Cladding effects on Wave propagation in Dielectric Slab waveguide.

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Keywords: Dielectric slab waveguide, wave propagation, MATLAB analysis.

ABSTRACT

Microwave with frequencies (12- 18) GHz propagation in dielectric material SrTiO3 (refractive index n1=2.41) with two different cladding, air(n2=1) and polyacrylate(n2=1.5) , were investigated. Better results had been found with cladding polyacrylate including increasing in the group velocity v_g for the fundamental mode by nearly 0.2%. Behavior of electromagnetic wave propagation along z-direction for different cladding was investigated graphically and numerically with the aid of MATLAB program. The graphically and numerically results are coincide. The modes of propagation have been analyzed and all parameters have been given. The transmission of microwave depends on the slab thickness and the frequencies applied and has been found to varied from 75% to 100%. The reflection amplitude inside the slab does not affected 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.
1. INTRODUCTION

The study of electromagnetic waves properties of dielectric materials are important elements which electromagnetic waves are used to transport energy from place to another, such as Television or broadcasting 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. 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]. 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 microwave since waveguides that allow the waves from optoelectronics devices to travel large distance without being obstructed and to be directed in small areas of 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, high bandwidth by allowing only the zero-order mode to propagate [8]. 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 [9].

The mathematical plane electromagnetic waves have transverse electric TE: (Ez = 0 & Hz≠0) and magnetic TM: (Ez≠0 & Hz=0) components that are perpendicular to each other and aimed in a propagation direction.

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, 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, the transmission coefficient are measured. Also the effect of cladding materials, the thickness of dielectric material and the modes in the slab, the propagation loss of the TE mode of a microwave slab waveguide have been studied. For this purpose, SrTiO3 (ε = 5.8081) as dielectric materials waveguide with different surrounding media, air and polyacrylate, has been selected.
2. THEORY

For TE solution that depends only the x-coordinates, the cutoff wave number \( k_c \) takes different values inside and outside

\[
k_c^2 = k^2 n_1^2 - \beta^2 \quad \text{outside} \quad \ldots \quad (1)
\]
\[
k_c^2 = k^2 n_0^2 - \beta^2 \quad \text{inside} \quad \ldots \quad (2)
\]

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

\[
E_y(x) = \begin{cases} 
E_1 \cos k_c x & \text{if } -a \leq x \leq a \\
E_2 e^{-\alpha_c x} & \text{if } x \geq a \quad \text{(even TE modes)} \\
E_3 e^{\alpha_c x} & \text{if } x \leq -a
\end{cases}
\]

\[
E_y(x) = \begin{cases} 
E_1 \sin k_c x & \text{if } -a \leq x \leq a \\
E_1 \sin k_c a e^{-\alpha_c (x-a)} & \text{if } x \geq a \\
-E_1 \sin k_c a e^{\alpha_c (x+a)} & \text{if } x \leq -a
\end{cases}
\]

The boundary conditions state 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

\[
\alpha_c = k_c \tan k_c a \quad \ldots \quad (5)
\]

and, for odd TE mode

\[
\alpha_c = -k_c \cot k_c a \quad \ldots \quad (6)
\]

The cutoff frequency defined by

\[
f_c = \frac{mc}{4aNA}, \quad m = 0, 1, M \quad \ldots \quad (7)
\]

Where \( NA = \sqrt{n_1^2 - n_0^2} \) is the numerical aperture of the slab, \( c \) is the speed of light in free space and \( m \) is the number of mode. In the case of a pulse confined to the core, the group velocity \( (v_g) \) can be given as:

\[
v_g = \frac{c_0}{(n_1 - \lambda \frac{dn}{d\lambda})} \quad \ldots \quad (8)
\]

Where \( c_0 \) is the velocity in free space, \( \lambda \) is wavelength, \( n_1 \) refractive index of core

The value of cutoff thickness \( (t_{co}) \) for \( m = 0 \) mode can be calculated by using the equation\[9]:

\[
t_{co} = \frac{\lambda}{2\pi} \left[ m\pi + \tan^{-1} \left( \frac{\sqrt{n_1^2 - n_0^2}}{n_1^2 - n_1^2} \right) \right] \quad \ldots \quad (9)
\]

\( m = 0, 1, 2, \ldots \)

In order to confined the wave in the slab waveguide, the incident angle \( (\theta) \),

\[
\theta = \sin \left( \frac{\beta}{K_1} \right) \quad \ldots \quad (10)
\]

should be greater than the critical angle \( (\theta_{cr}) \),

\[
\theta_{cr} = \sin \left( \frac{n_2}{n_1} \right) \quad \ldots \quad (11)
\]

In this case the total internal reflections will increase as the incident angle \( (\theta_1) \) increase. The transmission coefficients \( (T) \) from a slab of a dielectric material has been calculated by using
The equation [12].

\[
T = \frac{1}{\left[1 + \frac{(ka)^2}{n^2} \left(\frac{1}{2} \frac{\left(\frac{\omega}{c}\right)^2}{\epsilon - \frac{1}{2} \frac{(ka)^2}{n^2}} \right)\right]^{\frac{3}{2}}}
\]

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(12)

3. RESULTS AND DISCUSSION

In this work, a MATLAB programs have been developed to calculate most of the parameters representing the wave propagations in a dielectric materials such as SrTiO3 (\(\varepsilon = 5.8081\)) with different surrounding media, air and polyacrylate. For graphical solution equations(5&6) have been used.

Only one example for this solution has been given at 12 GHz for SrTiO3 with \(n_1=2.41\), \(n_2=1\) (air) and shown in figure (2). This figure shows the number of allowed modes one can get in different frequencies, thickness and consequently radius. Hence, for \(2a=0.56\) cm, there is only one intersection between the circle and the \(tan_k_a\) curve which means there is only one even mode (\(m=0\)). For \(2a=1.14\) cm, there are two intersections points, one gives even mode (\(m=0\)) and one odd mode (\(m=1\)), and so on. Number of mode founds from this method should be consistent with that for analytical solution.

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 Ku-band frequencies (12-18 GHz). Dielectric sample, SrTiO3, and two different cladding refractive index, one with air and 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 were calculated and compared with cutoff thickness condition results. The number of modes can propagate through the waveguide for different thickness are shown in figures (3-6).

The TEo mode is the fundamental mode of dielectric slab waveguide. For 12 GHz microwave, it has been found that for SrTiO3 waveguide, there are one, two, three and four modes for thickness 0.56, 1.14, 1.70 and 2.2 cm respectively. It should be mentioned that the above values are represented the maximum thickness which gives the number of modes. For instance, there will be two modes for thickness in the range between 0.57 – 1.14 cm. The difference in the propagation parameters when using different cladding for TE mode results found at 12 GHz, have been shown in table 1. For thickness 0.56 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 consistence with the results of the graphical method shown in figure(1).The results of the SrTiO3 sample with different cladding, air\((n_2=1)\) and other with polyacrylate \((n_2=1.5)\), with different frequencies and thickness are presented in tables 3 and 4. The results show that the lower thickness gives fewer mode. Moreover, the attenuation dependence on the mode order, also it has been noticed that as the mode number \(m\) increases , the propagation constant \(\beta\) and attenuation coefficient \(\alpha\) decreases, while \(k_c\) increases causing the fields outside the slab to be less confined. The cutoff frequency \(f_c\) is related with mode order where increase with number of modes and operating frequency. The propagation constant increasing with increase refractive index \((n)\). Furthermore, the analyses with \(n_2=1.5\) cladding gives better results as shown in the tables above.

The values of the cutoff thickness, for \(m=0\) mode, at the Ku – band frequency, have been calculated by using the equation (9).

The TE modes 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 are shown in figure(7 and 8). Hence it 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. it has been found that the group velocity of the fundamental mode will be increased by nearly 0.2% when the cladding is the polyacrylate.
No significant variation in the reflection amplitude when the incident wave angle is less than the critical angle and also has no effect on the propagation constant ($\beta$) inside the waveguide slab. This case can be shown in figure (9). As the incident angle ($\theta$) increase greater than the critical angle ($\theta_{cr}$), the reflection amplitude will increase and also the propagation constant ($\beta$) inside the waveguide slab will increase.

Figures (10&11), shows the relationship between the reflection amplitude and the wave incident angle, where the reflection amplitude values depending on the refractive index and on the propagation constant ($\beta$). The transmission coefficients from a slab of a dielectric material at the Ku-band have been calculated by using equation (12).

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 thickness 0.1 to 0.19 cm for different frequencies (12-18 GHz) in SrTiO3 sample with refractive index $n_1=2.41$, it can be seen that the transmission is decreased as the slab thickness increase and the transmission increase as the frequency increase for same thickness, since the thickness will cause more modes to be appear. The transmission varies from 0.60 % 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 (12).

4. Conclusions

Reflection amplitude increase as the incident angle of wave increase. More modes causes a decrease in the transmission of the wave. In this study, the results were better in case of using a polyacrylate material where the propagation constant increase and cut off wave number and loss decrease for different mode number. a good correspondence was seen between the number of modes and the cutoff thickness and 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 SrTiO3 with n1=2.41 and n2=1, 1.5. Upper thickness for n2=1 and the lower for n2=1.5.

| Thickness cm | n   | m   | β    | k_c  | α dB/cm | f_c GHz |
|--------------|-----|-----|------|------|---------|---------|
| 0.56         | 1   | 0   | 5.0729 | 3.3094 | 0.3829 | 0       |
|              | 1.5 | 0   | 5.2141 | 3.0822 | 0.3130 | 0       |
| 0.66         | 1.5 | 0   | 5.6895 | 2.0776 | 0.4436 | 0       |
|              | 1.5 | 0   | 5.7193 | 1.9941 | 0.3738 | 0       |
|              | 1   | 1   | 4.4957 | 4.0590 | 0.3239 | 6.0007  |
| 1.14         | 1.5 | 1   | 4.6763 | 3.8493 | 0.2405 | 6.9755  |
| 1.32         |     |     |       |       |         |         |
| 1.70         | 1   | 0   | 5.8633 | 1.5194 | 0.4603 | 0       |
|              | 1.5 | 0   | 5.8745 | 1.4756 | 0.3915 | 0       |
|              | 1   | 1   | 5.2533 | 3.0150 | 0.4009 | 4.0240  |
| 1.98         | 1.5 | 1   | 5.3086 | 2.9164 | 0.3248 | 4.6777  |
|              | 1   | 2   | 4.1184 | 4.4414 | 0.2835 | 8.0480  |
|              | 1.5 | 2   | 4.3244 | 4.2410 | 0.1841 | 9.3554  |
| 2.2          | 1   | 0   | 5.9320 | 1.2243 | 0.4669 | 0       |
|              | 1.5 | 0   | 5.9377 | 1.1961 | 0.3986 | 0       |
|              | 1   | 1   | 5.5441 | 2.4392 | 0.4294 | 3.1094  |
| 2.6          | 1.5 | 1   | 5.5706 | 2.3783 | 0.3564 | 3.6146  |
|              | 1   | 2   | 4.8486 | 3.6302 | 0.3603 | 6.2189  |
|              | 1.5 | 2   | 4.9274 | 3.5225 | 0.2757 | 7.2292  |
|              | 1   | 3   | 3.7416 | 4.7631 | 0.2409 | 9.3283  |
|              | 1.5 | 3   | 4.0030 | 4.5457 | 0.1170 | 10.8438 |
**Table 2:** Mode numbers, propagation constant, modes loss at different frequencies and thickness for SrTiO$_3$ for $n_1=2.41$, $n_2=1$.

| $f$ GHz | $2a$ cm | $m$ | $\beta$ | $k_c$ | $\alpha$ dB/cm | $f_c$ GHz | $R$ cm |
|---------|---------|-----|---------|-------|----------------|-----------|--------|
| 14      | 0.56    | 0   | 6.2408  | 3.3148| 0.3848         | 0         | 1.5487 |
|         | 1.12    | 0   | 6.7450  | 2.1071| 0.4444         | 0         | 3.0973 |
|         |         | 1   | 5.7463  | 4.1128| 0.3214         | 7.1001    |        |
|         | 1.70    | 0   | 6.9010  | 1.5204| 0.4621         | 0         | 4.7013 |
|         |         | 1   | 6.3900  | 3.0172| 0.4028         | 4.6777    |        |
|         |         | 2   | 5.4929  | 4.4456| 0.2859         | 9.3554    |        |
|         | 2.2     | 0   | 6.9595  | 1.2250| 0.4687         | 0         | 6.0840 |
|         |         | 1   | 6.6317  | 2.4405| 0.4313         | 3.6166    |        |
|         |         | 2   | 6.0613  | 3.6326| 0.3624         | 7.2292    |        |
|         |         | 3   | 5.2161  | 4.7673| 0.2437         | 10.8438   |        |
| 16      | 0.48    | 0   | 7.1092  | 3.8316| 0.4369         | 0         | 1.5170 |
|         | 0.98    | 0   | 7.7086  | 2.4081| 0.5079         | 0         | 3.0973 |
|         |         | 1   | 6.5672  | 4.7030| 0.3673         | 8.1144    |        |
|         | 1.48    | 0   | 7.8853  | 1.7448| 0.5280         | 0         | 4.6776 |
|         |         | 1   | 7.2963  | 3.4621| 0.4596         | 5.3730    |        |
|         |         | 2   | 6.2622  | 5.0996| 0.3246         | 10.7461   |        |
|         | 1.98    | 0   | 7.9595  | 1.3666| 0.5363         | 0         | 6.2578 |
|         |         | 1   | 7.6029  | 2.7234| 0.4957         | 4.0162    |        |
|         |         | 2   | 6.9834  | 4.0562| 0.4213         | 8.0324    |        |
|         |         | 3   | 6.0651  | 5.3325| 0.2949         | 12.0486   |        |
| 18      | 0.44    | 0   | 8.0365  | 4.2379| 0.4962         | 0         | 1.5645 |
|         | 0.88    | 0   | 8.6785  | 2.6887| 0.5721         | 0         | 3.1289 |
|         |         | 1   | 7.4139  | 5.2517| 0.4167         | 9.0365    |        |
|         | 1.32    | 0   | 8.8721  | 1.9575| 0.5941         | 0         | 4.6934 |
|         |         | 1   | 8.2132  | 3.8844| 0.5176         | 6.0243    |        |
|         |         | 2   | 7.0565  | 5.7229| 0.3668         | 12.0486   |        |
|         | 1.76    | 0   | 8.9545  | 1.5374| 0.6033         | 0         | 6.2578 |
|         |         | 1   | 8.5533  | 3.0638| 0.5577         | 4.5182    |        |
|         |         | 2   | 7.8564  | 4.5633| 0.4739         | 9.0365    |        |
|         |         | 3   | 6.8233  | 5.9991| 0.3318         | 13.5547   |        |
Table 3: Mode numbers, propagation constants, modes loss at different frequencies and thickness for SrTiO$_3$, $n_1$=2.41, $n_2$=1.5.

| f GHz | 2a cm | m  | $\beta$ | $k_c$ | $\alpha$ dB/cm | $f_c$ GHz | R cm |
|-------|-------|----|--------|------|----------------|-----------|------|
| 0.48  | 0     | 0.59184 | 3.8610 | 0.4468 | 0             | 1.5431    |
| 0.96  | 1     | 5.1929  | 4.7926 | 0.3724 | 7.1258        | 3.0861    |
| 1.46  | 1     | 6.1320  | 3.5120 | 0.4680 | 4.6855        | 4.6935    |
|       | 2     | 4.8129  | 5.1741 | 0.3317 | 9.3709        |           |
| 1.94  | 0     | 6.9276  | 1.3941 | 0.5454 | 0             |           |
|       | 1     | 6.4975  | 2.7781 | 0.5039 | 3.5262        |           |
|       | 2     | 5.7286  | 4.1374 | 0.4277 | 7.0523        | 6.2366    |
|       | 3     | 4.5123  | 5.4382 | 0.2981 | 10.5785       |           |
| 0.42  | 0     | 6.7639  | 4.4126 | 0.5106 | 0             | 1.5431    |
| 0.84  | 1     | 5.9348  | 5.4772 | 0.4257 | 8.1438        | 3.0861    |
| 1.28  | 0     | 7.8194  | 2.0194 | 0.6139 | 0             |           |
|       | 1     | 7.0116  | 4.0074 | 0.5352 | 5.3443        | 4.7027    |
|       | 2     | 5.5095  | 5.9048 | 0.3800 | 10.6887       |           |
| 1.70  | 0     | 7.9177  | 1.5912 | 0.6234 | 0             |           |
|       | 1     | 7.4274  | 3.1710 | 0.5760 | 4.0240        | 6.2457    |
|       | 2     | 6.5511  | 4.7227 | 0.4892 | 8.0480        |           |
|       | 3     | 5.1654  | 6.2081 | 0.3416 | 12.0719       |           |
| 0.38  | 0     | 7.6409  | 4.9156 | 0.5775 | 0             | 1.5706    |
| 0.76  | 1     | 6.7436  | 6.0886 | 0.4859 | 9.0010        | 3.1412    |
| 1.14  | 0     | 8.7978  | 2.2682 | 0.6908 | 0             | 4.7119    |
|       | 1     | 7.8920  | 4.5013 | 0.6025 | 6.0007        |           |
| 1.52  | 0     | 8.9092  | 1.7811 | 0.7015 | 0             | 6.2825    |
|       | 1     | 8.3634  | 3.5497 | 0.6488 | 4.5005        |           |
|       | 2     | 7.3885  | 5.2874 | 0.5522 | 9.0010        |           |
|       | 3     | 5.8488  | 6.9526 | 0.3886 | 13.5015       |           |
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 SrTiO3 waveguide with thickness 0.56 cm at 12 GHz for n1=2.41 and n2=1.

Figure 4: TE(m=0,1) modes in SrTiO3 waveguide with thickness 1.14 cm at 12 GHz for n1=2.41 and n2=1.
Figure 5: TE(m=0,1,2) modes in SrTiO₃ waveguide with thickness 1.7 cm at 12 GHz for n₁=2.41 and n₂=1.

Figure 6: TE(m=0,1,2,3) modes in SrTiO₃ waveguide with thickness 1.7 cm at 12 GHz for n₁=2.41 and n₂=1.
Figure 7 : Critical cutoff thickness as function to the number of modes for SrTiO3 with n2=1.

Figure 8 : Critical cutoff thickness as function to the number of modes for SrTiO3 with n2=1.5.
Figure 9: Reflection amplitude when incident angle(\(\theta_i\)) less than critical angle for SrTiO\(_3\) and \(n_2=1\).

Figure 10: Reflection amplitude when incident angle(\(\theta_i\)) is greater than critical angle for SrTiO\(_3\) and \(n_2=1\).
Figure 11: Reflection amplitude when incident angle (\(\theta\)) is greater than critical angle for SrTiO3 and \(n_2=1.5\).

Figure 12: Transmission as function to the thickness of slab for SrTiO3 sample with different frequencies.