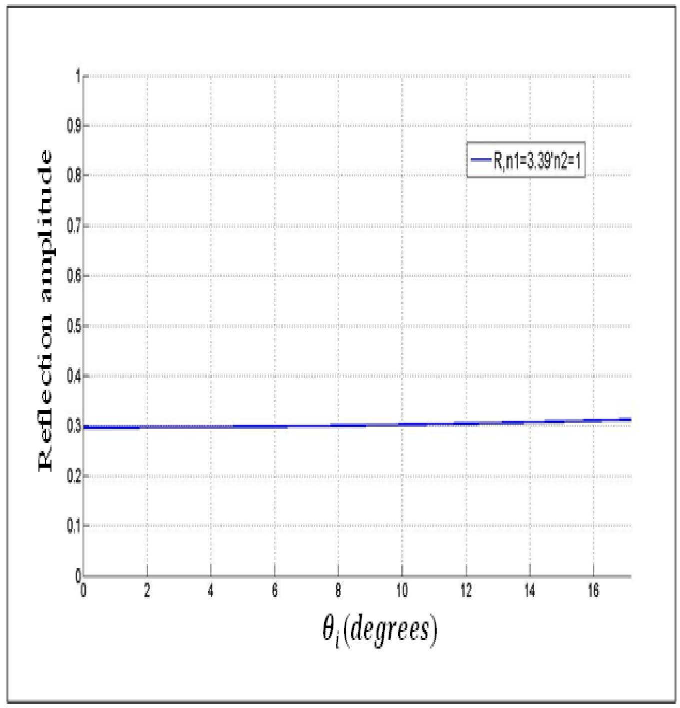


Figure (9): Reflection amplitude when incident angle(θ_i) less than critical angle for InGaAsP and n2=1.

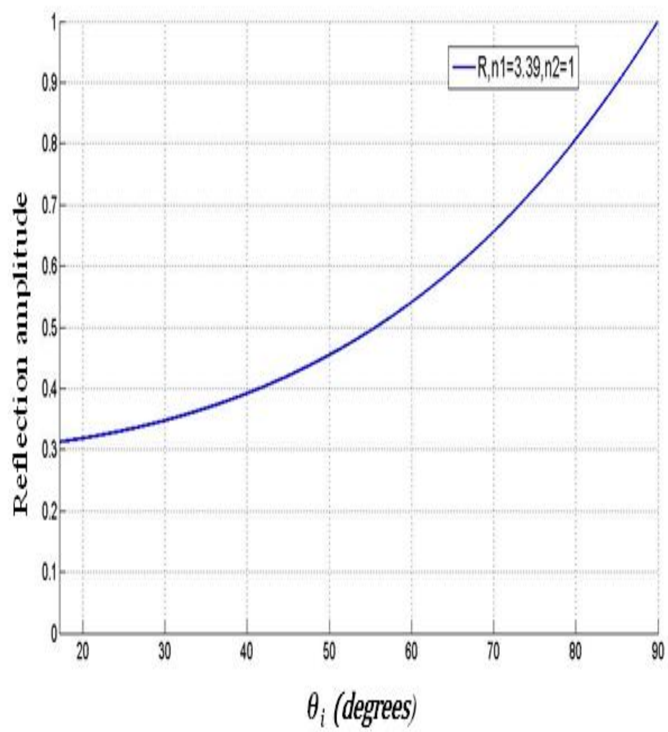


Figure (10): Reflection amplitude when incident angle(θ_i) is greater than critical angle for InGaAsp and n2=1.

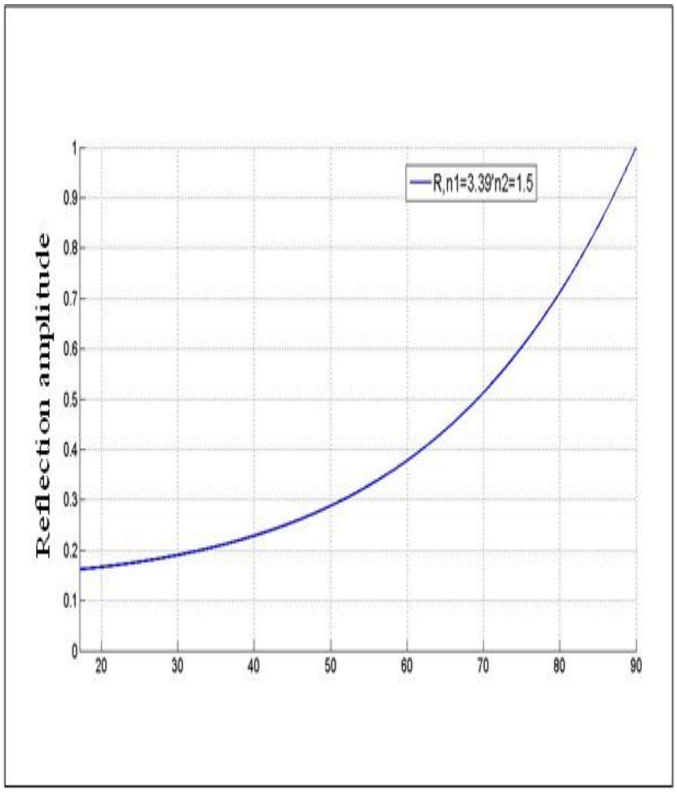


Figure (11): Reflection amplitude when incident angle(θ_i) is greater than critical angle for InGaAsP and n2=1.5.

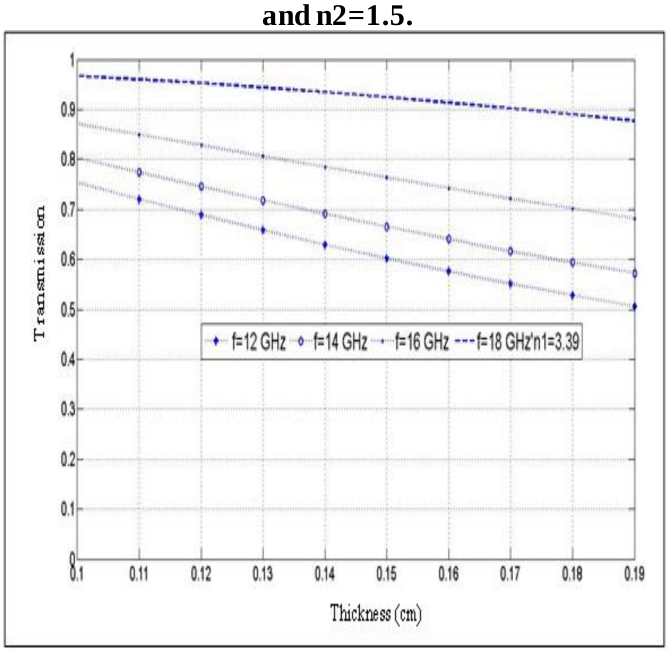


Figure (12): Transmission as function to the thickness of the slab for InGaAsP sample with different frequencies.

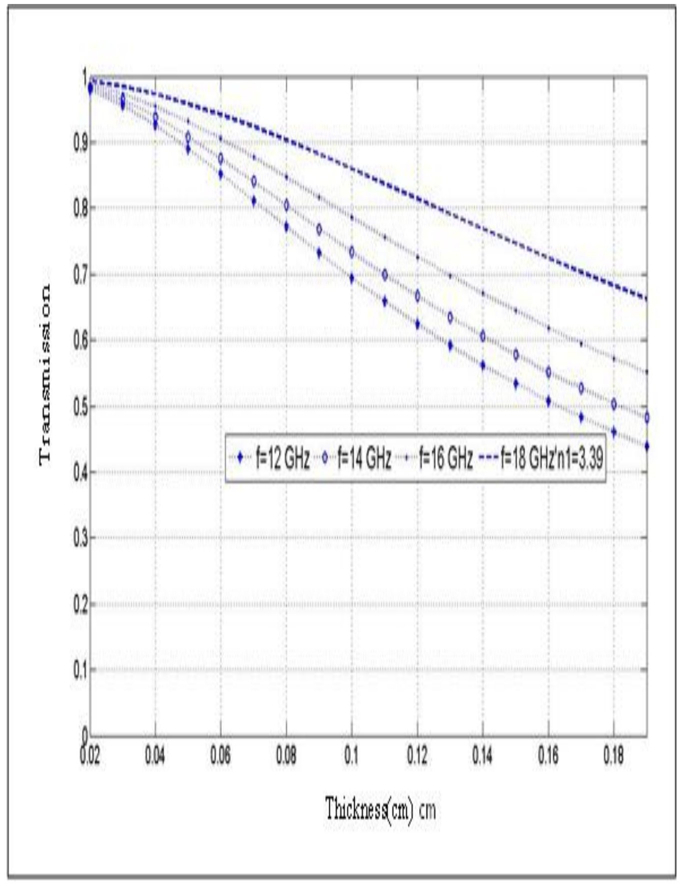


Figure (13): Transmission as function to the thickness of slab for Inga Asp with different frequencies

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انتشار الموجه في دليل الموجه اللوحي العازل محاطا بمادتين مختلفتين

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الخلاصة:

في هذه الدراسة حزمة -Ku المايكرويه ذات الترددات GHz (12-18) والمنتشره في المادة العازلة InGaAsP (معامل الانكسار n1=3.39) مع طبقتين مختلفه, الهواء(n2=1) والبولي اكريليت(n2=1.5) تم تحليلها. استخدام الطبقة البولي اكريليت اعطت نتائج افضل. النتائج البيانية والحسابية لسلوك انتقال الموجه الكهرومغناطيسية على طول اتجاه محور -Zفي دليل الموجه اللوحي العازل في كلا الحالتين من الطبقات تم البحث فيها من خلال برنامج MATLAB. النتائج البيانية والحسابية كانت متطابقة. انماط الانتشار تم تحليلها وتم اعطاء قيم جميع المعلمات. قيم المعاملات المختلفه مثل حد العدد الموجي وحد التردد وحد السمك وثوابت الانتشار ونصف قطر الدائره لكل نمط ونفاذية الموجات الكهرومغناطيسية تم حسابها. نفاذية الموجات المايكرويه تعتمد على سمك الشريحه وعلى تردد الموجه الساقطه وقد وجد بأنه يتغير بين 75% الى 100% . سعة الانعكاس في داخل الشريحه وجد بأنها لاتتأثر عندما تكون زاوية السقوط اقل من الزاوية الحرجة ولكنها تزداد بسرعة عندما تكون زاوية السقوط اكبر من الزاوية الحرجة.