RESEARCH ARTICLE OPEN ACCESS

Optical Properties of One- and Two-Dimensional Periodic Photonic Structures

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ABSTRACT
This paper presents a theoretical exploration of the electrodynamic behaviours of one- and two-dimensional photonic crystals, consisting of composite material and dielectric layers. Specifically, we determine the photonic-bandgap for various photonic materials, such as Gallium Arsenide (GaAs), Sapphire (Al_2O_3), and Plexiglas $(C_5O_2H_8)_n$. It is shown that the width of the photonic-bandgap depends primarily on the physical parameters of the structure. In addition, the higher the permittivity of the material, the greater the number of bands of significant width. Using the method of decomposition of plane waves, we show that GaAs is the material having a larger prohibited bandwidth. Finally, we compare numerical results in 1-D and 2-D system.
Keywords –. Photonic crystal, Photonic-bandgap, Permittivity

Date Of Submission:05-10-2018 Date Of Acceptance: 17-10-2018

I. INTRODUCTION

Substantial advances in semiconductor physics have allowed researchers to tailor the conducting properties of certain materials, which initially led to the transistor revolution in electronics. Within the last decade, there has been a breakthrough in the control of the optical properties of materials, which allows the control of the emission and propagation of light [1, 2]. Many major discoveries in physics originate from the study of waves in periodic structures; examples include X-ray and electron diffraction by crystals, electronic band structure and holography. Photonic-bandgap (PBG) materials are a new class of periodic dielectrics, which are the photonic analogues of semiconductors. Electromagnetic waves in photonic crystals behave as electrons behave in semiconductors [2-4]. These artificially engineered periodic materials, which control the propagation of electromagnetic waves, may play a role that is as important in the field of photonics as the laser plays today in optoelectronic systems. In practice, due to their potential ability in controlling light propagation, photonic crystals have many applications in optoelectronics such as ultra-small optical circuit devices, filters, switches, and lasers.

A photonic crystal is a medium with a periodic structure, made up of cells of constant values of dielectric permeability. Such a structure can be classified as composed of one, two, or three dimensions. In the case of a 1-D medium, the structure consists of an infinite succession of parallel-plane layers of uniform dielectric. In addition, each layer or cell consists of two different thicknesses of dielectric, each with a constant value of dielectric permeability. The 1-D structure is isotropic in the two dimensions parallel to the layers. A 2-D photonic structure is represented by a bulk dielectric medium in which, in a periodic way, cylinders are arranged with specific indices of refraction. The 2-D structure is isotropic in the dimension parallel to the axis of the cylinders.

In recent years, the study of the optical and electrodynamic properties of such structures has resulted in many publications [2–12]. If the medium is infinite, it has fixed frequency bands allowing the propagation of electromagnetic waves, as well as a bandgap in which the transmission of electromagnetic energy inside the structure is blocked. These properties, giving rise to a series of research topics, are consequences of the Bloch theorem and the fact that the oscillatory field in such a structure satisfies the Floquet condition.

In making practical use of these properties, it is necessary to conceive of structures with a large, but finite number of periodic variations in media, for which the theory just mentioned is already strictly incorrect. However, such structures will have properties approaching those of an infinite structure, if the number of cells is sufficiently large. The most natural method to theoretically study the properties of such structures

is the numerical method of mathematical modelling, which is commonly done in the majority of publications along this line [13]. There are many areas of applications for photonic crystals: telecommunications engineering, information systems, laser technics and others. In nature, we also find structures having the characteristics of photonic crystals, such as diamond, opal, calcium, and others.

This paper aims at studying optical properties of both one-and two-dimensional photonic crystal by investigating the band structure diagram for different types of materials, particularly, Gallium Arsenide **(**GaAs), Sapphire (Al_2O_3) and Plexiglas $(C_5O_2H_8)_n$. The positions and widths of the bandgaps in the spectrum depend on the thickness and lattice. We make a detailed analysis of the influence of the internal and external basis vectors for each type of material period of the structures, and consider the thickness of the materials and the periodicity of the structure on the evolution of the bandwidths. Finally, we show numerical results of the dispersion relation for three different materials and compare a photonic band structure for three different materials.

The paper is organized as follows: In Section II, theoretical model of the photonic structure is presented. Section III considers one-dimensional photonic structure. The two-dimensional structure is considered in Section IV. Numerical results are shown in Section V. Finally, Section VI is devoted to the conclusion.

II. THEORETICAL MODEL OF PHOTONIC CRYSTAL

According to the general theory developed for periodic structures, when the lattice spacing $a_0 = (2p+1) \times \frac{\lambda}{2}$ (λ is a wavelength, $p = 0,1,2 \ldots$), the wave resulting from interactions with the crystalline lattice is reflected from the corresponding crystalline plane. The interference of incident and reflected waves leads to the formation of standing waves. In this process, the propagation of photonic energy, which satisfies the Bragg's condition in an ideal crystal, turns out to be impossible. In plots of the energy spectrum, energy gaps are formed; i.e., the formation of prohibited zones of wave transmission, which appear in general for all periodic structures [9].

Theoretical descriptions of photon dispersion and the optical behaviour of photonic crystals begin by solving Maxwell equations for a periodically modulated heterogeneous dielectric medium. For 1-D and 2-D photonic crystals, Maxwell's equations are conveniently presented in the form of a system of equations involving the electric (E) and magnetic (H) fields separately [8]:

$$\begin{cases} \mu^{-1}\nabla \times [\varepsilon^{-1}(r)\nabla \times H(r)] = (\omega/c)^2 H(r) \\ \varepsilon^{-1}(r)\nabla \times [\mu\nabla \times E(r)] = (\omega/c)^2 E(r) \end{cases}, \quad (1)$$

where ω is the frequency, c is the speed light in vacuum, ε and μ are dielectric and magnetic permeability of the materials. Here, we will focus on $H(r)$ as the eigenvector, where $(\omega/c)^2$ is the eigenvalue. Since the value $\varepsilon(r)$ in this case is material-dependent, the goal with Eq. (1) is to find the eigenvalues $(\omega/c)^2$ for the Hermitian operator $\hat{A} = \mu^{-1}\nabla \times [\varepsilon^{-1}(r)\nabla \times H(r)]$, as expressed in Eq. (2):

$$\hat{A}\, H = (\omega/c)^2 H. \quad (2)$$

All the information about the characteristics of photonic crystals, necessary for the analysis of Eq. (1), is contained in the functions of the dielectric and magnetic permeabilities which are assumed to be local functions of the position coordinate. For a non-magnetic substance, $\mu = 1$. Equation (1) is an eigenvalue equation, whose solution comprises a problem often encountered in the mathematical physics. This equation is the main equation to characterize the photonic crystals.

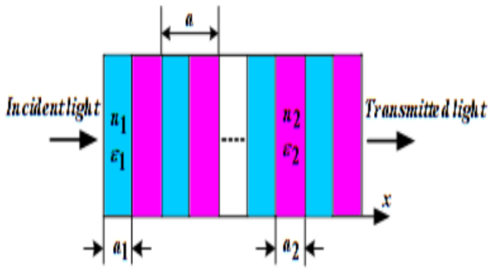

Figure 1. Geometry of a 1-D photonic crystal structure. ε_1 and ε_2 are constant permittivities of the first and second materials, respectively. n_1 and n_2 are the refractive index constants of the first and second materials, respectively. a is the periodic spacing.

III. ONE-DIMENSIONAL PHOTONIC CRYSTAL

III.1. Statement of the problem

Let us consider the 1-D photonic crystal formed of alternating dielectric layers of permittivities ε_1 and ε_2, with spacings a_1 and a_2 (Figure 1). The crystal is subject to a wave at normal incidence. The period of the array is

$a = a_1 + a_2$. Along the *x*-axis, the Bloch electromagnetic waves propagate in a direction perpendicular to the surface of the dielectric layers. The polarization of the wave is linear, and the electric field vector is taken to be parallel to the *y*-axis. The goal of the computations is to determine the forbidden bands and their widths for the various materials mentioned in the Introduction.

III.2. Formulation of equations

It is known that functions satisfying Eq. (2) in a periodic medium have the Bloch form:

$$\varphi_k(x) = e^{ikx}\, u(x), \qquad (3)$$

where *x* is the coordinate in the direction of propagation, and *k* is the wave vector. The eigenfunctions of operator $\hat{A}$ as defined in Eq. (2), are determined by the defining functions, ε(x), and the appropriate boundary conditions:

$$\varepsilon(x) = \begin{cases} \varepsilon_1, & na \le x < a_1 + na \\ \varepsilon_2, & a_1 + na \le x < (n+1)a \end{cases} \qquad (4)$$

where *n* is a whole number. The eigenfunctions in the regions with dielectric permeability ε_1 and ε_2 have the corresponding form

$$\begin{cases} \varphi_1(x) = Ae^{ik_1x} + Be^{-ik_1x} \\ \varphi_2(x) = Ce^{ik_2x} + De^{-ik_2x} \end{cases} \qquad (5)$$

where A, B, C and D are constant coefficients and $k_i = \sqrt{\varepsilon_i}\,\omega/c$.

Since at the zone boundaries separating layers with different dielectric permeability the eigenfunctions and their derivatives must be continuous, we can form a system of equations based on these boundary conditions:

$$\begin{gathered} (A+B)e^{ika} = Ce^{ik_2a} + De^{-ik_2a} \\ k_1(A-B)e^{ika} = k_2\left(Ce^{ik_2a} - De^{-ik_2a}\right) \\ Ae^{ik_1a_1} + Be^{-ik_1a_1} = Ce^{ik_2a_1} + De^{-ik_2a_1} \\ k_1(Ae^{ik_1a_1} - Be^{-ik_1a_1}) = k_2(Ce^{ik_2a_1} - De^{-ik_2a_1}) \end{gathered} \qquad (6)$$

In matrix form, this system of equations relative to A, B, C and D can be written in the for

$$M(k_1, k_2, k)V = 0, \qquad (7)$$

where

$$M(k_1,k_2,k) = \begin{pmatrix} 1 & 1 & -e^{ia(k_2-k)} & -e^{-ia(k_2+k)} \\ k_1 & -k_1 & -k_2e^{ia(k_2-k)} & k_2e^{-ia(k_2+k)} \\ e^{ik_1a_1} & e^{-ik_1a_1} & e^{-ik_2a_1} & -e^{-ik_2a_1} \\ k_1e^{ik_1a_1} & -k_1e^{-ik_1a_1} & -k_2e^{-ik_2a_1} & k_2e^{-ik_2a_1} \end{pmatrix},$$

and

$$V = \begin{pmatrix} A \\ B \\ C \\ D \end{pmatrix}.$$

This system of homogeneous equations has a solution different from zero if and only if $det\ M = 0$. Calculating the determinant, we can obtain an implicit form of the dispersion relation, $\omega(k)$:

$$\begin{gathered} cos(k_1a_1)\, cos(k_2a_2) \\ -\frac{1}{2}\frac{\varepsilon_1+\varepsilon_2}{\sqrt{\varepsilon_1\varepsilon_2}} sin(k_1a_1)\, sin(k_2a_2) = cos(ka). \end{gathered} \qquad (8)$$

Since we must have $|\cos(ka)| \le 1$, forbidden zones arise in the spectrum, i.e., values of k_i for which,

$cos(k_2a_2) - \frac{1}{2}\frac{\varepsilon_1+\varepsilon_2}{\sqrt{\varepsilon_1\varepsilon_2}} sin(k_1a_1)\, sin(k_2a_2)| > 1$. In these zones, the propagation of radiation in the crystal is not possible.

Equation (8) illustrates the close analogy between the one-dimensional model of photonic crystals and the electronic model of Kronig-Penney, which helps clarify the nature of the photonic forbidden zone. In a 1-D photonic crystal with two different dielectric layers having a periodicity of length *a*, the band structure will start to open at the border of the Brillouin zone and a forbidden band appears. In the forbidden band, there is not any state which can propagate; on the contrary each state is evanescent, being characterized by a complex wave number. In one dimensional crystals a forbidden band will always appear, since there is a periodic variation of the dielectric constant. The greater the variation, the greater the width of the forbidden band.

IV. TWO-DIMENSIONAL (2-D) PHOTONIC CRYSTAL

IV.1. Statement of the problem

This section generalizes the preceding results with the case of 2-D photonic crystals. We study square structures of 2-D photonic crystals formed into an array of dielectric cylinders of permittivity ε_2 embedded in a dielectric medium of permittivity ε_1 (Fig. 2a). The media are assumed to be non-magnetic, i.e., their magnetic permeability corresponds to that of the vacuum, equal to μ_0. The array is generated by the elementary basis vectors a_1 and a_2. The cross-section of the cylinders is arbitrary, but is identical for all the cylinders. Finally, the *z*-axis is selected parallel to the axis of the cylinders. As in sub-section III.1, it is necessary to determine the forbidden zones and the widths of the bands for these various materials.

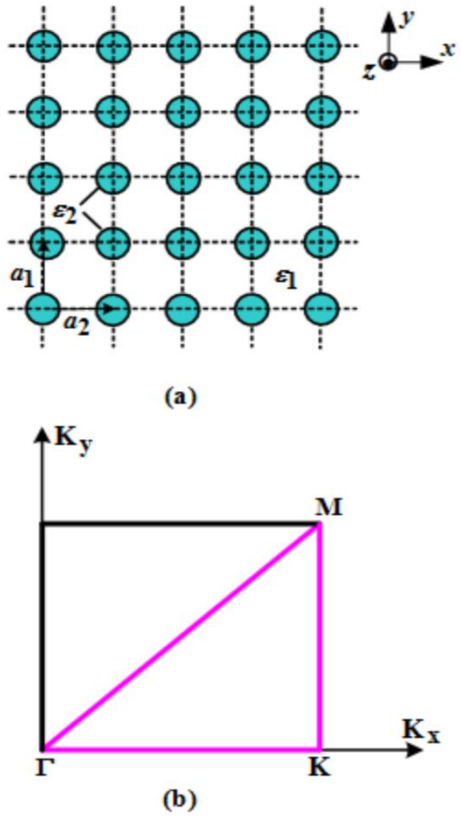

Figure 2. (a) Structure of a 2-D photonic crystal and (b) the corresponding Brillouin zone (purple line). ε_1 **and** ε_2 **are constant permittivities of the first and second materials, respectively.** a_1 **and** a_2 **are the basis vectors of the network, in the** y **and** x**-directions, respectively**.

IV.2. Formulation of equations

For a two-dimensional photonic crystal, the numerical solution of Eq. (1) can be obtained more easily in the matrix representation for the polarisation of E and H, given in the form [8]:

$$\sum_{G'} \varepsilon^{-1}(M(k/GG') - (\omega/c)^2)\, F(nk/G) = 0, \quad (9)$$

where $G = |G|$ is the size of the inverse grating or lattice, vector F is equal to E or H depending on the polarization, n is an index zone, and k is wave vector of Brillouin. The matrix $M(K/GG') = |K+G||K+G'|\epsilon^{-1}(G-G')$ for E polarization, and $M(K/GG') = (K+G)(K+G')\epsilon^{-1}(G-G')$ for H polarization. The solution of Eq. (9) can be obtained numerically for different filling factors, indices of refraction, and the chosen number of plane waves.

V. RESULTS AND DISCUSSION

The simplest photonic crystal that we can conceive is the traditional Bragg mirror, obtained by periodic alternation of dielectric plane layers with optical thickness $\lambda/4$ [7, 8]. The in-depth analysis of its properties nicely illustrates multiple aspects related to the concept of forbidden photonic bands.

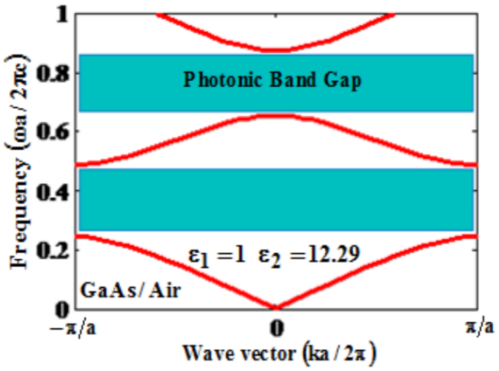

Figure 3. The photonic band structures for a 1-D photonic crystal. This relation is presented for the GaAs material of permittivity $\varepsilon_a = 12.29$ **and the coefficient r/a was varied over the range from 0.1 to 0.3, with** $a = 0.775\,\mu m$**. The number of elements is** $N = 5$**. Two photonic bands are counted and the greatest bandwidth obtained is 0.24µm with** $r/a = 0.1$**.**

The figures below present the dependence of the wave vector and the normalized frequency for various photonic materials (gallium arsenide (GaAs), sapphire (Al_2O_3) and Plexiglas $(C_5O_2H_8)_n$. In 1-D, the dispersion curves are presented for TM polarization. The band structure as a function of the normalized frequency is given in Fig. 3 for the GaAs material with permittivity $\varepsilon_a = 12.29$. The coefficient r/a was varied from 0.1 to 0.3, with $a = 0.775$ µm. The analysis of the results shows that the greatest bandwidth corresponding to the optical field, 0.24µm, is obtained with $r/a = 0.1$. The optimal number of bands is equal to 2 for a number of elements equal to $N = 5$. Let us note that for $r/a = 0.3$, we obtain three forbidden bands but with a total width that is lower than that obtained for $r/a = 0.1$. We also note that an increase in the number of layers does not change anything in the dimensions bandwidths obtained. Thus, for different values of crystal spacing $(a = 1 = 2. = \ldots)$ the number of bands and their widths does not change. We choose to work with $a = 2$.

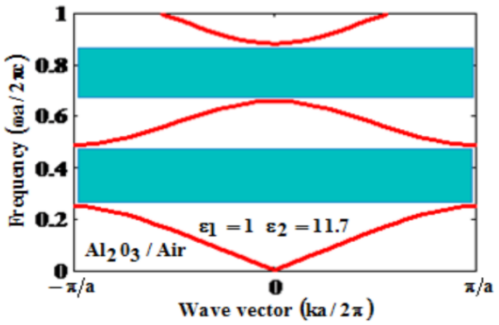

Figure 4. Dispersion relation for the Al_2O_3 material with permittivity $\varepsilon_a = 11.7$ for the same values of the coefficient r/a as in Fig. 3. Two photonic bands are observed with a greatest bandwidth of 0.23µm obtained for $r/a = 0.1$. The number of elements is the same as in Figure 3.

Figure 4 reveals the presence of two photonic forbidden bands for sapphire (Al_2O_3) with permittivity $\varepsilon_a = 11.7$, using the same values of the coefficient r/a as in Fig. 3. The greatest bandwidth here, 0.23µm, is again obtained for $r/a = 0.1$. As in the preceding case, the number of bands and elements is the same. We also note that for the ratio $r/a = 0.3$ we obtain three forbidden bands, but their total width is lower than that obtained with $r/a = 0.1$.

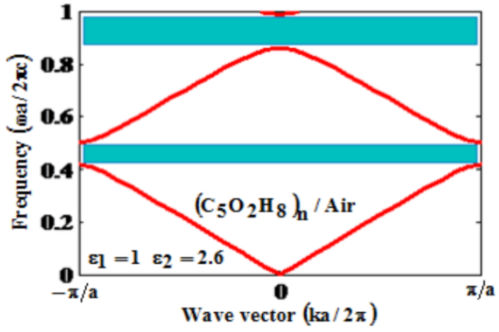

Figure 5. Dispersion relation for the Plexiglas $(C_5O_2H_8)_n$ material with permittivity $\varepsilon_a = 2.6$ for the same values of the coefficient r/a as in Fig. 3. Two photonic bands are observed with a greatest bandwidth of 0.11µm obtained for $r/a = 0.1$. The number of elements is the same as in Figures 3 and 4.

Lastly, Fig. 5 presents the results for Plexiglas $(C_5O_2H_8)_n$ with permittivity $\varepsilon_a = 2.6$. In this case, the greatest bandwidth, 0.11µm, is obtained with $r/a = 0.1$. As in Figs. 3 and 4, the number of bands and elements is the same. Let us observe that in general, for all these materials, the number of bands can be higher for certain values of N, but the total width of the bands is then lower.

r	a=0.775µm	GaAs (12.29)		Saphir (11.7)		Plexiglass (2.6)	
		NB	TW	NB	TW	NB	TW
	N	Mode TM/TE	Mode TM/TE	Mode TM/TE	Mode TM/TE	Mode TM/TE	Mode TM/TE
0.1a	5	2	0.50	2	0.44	2	0.46
	6	2	0.48	2	0.49	2	0.49
	7	2	0.47	2	0.47	-	-
0.2a	5	1	0.24	2	0.37	2	0.37
	6	1	0.24	2	0.38	2	0.38
0.3a	5	3	0.43	3	0.44	3	0.43
	6	3	0.38	3	0.40	3	0.40

Table 1. Summary of results for the three materials in terms of the number of bands (NB) and their total width (TW) for different values of a and of N in TE and TM modes. We note that in 1-D, the TE and TM modes have the same values. GaAs is the material having the best prohibited bandwidth.

Table 1 presents a summary of results for the three materials in terms of the number of bands (NB) and their total width (TW) for different values of a and *N*, for TE and TM modes. We note that in 1-D crystals, the TE and TM modes give the same values. In other words, there is not any difference between these modes. We also notice that the bandwidths are higher when $r/a = 0.1$ for all materials. GaAs is the material having the largest forbidden bandwidth. For this material, the number of forbidden bands increases when the basis vector of the cylindrical array reaches the value of $0.3a$. Moreover, the forbidden bands for GaAs appear only for *N* equal to or higher than 5.

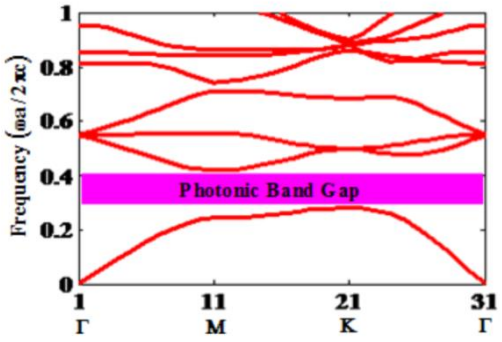

Figure 6. Band diagram for a 2-D structure showing the photonic bandgap in polarization TM for the material GaAs. The diagrams represents propagation of the wave vector in the *x*-direction, giving the points of high symmetry Γ, M, K in the first Brillouin zone. On the *y*-axis are plotted the frequencies of the calculated modes. In the TM mode, there is a forbidden band of width 0.1367µm for the ratio $r/a = 0.2$.

A photonic crystal is generally characterized by its band diagram. In what follows, we study periodic crystals with two-dimensional structure that are isotropic in the third dimension. The structure that we treat is an array of size 5x5 with a square symmetry as shown in Fig. 2(a). Figures 6 and 7 present the dependence of the wave vector and the normalized frequency for two materials, GaAs and Al_2O_3, respectively. These materials are 2-D planar photonic crystals of square arrays, consisted of an array of air pockets. The dispersion curves are presented for polarizations TM and TE. In the TM mode (Fig. 6), there exists a forbidden band of width 0.1367µm for the ratio $r/a = 0.2$. The first material is considered to be air, of index 1, and the second is gallium arsenide (GaAs) of index 12.29. It is important to note that the more we increase the ratio r/a, the more forbidden bands we obtain. On the other hand, if we reverse the materials we do not observe any forbidden band, no matter what the value of the ratio r/a.

Figure 7 presents the sapphire (Al_2O_3) material dispersion curves for the TM mode. The bandwidth of this mode equal to 0.1331µm**.** It is slightly lower than that observed with gallium arsenide (GaAs). Finally, when calculating the dispersion curves for Plexiglas $(C_5O_2H_8)_n$, we do not observe any forbidden bands in either TM or TE mode.

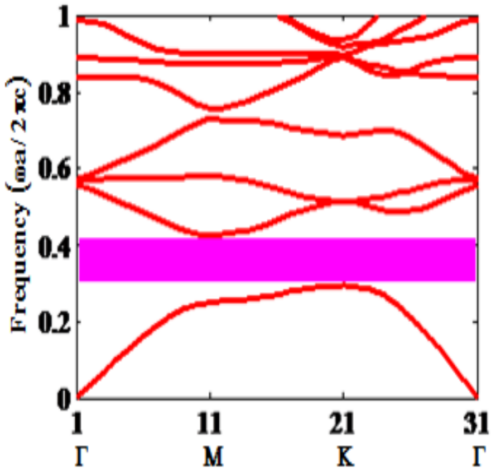

Figure 7. Band diagram for a 2-D structure showing the photonic bandgap in polarization TM for the sapphire (Al_2O_3) material. The bandwidth is equal to 0.1331µm. It is slightly lower than that observed with the gallium arsenide (GaAs) material. In the TE mode, we do not observe any forbidden band.

r	a=0.775µm	GaAs (12.29)		Saphir (11.7)		Plexiglass (2.6)	
		NB	TW	NB	TW	NB	TW
	N	Mode TM	Mode TM	Mode TM	Mode TM	Mode TM	Mode TM
0.1a	5	1	0.077	1	0.06	0	0
	6	1	0.077	1	0.06	0	0
	7	1	0.079	1	0.06	0	0
0.2a	5	2	0.17	1	0.13	0	0
	6	2	0.73	1	0.13	0	0
	7	2	0.17	1	0.13	0	0
0.3a	5	3	0.24	3	0.23	0	0
	6	3	0.25	3	0.23	0	0
	7	3	0.24	3	0.23	0	0

Table 2. Summary of results for 2-D structures of the three materials. The numerical results show that there is not any forbidden band for the Plexiglas material and that the TE mode does not result in any forbidden band for these materials. GaAs is the material having the best forbidden bandwidth, for a vector of $0.2a$ **with** $N = 6$**. Taking into consideration these two tables, it is advisable to use the 2-D structure with vectors of** $0.2a$ **and** $N = 6$ **bands, because it is on this level that we observe a higher prohibited bandwidth.**

Table 2 presents the results for the three 2-D materials. The numerical results show that there is not any forbidden band for the Plexiglas material. Further, the TE mode does not result in any forbidden bands for any of these materials. As in Table 1, the forbidden bands appear only for $N \geq 5$**.** GaAs is still the material having the largest forbidden bandwidth, for a vector of $0.2a$ with $N = 6$**.** Let us note that for $r = 0.4a$ and larger, we do not observe any forbidden bands for any of these materials. Taking into consideration the results for GaAs shown in both tables, we conclude that it is advisable to use the 2-D structure with basis vector $r = 0.2a$ and $N = 6$ bands, because it is on this level that we observe a higher prohibited bandwidth. Moreover, normally in a waveguide we would prefer that only one mode be propagated, and this is one of the fundamental advantages of the 2-D structures over the 1-D structures, in which two modes are propagated.

VI. CONCLUSION

In summary we have studied the optical properties of 1-D and 2-D periodic photonic structures for various materials. We explored the dynamic change of the forbidden zone picture with dependence on the physical parameters of the structure. We observe that a number of bands and a significant bandwidth are obtained for materials having high permittivities. Moreover, we conclude

that the 2-D structure is preferable because it gives a higher prohibited bandwidth and single-mode propagation. Ultimately, photonic crystals present themselves as having qualitatively new properties for the control and propagation of light due to the presence of the full forbidden zones in the electromagnetic spectrum in the desirable frequency range. Such capabilities have already been demonstrated for the microwave region. Finally, the structures studied can be used as an independent solution to the problem of backscattering from patch antennas. In addition, the properties of photonic crystals may be utilized as a first step in further optimization of these antenna structures, with the help of non-linear programming methods. Future research will investigate this question as well.

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Jean-François D. Essiben "Optical Properties Of One-And Two-Dimensional Periodic Photonic Structures "'International Journal of Engineering Research and Applications (IJERA), vol. 8, no.10, 2018, pp 63-69