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Finite element method analysis of band gap of photonic crystals

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Abstract – *By running a nonlinear scan of a proper values analysis using the nonlinear solver with an additional normalization equation for the proper value and 2D FEM simulations, we show the influence of some parameters such as the electric field; the magnetic field and the heating by joule effect of the photonic band gap structures 2D. The study is carried out in consideration of wave propagation in a photonic crystal composed of GaAs columns equidistant from one another. This model extracts the band diagram for the lowest frequencies of the crystal.*

Keywords*: Photonic band gap (PBG); Gallium arsenide (GaAs); finite element method (FEM); dimensional Structure.*

I. Introduction

Lord Rayleigh, in 1887, was the first to show that the we could produce a gap or band gap, even if the term "photonic crystal" was introduced in 1987 with the publication of two major articles of Eli Yablonovitch and Sajeev John ([1] and [2]), which seeks to reduce the spontaneous emission of light in lasers and semiconductors, offering a new way to build a Bragg mirror, proposed by W. L. Bragg since the late nineteenth century `on several dimensions. The idea is to make a three-dimensional periodic structure by a regular assembly of spheres, cylinders and / or beams [3].

In 1991, Yablonovitch designed the first three-dimensional photonic crystal with a band gap in the microwave. He showed that these materials whose dielectric constant was structured periodically possessed frequencies for which there was no mode of propagation possible, hence the name of photonic band gap materials (beeps) [4].

A *BIP* said one, two or three dimensions (*1D, 2D* and 3D) when the variation of the refractive index therein is done in one, two or all three directions of space. The first property of a *BIP* is totally reflecting the light without absorption loss, this resulting in the appearance of a photonic band gap. The photonic band gap is even larger than the refractive index contrast related to the alternation of its component materials is high. For a given wavelength, the penetration of the light beam in a one-dimensional *BIP* is still possible under certain angles. For an independent band gap of the angle of incidence (band gap full-*BCS*), it is necessary that the periodicity of the index extends to the three dimensions of space and the index ratio between the materials constituting the alternate is greater than or equal to 2 [5]

From a theoretical point of view, the study and development of the properties of photonic band gap materials based on the strong similarity between the Schrödinger equations and Maxwell. (1) and (2) respectively, the frequency of the dielectric permittivity (where the refractive index) can be exploited in the electromagnetic field.

$$\nabla^2\psi(r) = -\frac{2m}{\hbar^2}\left(E - V(r)\right)\psi(r) \qquad (1)$$

$$\nabla \times \nabla \times E(r) = \frac{\omega^2}{c^2}\varepsilon(r)E(r)(\ ) \qquad (2)$$

The only difference is the nature of the wave equation, vectorial in the case of photons, scalar in the case of electrons. These equations are two linear systems of proper values whose solutions are determined by the properties of the potential $v(r)$, or of the dielectric function $\varepsilon(r)$. This analogy allows us to apply the tools and concepts developed in solid state physics, such as the notions of reciprocal lattice, Brillouin zone or the Bloch theorem [6].

Many applications of photonic crystals have an interest in the field of optics for wavelengths close to a micron. The peculiarity of a photonic crystal comes from its ability to prohibit the propagation of light; it is highly advisable to work with a crystal that has a band gap as complete as possible. Only three-dimensional photonic crystals can exhibit this kind of band. However, their technological achievement is particularly difficult at this level. In contrast two-dimensional photonic crystals are

easier to achieve in the field of wavelengths of near-infrared and even of the visible. This is the type of crystals that we consider in our simulation.

In this work, we are interested in examining the propagation of waves in a photonic crystal consisting of columns of *GaAs* equidistant from each other. this model extracts the band diagram for the lowest frequencies of the crystal. It executes a scanning nonlinear analysis of proper values, using the nonlinear solver with a normalization equation again for the proper value, and see the influence of some parameter such as the electric field and the magnetic field and the heating by the Joule effect of the photonic band gap structures.

II. Model definition

In this model, the crystal itself is analyzed. Because it has a repeating pattern, it is possible to use periodic boundary conditions. As a result, one pillar is required for this simulation.

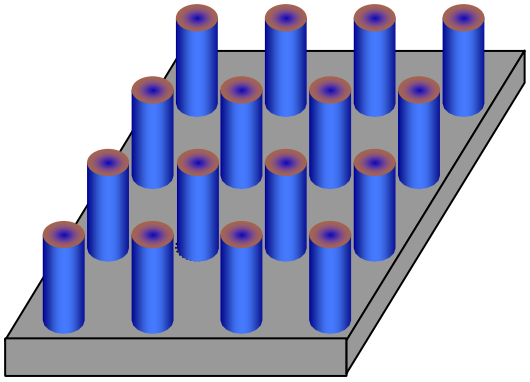


Figure 1 .Structure of a square two-dimensional photonic crystal.

The model contains a small asymmetry, eliminating the difficulties of proper functions with proper values identical. There are two main complications with this analysis band gap.

- On the one hand, the refractive index of GaAs is dependent from the frequency.
- Second, the wave vector must be inclined to the band diagram.

The parametric solver can scan the wave vector k. The proper value is equal to the square wave vector in the free space:

$$k_0^2 = \Lambda \qquad (3)$$

The proper value is denoted by Λ to avoid confusion with the wavelength in free space, which is graded with λ_0. The relationship between Λ and λ_0 is:

$$\lambda_0 = \frac{2\pi}{\sqrt{\Lambda}} \qquad (4)$$

The scanned range k is determined by the reciprocal lattice vectors of the photonic crystal, and they are determined from the primitive lattice vectors. For a 2D crystal, there are two lattice vectors, a_1 and a_2, defined in the following figure.

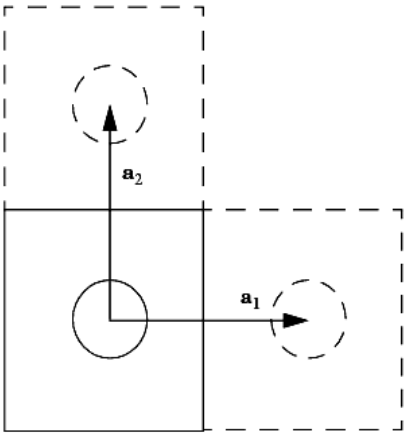


Figure 2.the grating vectors, a_1 and a_2

The reciprocal network vectors are calculated from a_1 to a_2 by using the relationships

$$b_1 = 2\pi \frac{a_2 \times a_3}{a_3.(a_2 \times a_3)} \qquad (5)$$

$$b_2 = 2\pi \frac{a_3 \times a_1}{a_1.(a_2 \times a_3)} \qquad (6)$$

By the Finite element method *(FEM)* we can first use the proper value solver to find an approximate solution for every k-vector. The solution is not exactly due to the frequency dependent refractive index of *GaAs*. It is possible to repeat the calculation of the proper values to be closer to the final solution. We can often go directly to the type of analysis to harmonic time after the first iteration of the proper value problem, using this solution as initial estimates for the nonlinear solver. With the nonlinear solver in we must now perform a linear ramp from $k = 0$ to $k = 0.5$, which is half of the reciprocal data vector as a linear combination of b_1 and b_2 in a certain predetermined direction.

III. RESULTS AND DISCUSSIONS

III.1. Isovalues of the electric field Ez

"Figure 3.". and "Figure 4."represent the variations of the electric field component *Ez(x, y)* in the semiconductor material of *III-V* (*GaAs*) for different values of the wave vector $k \in [0;0.5]$.

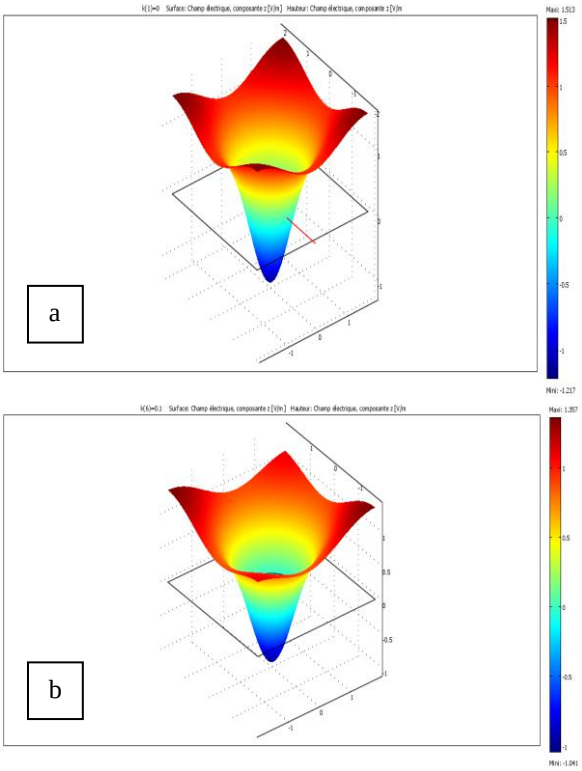
For $k \neq 0.5$ the electric field component *Ez* looks the same. The value of the electric field is zero on the circumference of the crystal *GaAs* and increases in absolute value on the way to the centre of the crystal. The field increases away from the material in the fluid (air).

"Table 1." includes the maximum and minimum values of the electric field for different values of the wave vector. We can be clearly notice that the maximum value of the *z* component of the electric field decreases with increasing value of the wave vector, therefore it decreases with the frequency decreasing.

k	0	0.1	0.2	0.3	0 .4	0.5
Ezmin (V/m)	1.513	1.357	1.285	1.165	0.837	0.002
Exmax (V/m)	-1.217	-1.041	-0.848	-O.579	-0.677	-0.002

Table 1. the maximum and minimum values of the electric field for various values of the wave vector

The three "Figure 5." and "Figure 6." represent the isovalues of the third component of the electric field in the form of surfaces. This performance confirms the findings mentioned above.



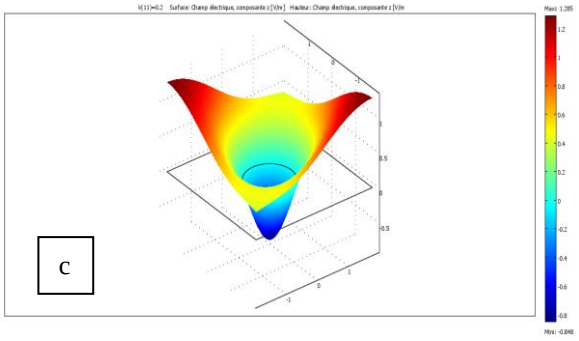


Figure 3. changes in the z component of the electric field Ez (x, y) for different values of the wave vector *a) k= 0, b) k = 0.1 and c) k = 0.2*

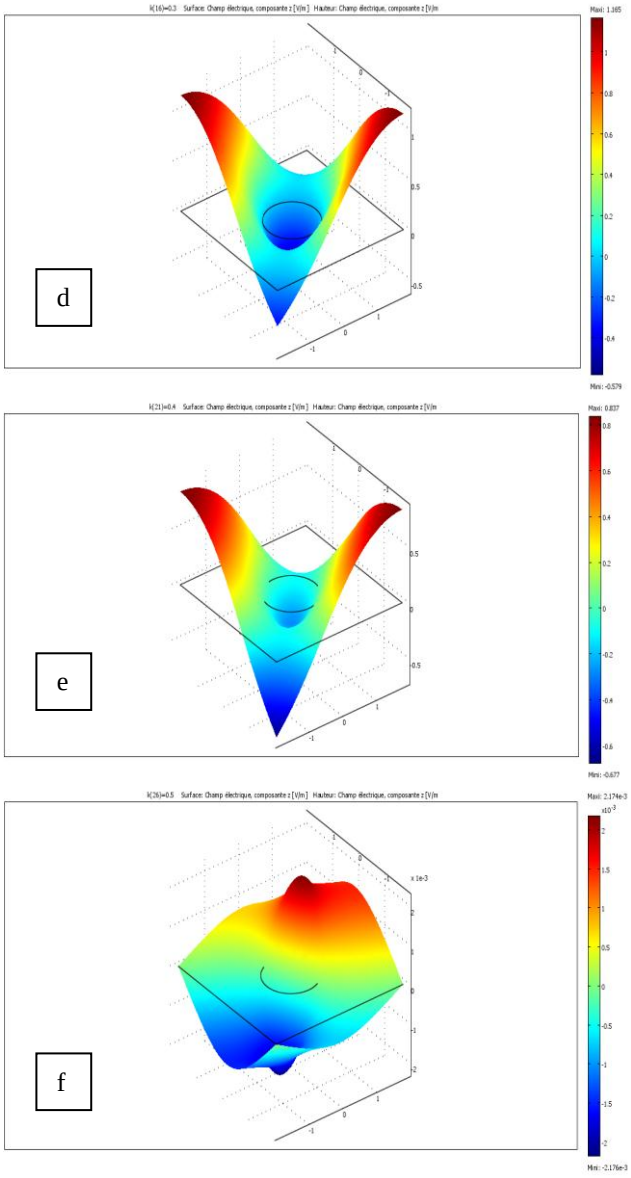


Figure 4. the following changes in the z component of the electric field Ez (x, y) for different values of the wave vector *d) k = 0.3, e) = k=0.4 and f) k = 0.5*

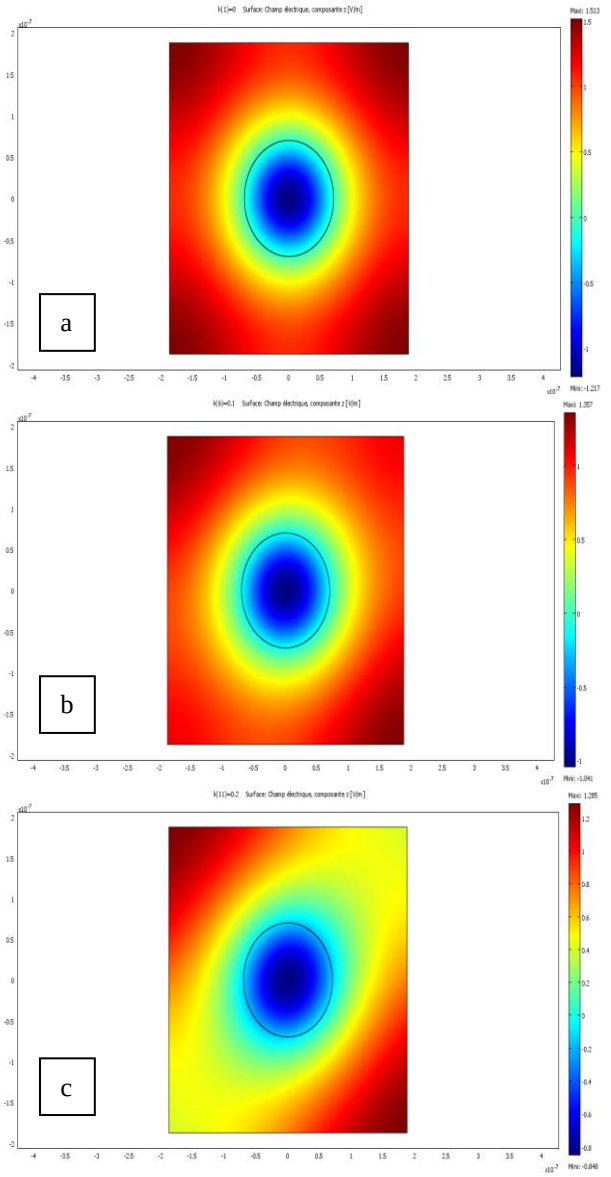
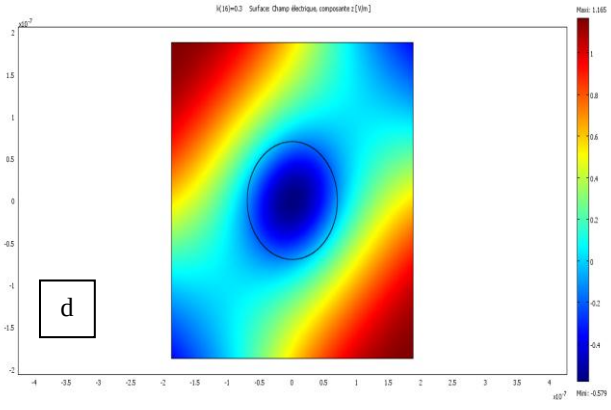


Figure 5. isovalues of the third component of the electric field in the form of surfaces *a) k = 0, b) k = 0.1 and c) k = 0.2*



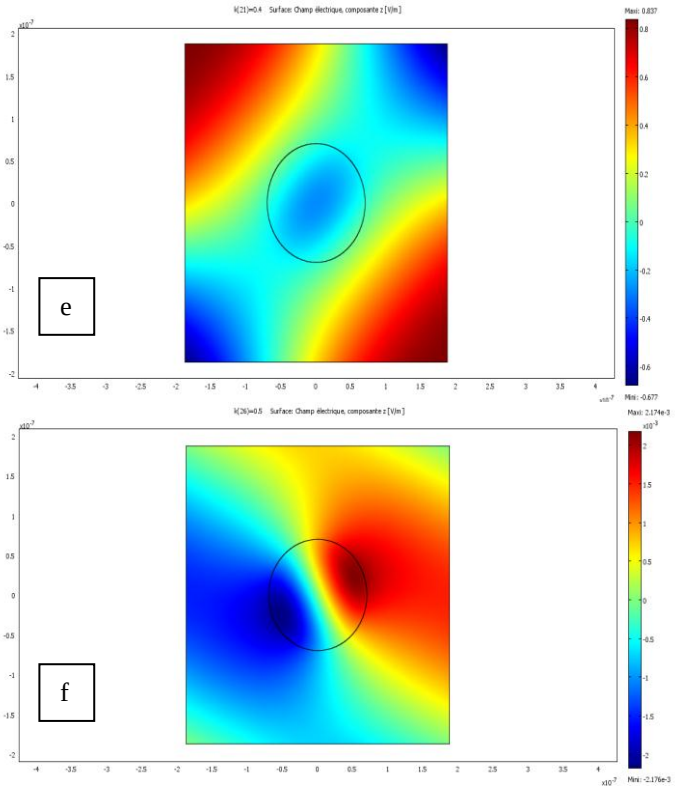


Figure 6. isovalues of the third component of the electric field in the form of surfaces *d) k = 0.3,e) k = 0.4 and f) k = 0.5*

III.2. Evolution of the electric field Ez

"Figure 7.".shows the variation of the component of the electric field *Ez (x, y)* in the semiconductor material of *III-V* (*GaAs*) in terms of y, for different values of the wave vector $k \in [0;0.5]$. The curves represent the symmetry axis passing through the mid-height of the cavity is in the region in the semiconductor or fluid zone. Whatever the value of the frequency curve is an extremism (minimum) in the centre of the material. We notice the same findings of the previous paragraph.

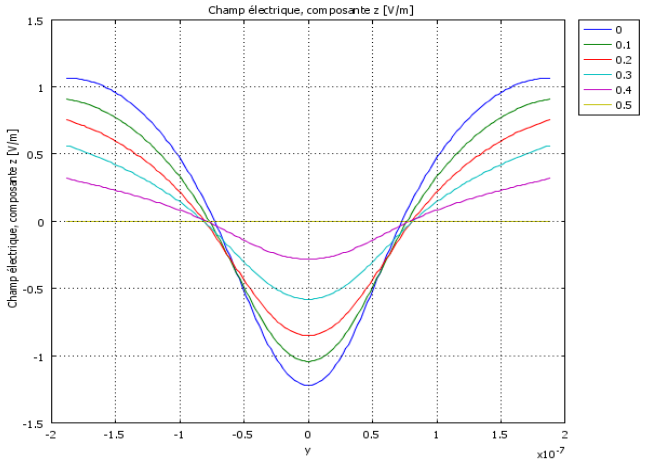


Figure 7.changes in the component of the electric field Ez (x, y) in the semiconductor material of *III-V* (GaAs) in terms of y, for different values of the wave vector $k \in [0;0.5]$.

III.3. Isovalues of the magnetic field

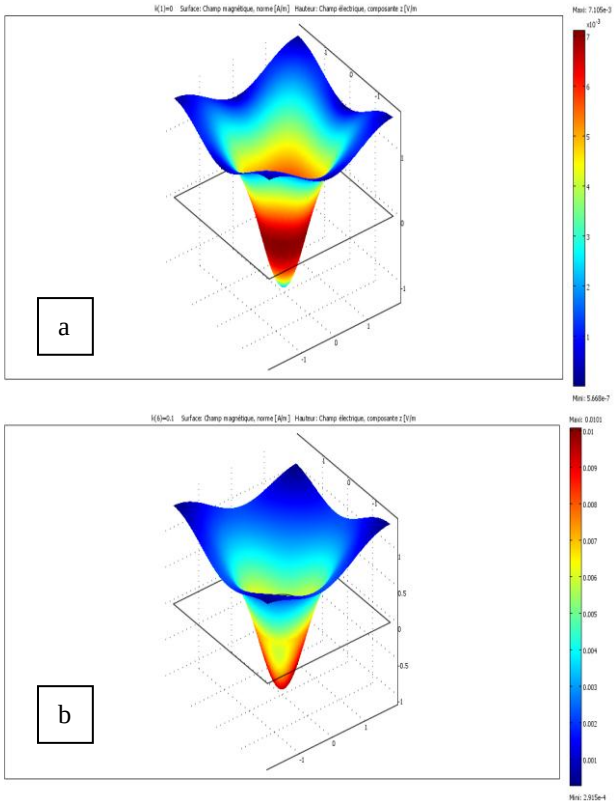
"Figure 8." and "Figure 9." represent the of the magnetic field module variations H (x, y) in the semiconductor material of *III-V* (GaAs) for different values of the wave vector $k \in [0;0.5]$, which corresponds at an interval of variation of the frequency *0* and *12.56Hz*.

For $k \neq 0.5$, the magnetic field *H* has the same shape. The value of the magnetic field is zero on the circumference of the crystal *GaAs* and increases in absolute value on the way to the centre of the crystal. The field increases away from the material in the fluid (air).

"Table 2." includes the maximum and minimum values of the magnetic field for different values of the wave vector. We can clearly notice that the lowest value of the z component of the magnetic field with the increase in the value of the wave vector, therefore it decreases when the frequency decreases.

Table 2. the maximum and minimum values of the magnetic field for various values of the wave vector

k	0	0.1	0.2	0.3	0 .4	0.5
Hzmin (V/m)	7.105 10^{-3}	O.0101	0.0111	0.0123	0.0149	0.0174
Hxmax (V/m)	5.668 10^{-7}	2.915 10^{-4}	2.45 10^{-4}	2.272 10^{-4}	1.077 10^{-4}	4.126 10^{-4}



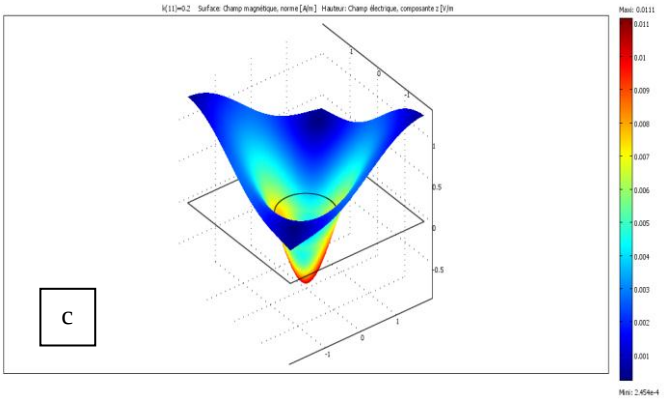


Figure 8. module variations of the magnetic field H (x, y) for different values of the wave vector *a) k=0 ; b) k=0.1 and c) k=0.2*

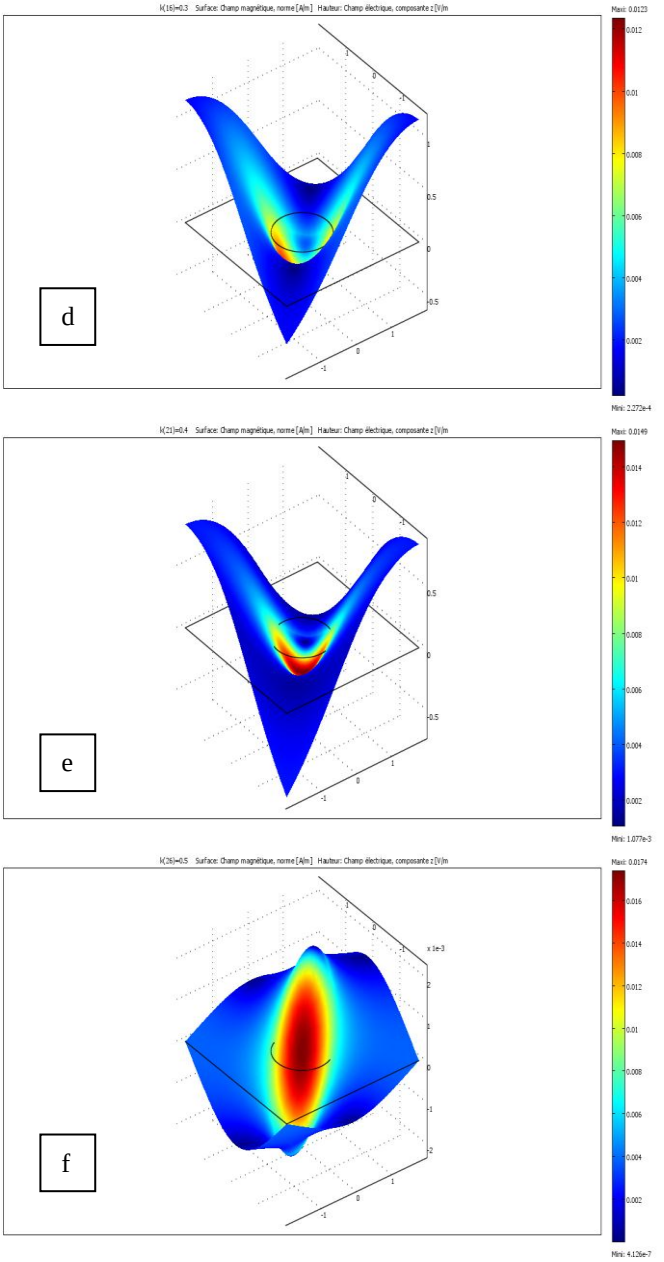
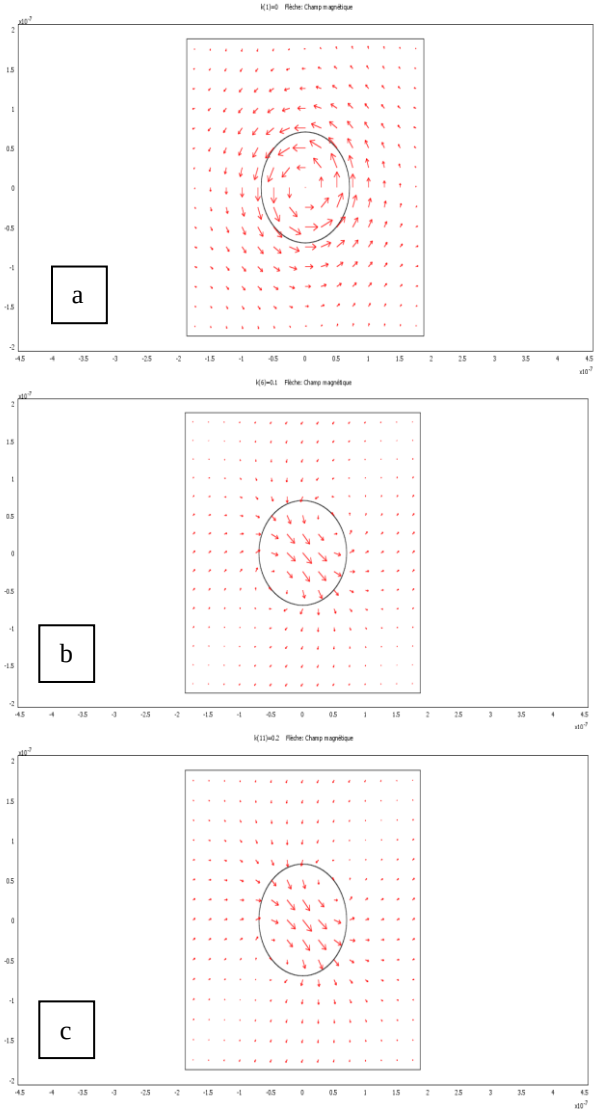


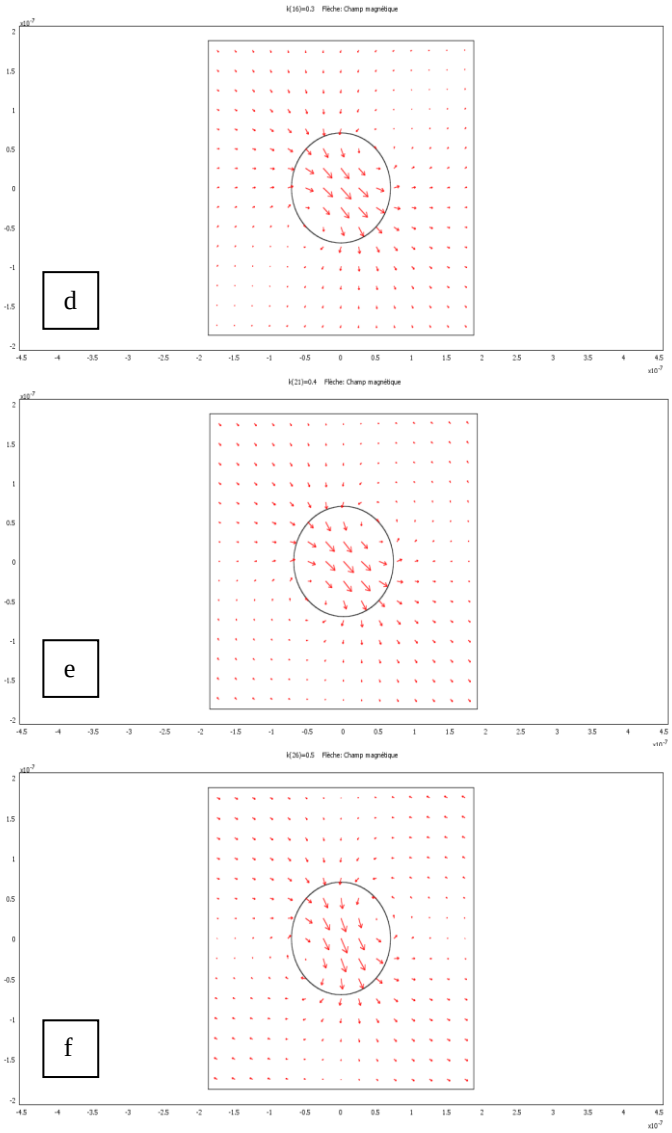
Figure 9. module changes the magnetic field H (x, y) for different values of the wave vector d) k=0.3 ; e) k=0.4 and f) k=0.5

III.4. Orientations of the magnetic field vector

"Figure 10." and "Figure 11." show the orientation of the magnetic field vector in the two studied areas (Crystal and Air) and that for different values of the wave vector. The vector field is most accentuated in toward the centre of the semiconductor material. The vector is oriented in the opposite direction of the hand of a clock.



Figures 10. the orientation of the magnetic field for various values of the wave vector has *a)k=0 ; k=0.1 and c)k=0.2*



Figures 11. the orientation of the magnetic field for various values of the wave vector *d) k = 0.3, e) k = 0.4 and f) k = 0.5*

III.5. Heating through Joule effect.

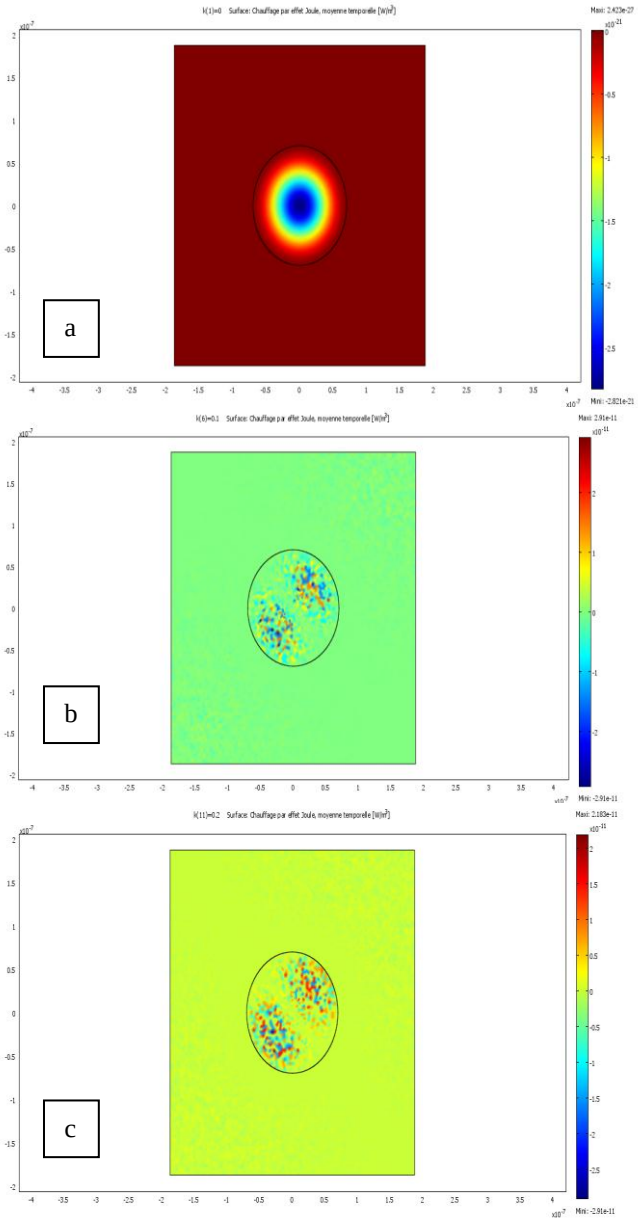
"Figure 12." and "Figure 13." represent the distribution of the semiconductor material heating by the Joule effect for different values of the wave vector $k \in [0;0.5]$.

For *k = 0,* The heating is intense in the centre of the crystal and decreases towards the circumference. The Isovalues of heat have circular shapes. For other values of the wave vector, the heat distribution in the crystal is random.

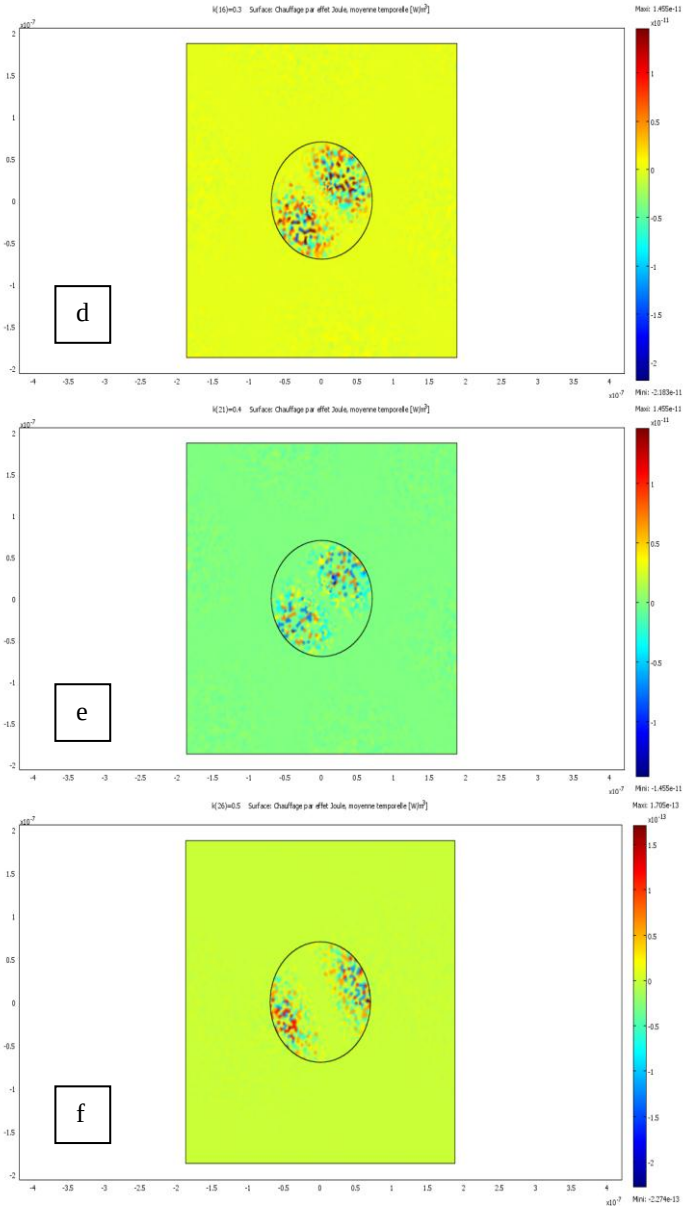
"Table 3." includes the maximum and minimum values of the *heat* of the material per unit volume for the different values of the wave vector. We can clearly notice that the maximum heat value decreases with the increase of the value of the wave vector.

Table 3. the maximum and minimum values of the magnetic field for various values of the wave vector

K	0	0.1	0.2	0.3	0 .4	0.5
Qmax (W/m3)	2.423 10^{-27}	2.91 e-11	2.183 10^{-11}	1.455 10^{-11}	1.455 10^{-11}	1.705 10^{-13}
Hxmin (W/m3)	-2.821 10^{-21}	-2.91 10^{-11}	-2.91 10^{-11}	-2.183 10^{-11}	1.455 10^{-11}	-2.274 10^{-13}



Figures 12.representing distribution of heating the semiconductor material by the Joule effect for different values of the wave vector *a) k = 0, b) k = 0.1 and c) k = 0.2*



Figures 13.represent the distribution of heating the semiconductor material by the Joule effect for different values of the wave vector *d) k = 0.3, e) k = 0.4 and f) k = 0.5*

IV. CONCLUSION

In this work, we have examined the wave propagation in a photonic crystal consisting of columns of *GaAs* equidistant from each other. This model extracts the band diagram for the lowest frequencies of the crystal.

The results of the simulation thus found are in the form of isovalues and curves for the electric field, magnetic field and Joule heating.

For the electric field and the magnetic field, it was found on the one hand, that, whatever the value of the wave vector, the value of the field increases towards the centre of the crystal and no circumferentially. On the

other hand the maximum value of the electric or magnetic field is decreased with increase in the value of the wave vector.

For heating by Joule effect, it increases towards the centre of the crystal for a zero value of the wave vector. For other values, the heating of the material is aléatoire.de.

As perspectives, we consider the 3D case study and a comparative study of different materials such as silicon, gallium arsenic, ...

References

[1] [1] E. Yablonovitch, « Inhibited Spontaneous Emission in Solid-State Physics and Electronics », Physical Review Letters, vol. 58, no 20, 1987.

[2] [2] S. John, « Strong localization of photons in certain disordered dielectric superlattices »,Physical Review Letters, vol. 58, no 23, 1987.

[3] [3] Abdelwaheb Ourir, «Applications de Matériaux `a Bandes Interdites Photoniques et de métamatériaux en Télécommunications», Doctorate theses, University of Paris Sud XI , N◦d'Ordre : 8509, décember 2006.

[4] [4] Soumia MASSAOUDI, «Etude théorique et expérimentale des matériaux à bandes interdites photoniques bidimensionnels (BIP 2D) en Micro-Ondes: Application à l'ultraréfraction», Doctorate theses, University of PARIS XI UFR SCIENTIFIC D'ORSAY, February 2005.

[5] [5] STENGER Nicolas, «Croissance de méta-cristaux sur des patrons en pavages de Penrose», Doctorate theses, University of Louis Pasteur Strasbourg, March 14, 2008.

[6] [6] Sandrine MASSY, «Contribution à la réalisation de fonctions optiques à base de cristaux photoniques sur LiNbO3», Doctorate theses, University of Limoges, 2004.

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