Negative Refraction, Subwavelength Lensing Effect and Total Mirror with a Photonic Crystal Structure

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ABSTRACT:
We have presented the investigation on the slab of photonic crystals that was made of a honeycomb lattice of silicon embedded in free space. For the simulation of this structure the two-dimensional finite-difference time-domain (FDTD) method was used. This arrangement has shown that with suitable choice of frequency can have negative refraction with an metamedium effect with $n = -1$. In this conditions, in TE polarization can act as total mirror and in TM polarization can act as superlens. In a certain frequency, this type of photonic crystal structure acts as left handed martial that they were named metamaterials. A wide range effects were studied by this structure. To show these unusual phenomena, we analyzed the contour map and solid model of electric field and magnetic field for a photonic crystals structure. This structure has negative refraction of light, subwavelength lensing effect and 100% reflector. These feathers are in metamaterials that also can be seen in photonic crystals.

KEYWORDS: Imaging, Left-handed materials, Mirror, Negative refraction, Photonic crystals.

1. INTRODUCTION

There are some theories in science that we think impossible in the actual world. One of these theories is the Veselago model. Authors in [1] planned negative refractive index idea in 1967 and named this material, Negative Index Materials (NIMs). Pendry, Smith, and coworkers have worked [2], [3] on this property and resaved to Veselago theories. They have seen this principal in the material that birth to an unusual set of metallic structures became documented as left-handed matrial or "metamaterials" [1].

Metamaterials have property which there were not in the environment that can lead to a variety of unusual electromagnetic and optical phenomena [4–6]. They exhibited new electromagnetic answer. In word of metamaterial, the prefix Meta is interpreted as "outside of" that has the Greek basis and understands the term "meta-substances". Meta-substances arrangements have effective electromagnetic behavior drops outside of the property limits that it is forming device.

Metamaterials are achieved by a simultaneously materials, negative values of effective permittivity and effective magnetic permeability.

The natural materials have a right-hand law with electric field, magnetic field and the wave vector. Their Poynting vector of a wave and the energy velocity has the equal way as their phase velocities. In metamaterial, vectors of electric field, magnetic field and the wave create a left-handed set of vectors. In metamaterials, the Poynting vector is anti-parallel to the wave vector [1, 2].

Metamaterials are artificially structures that have number of attractive properties. That is to say, Negative refraction [4], [6], subwavelength focusing [5] are the reasons to have variation applications. A type of metamaterials was shaped in [3]. This paper have investigated a new design of transmission properties of metamaterials which can be used for electromagnetic cloaking [5] and improve the directivity of dual band patch antennas and dual polarization [6].

In other hand, it has established that dielectric arrangements such as photonic crystals [8, 9], may qualify alike light behaviors in metamaterials [7-10]. So, in these certain, Photonic Crystals (PhCs) arrangements in two-dimensional [11] can be active as a medium with negative refractive index [12]. These unusual facts in the physical principles are based on complex Bragg scattering.

PhCs with the optical refractive index are one, two or three dimensions dielectric configurations [13]. Such periodicity arrangements in certain frequency ranges can forbid propagation of the electromagnetic waves. In these periodic structures, a band gap is produced by electromagnetic waves which did not published at certain frequencies [14].

PhCs can demonstrate another group of material with negative refractive index in a certain frequency. For example, subwavelength imaging can be recognized in photonic crystals with a positive refraction index and negative refraction behavior [9, 18]

Several key ideas and proposals for application of photonic crystals have been proposed by these characteristic. A perfect lens with PhCs is made based on a negative which lead to exciting requests, [15].

PhCs with negative refractive made up a structure that can be used as biosensors with superlensing property in micro and nano dimensional. It is shown that by an appropriate choice some of factors in PhCs slab, can reach sensing property by two-dimensional triangular structure. The slab of the hexagonal two-dimensional PhCs of structure in micro dimensional is suitable for application of biomedical imaging and sensing [16].

Haxha [17] exhibited a plano-concave lens with PhCs of negative refractive index working at optical frequency. Lens was used as a converter that was mixed light and could be added to a compressed photonic combined circuitry. Luo [10] et. al. has shown that the all-angle negative refractive are results of sulb wavelength imaging planned in two- PhCs arrangements.

One another, a main idea were purposed; collimation effects in two-dimensional PhCs with tube-type air holes [19]. It is obvious that in PhCs arrangements, the negative refraction phenomenon can be used to realize a difference of devices. These devices could have remarkable potential to grow science such as the development of detailed optic nanosensors, telecommunication devices and biosensors.

We investigated a simple arrangement of PhC based on negative refraction that has several applications.

Hence, first, theory of negative refraction was proposed, then the structure was designed and was the choice value of factors of this arrangement. In study section, solving band method, band structure of the photonic crystal was achieved, employing FDTD technique to design contour map and solid model. Conclusion is the final step.

2. CONCEPTS OF NEGATIVE REFRACTION

First, the properties of propagating waves are focused on the usual martial. We study the ideal materials, in which the electric field is zero everywhere without losses.

Permittivity and permeability of these kinds of materials are positive. So, refraction index [20, 21] was achieved according to equation 1:

$$n = \sqrt{\varepsilon\mu} \tag{1}$$

This rule shows that the electromagnetic wave refracted crossing the border between two settings with two environments. Issue of refraction is depended on the difference in the refractive indices: Snell's law with positive permittivity and permeability state:

$$n_1 sin\theta_1 = n_2 sin\theta_2 \tag{2}$$

Where n_1 and n_2 are refractive indices in environs 1 and 2 respectively, θ_1 and θ_2 are the angles incident and refracted waves, respectively.

Figure 1 shows this law in boundary of two different materials environments.

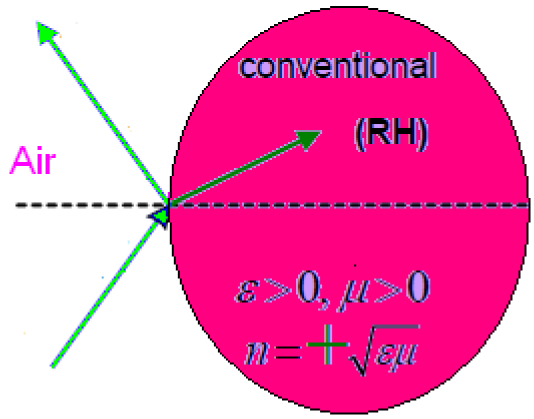


Fig. 1. The light propagation in positive refractive index perimeter.

In the optical frequency range, the combined material with simultaneously permittivity and permeability negative values was made up.

There are numbers of questions:

Do different the equations (1) and (2) in meta-material and natural materials?

To be changed these equations in metamatrial?

To response these questions, the rules of the Maxwell is investigated.

$$\nabla \times E = -j\omega B \qquad (Faraday's \quad Low) \tag{3}$$
$$\nabla \times H = j\omega D \tag{4}$$
$$(Generalized\ Amper\ Low)$$
$$\nabla . E = \rho/\varepsilon_0 \tag{5}$$
$$\nabla . B = 0 \tag{6}$$

Where, E and H are electric and magnetic field intensity, respectively. B and D is magnetic flux intensity and electric flux intensity, respectively. ρ is electric charge density and ε_0 is the permittivity of free space.

In the constant plane waves we have:

$$E = \mu\, {}^{\omega}/_{kc}\, H \tag{7}$$
$$H = -\varepsilon\, {}^{\omega}/_{kc}\, E \tag{8}$$

Above equations represents that E, H and k forms a right-handed principle of vectors.

$$S=E\times H \tag{9}$$

Using the rule 9, a right-hand law can be realized in natural materials and this rule is for positive μ and ε values. Therefore, the phase velocity direction (v_{ph}) matched with the group velocity direction (v_g). So, the direction of the group velocity consents matched with the direction of the vector S.

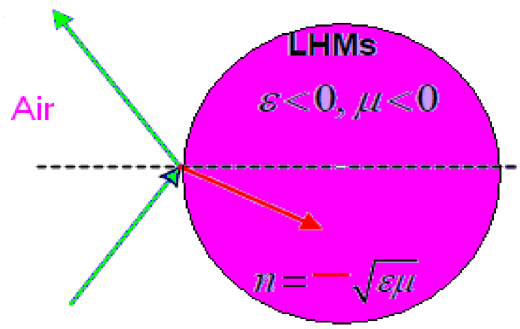


Fig. 2. The light propagation in negative refractive index perimeter.

If μ and ε are negative, then the phase velocity direction and the group velocity directions are anti parallel. Therefore, a left-hand set of E, H and k must conform. Therefore, E, H and k obey a left-hand set. Figure 2 shows the refraction in environment 2 with negative μ and ε that the direction of the refracted wave vector is reformed. In this condition, the index of refraction is negative.

Now, the equation (1) is modified and the negative sign is added for metamaterial:

$$n=\mp\sqrt{\mu\varepsilon} \tag{10}$$

3. DESIGN

A hexagonal lattice of silicon hexagon rods is involved the PhC arrangement. For this array, value of parameters must be chosen that contains Effective permittivity of hexagonal and background, number of units, long of two opposite top hexagonal units, lattice constant.

Effective permittivity of silicon is 11.8 that was choice for rods. The background medium is free space. The structure consisted of 7 × 28 hexagonal units, thus, number of hexagonal units in x direction is 7 and number of hexagonal units in z direction is 28.

Figure 3 shows Unit cell of the Phc.

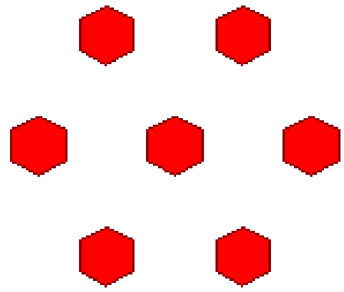


Fig. 3. Unit cell of the lattice two-dimensional photonic crystal configuration with relative permittivity ε_r=11.8 and in a background of free space.

R is long of two opposite top hexagonal units and equal 0.4×A. A is the center to center partition between hexagonal units that called lattice constant and A=1. These parameters are micrometer. Value of parameters were placed in the table 1.

Table 1. Value of parameters

Effective permittivity	11.8
effective magnetic permeability	1
number of hexagonal units in x direction	7
number of hexagonal units in z direction	28
A	1
R	0.4×A

4. ANALYZE

The periodic margin conditions with perfectly matched layer (PML) in electromagnetic modeling are necessary to be used. PLM has been efficiently employed by frequency domain numerical methods.

FDTD technique have employed two-dimensional for the modeling of periodic structures to investigate electromagnetic waves. This technique describes Maxwell's equations in both the time and space domain. These formulas performed in the time domain; therefore the temporary data from a model can be changed to the frequency domain to achieve a wideband answer.

In this structure, normalized frequency is between f_1=0.268(a/λ) and f_2=0.440(a/λ) (figure 4), that these rang is named Bragg band gap. Therefore, under the Bragg band gap, i.e. the first photonic band has a frequency area for negative refraction and in f=0.2(a/λ) acts such as metamatirials and has negative refraction index.

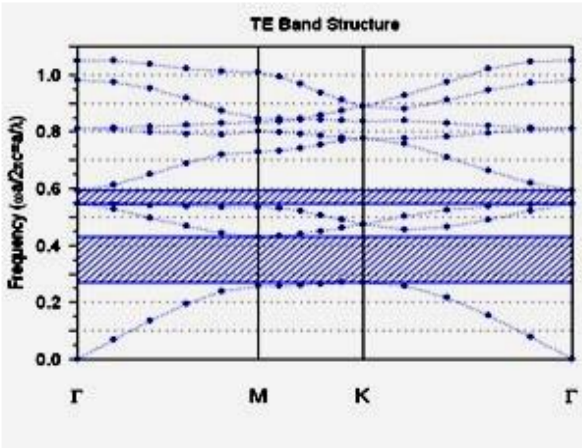


Fig. 4. Band structure of the 2D photonic crystal in frequency f=0.2(a/λ).

A Gaussian source of wave was switch on outside and left of the slab of the PhC arranged systematically into TE and TM polarizations. We study in detail and investigate this structure and reach maps of propagating waves.

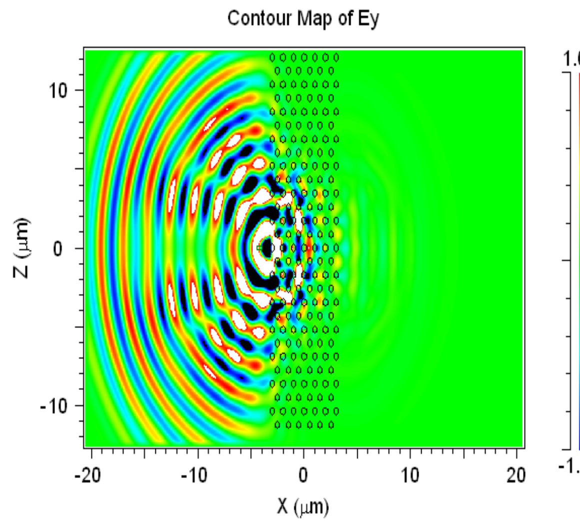
In a photonic crystal structure, the TM waves apply the maximum possible simulated spatial modulation.

Therefore, the TM band structure in FDTD was computed by applying Bloch-periodic boundary conditions.

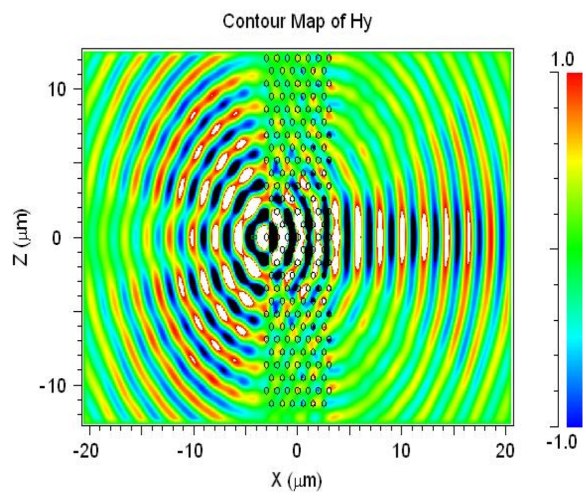
S component moved over a half net spacing, both in time and space. The electric and magnetic fields are performed by employing FDTD method at different grids and shifted over a half-grid in space. Their components are calculated at different having the same field.

The amplitude of H_y and E_y components are measured at outside and to the right of the slab.

Figure 5 shows the results of FDTD simulation for TE and TM polarization. This figure compares the characteristics of the propagation map, which contains the electric field distribution across space and the magnetic field distribution across space. As can be observed, the propagation of the refracted wave occurs in left. In this condition it shows the mirror (figure 5(a)). Figure 5(b) illustrates the magnetic field distribution across space for slab of the 2D-PhC of structure in frequency= 0.2(a/λ). The propagation of the wave in both of left and right of the slab makes a conventional lens in TM polarization.



(a)

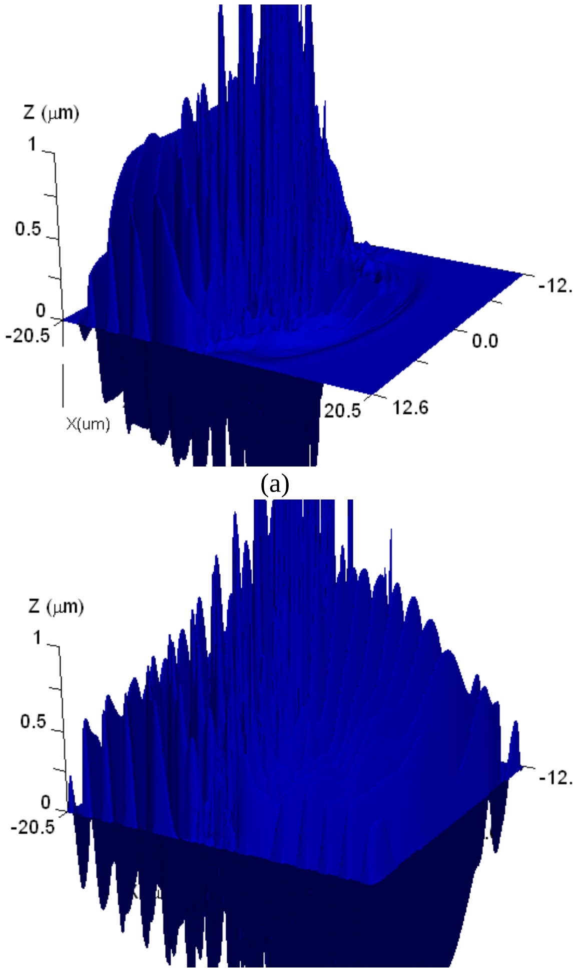


(b)

Fig. 5. The propagation map (a) electric field distribution across space, (b) magnetic field distribution across space for slab of the 2D-PhC of structure in frequency f=0.2(a/λ).

Figure 6 illustrates solid model for H_y and E_y amplitude of the slab for TE polarization that can focus the near field. The keep information was in the near fields which are localized near the object. Therefore, in TE polarization there is total mirror and in TM polarization there is superlens.

In next part, a monitor was placed in the left of the slab. The frequency was changed and E_y amplitude was achieved for the frequencies between f=0.1(a/λ) to f=0.6(a/λ).



(b)

Fig. 6. The solid model of The propagation map (a) electric field distribution across space, (b) magnetic field distribution across space for slab of the 2D-PhC of structure in frequency= f=0.2(a/λ).

Figure 7 shows the results of simulations for different frequencies. The results of this figure shows that E_y amplitude increases to frequency=0.2(a/λ) and then decreases for others frequencies. Therefore, the lens based on negative refection is affected with metamedium value by $n = -1$ in this condition. The field amplitude is at the utmost, in this frequency.

5. CONCLUSIONS

In this paper, the negative refraction is proposed in two-dimensional photonic crystal and the effect of the output interface is investigated in the arrangement. We showed the contour map and solid model of electric field and magnetic field for a 2D-Phc structure.

The several unusual phenomena were shown in photonic crystals that include negative refraction of light, subwavelength lensing effect, total mirror and 100% reflector. Also, we showed to scale the idea to the optical frequency range, which at present is not possible with the right-handed materials.

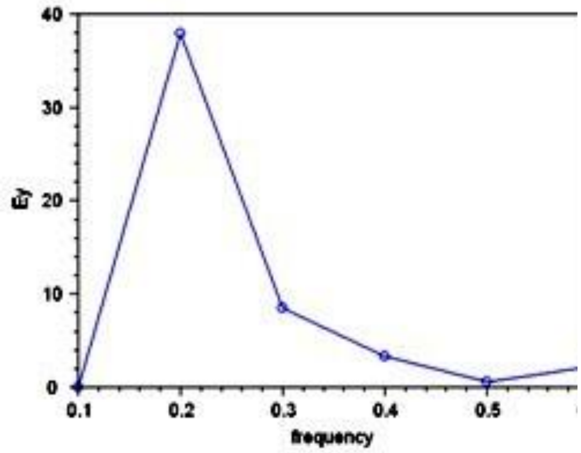


Fig. 7. Amplitude of electric field across frequency changes from 0.1 to 0.6.

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