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Dual negative refraction in a two dimension square photonic crystal

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ABSTRACT

Dual refraction effect based on the overlapping bands in a two dimensional (2D) photonic crystal (PhC) is demonstrated. The PhC consists of alumina rods with a dielectric constant $\varepsilon=8.9$, arranged in a square lattice in air. To disperse light which has special excitation frequency and a specific incident angle, by this PhC we optimize his structural parameters such as the radius of dielectric rods). It is shown that two focusing phenomena are formed in the PhC image plan; the degeneracy of modes can be applied to realize optical interference and wave front division. The simulation results are obtained by employing the PWM for analyzing bands structure and the finite-difference time-domain (FDTD) to predict the evolution of the electric fields.

1. Introduction

Photonic crystals (PhCs) are periodic dielectric structures in one or two or three directions. PhCs offer the possibility to control and manipulate the propagation of the light at frequencies scale [1–9]. Among other properties, the negative refraction is one of the most promising futures for building very compact integrated circuits [10–12]. Materials with negative refraction or left hand photonic crystals have simultaneously negative permittivity and negative permeability. Negative refraction in photonic crystal has attracted many applications in light manipulation such as focusing imaging in which the photonic crystal is employed as super-lens or super-prism [13], switch [14,15], router [16] and optical logic gates [17]. Several research works are based to the photonic band structure which describes the states of the photon, and especially the photonic band gap (PBG) properties. These properties are essential to design novel devices efficient for light guiding. For the proposed photonic crystal (PhC), the higher frequency bands provides dual modes also called dual negative refraction because for the same polarization state photonic bands with different wave vectors might locate in the same frequency region. So, to find the best result we trend to play on the PhC parameters (the filling ratio) and the source parameters.

In this work, our idea is based on studying the overlapping between bands which generates the degeneracy of modes. We are interested on analyzing the overlapping to find many energy bands. The energy band overlapping generate two phenomena namely the positive refraction and the negative refraction because these bands have different wave vectors at the same frequency, which may lead to two refractions at the same frequency with different phase and group velocities, so focus our attention on the negative refraction concept because photonic crystal, used as left-hand material, amplifies the evanescent waves so it gives the possibility to fabricate new devices with diverse and efficient functionalities compared to their counterparts that are based on usual materials. In this work we trend to build a new slot array, super-lens and super-prism.

2. Results and discussions

The motivation of this study is to design some structures based on left-hand photonic crystals which are anisotropic medium with different refractive indices in the x, y and z directions, therefore the propagation of light is not similar along these directions. It means that light propagation depends on the polarization direction of waves. These proposed structures play the same role as optical devices generating new phenomena and effects such as the dual self-collimation, the super-focusing and the super-dispersion. The schematic of the structure is described in Fig. 1.

The structure under investigation is formed by an arrangement of cylinder rods of alumina in air. Certain conditions, by launching a single beam light into the left-hand photonic crystal, give possibility to light to disperse into two negative refracted waves with

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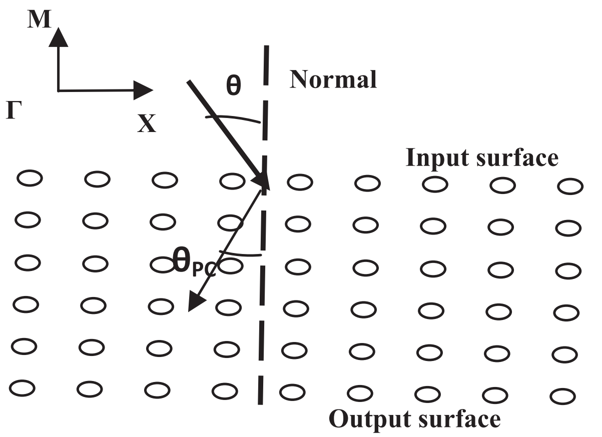

Fig. 1. Schematic of the 2D square PhC with cylinders dielectric rods in air.

the same frequency and polarization state, however with different phase and group velocities.

By varying cylinder radius, which imposes a variation of energy bands, and the angle of incident light, we optimize the range where the beam penetrates and propagates down the photonic crystal and therefore inhibits the reflection.

2.1. TE polarization

As first step, we calculate the energy bands diagram by using the plane wave method (PWM). Fig. 2 describes the bands overlapping for TE polarization.

As identified with the black circle in Fig. 2, the third and fourth bands of the PhC satisfy the condition of dual negative refraction in a single band and should be the ideal candidates to induce dual refraction effects.

To verify this property of dual self-collimation refraction, we use the results reported in [18] for TE polarization. Gajic et al. have demonstrated the appearance of convex equal frequency contour (EFC) around the center of Brillion zone with an inward gradient. By inspecting the EFC figures one may notice that the form of the curves are square, this is an evidence of the self-collimation effect that results in two parallel group velocities perpendicular to the EFC.

After this design step and in order to validate the results of band diagrams, we consider a photonic crystal composed of 6 layers of rods in the ΓM direction. We excite the structure with a continuous sino-Gaussian plane wave with frequency

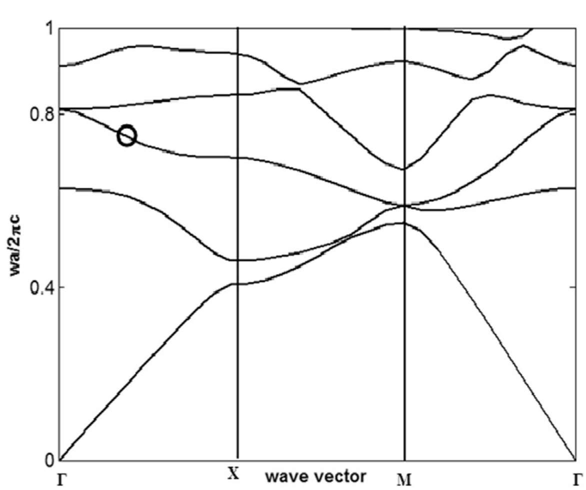

Fig. 2. The band structure for TE modes in a 2D square photonic crystal composed of alumina rods in air.

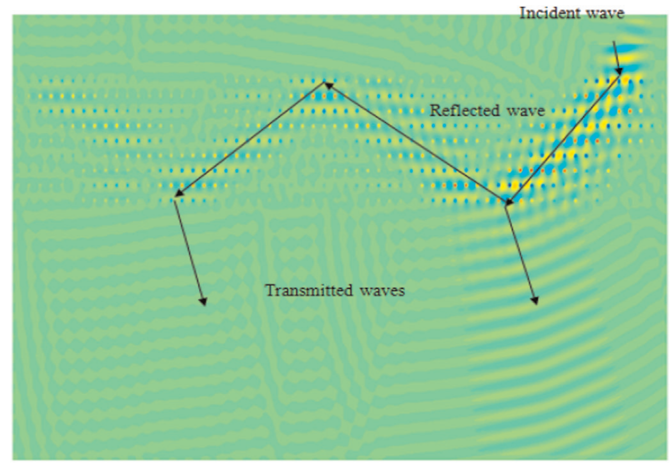

Fig. 3. Dual self-collimation effect for TE polarization in 2D square photonic crystal.

$f=a/\lambda=0.732$, where a is the square lattice constant. The beam light hits the input surface of the structure with an incident angle $\theta i=10°$, as it is shown in Fig. 1. The evolution of the electric field is performed by using the FDTD [19–21] with perfectly matched layer (PML) [22] used as the absorbing boundary conditions which absorb outgoing waves from the computation domain. The time domain snapshot of beam signal is shown in Fig. 3.

This figure shows the snapshot of Hz propagating along the ΓM direction, one may observe two separated parallel outgoing waves in the output surface this demonstrates the dual negative refraction effects. This effect is a dual self collimation indicated by two parallel group velocities which are perpendiculars to the EFC $v_g = \nabla_k\ \boldsymbol{\omega}$. In this case, the scalar product $v_g.\ k < 0$ is negative this justifies the dual negative refraction observed between the third and forth bands. This system can be used to design novel array of slots. The proposed structure is more se lective and ensures the dispersion of the polychromatic light.

2.2. TM polarization

In this part we focus on studying the propagation of light along the ΓX and ΓM directions, we calculate the band energy as a function of the wave vector; the result is reported in Fig. 4.

This figure shows multiple overlapping between bands. We select the second and the third bands as it is indicated by a blue circle where the overlapping occurs at the frequency $f=0.545$. We use this frequency to excite the electromagnetic wave propagating along the two directions ΓX and ΓM.

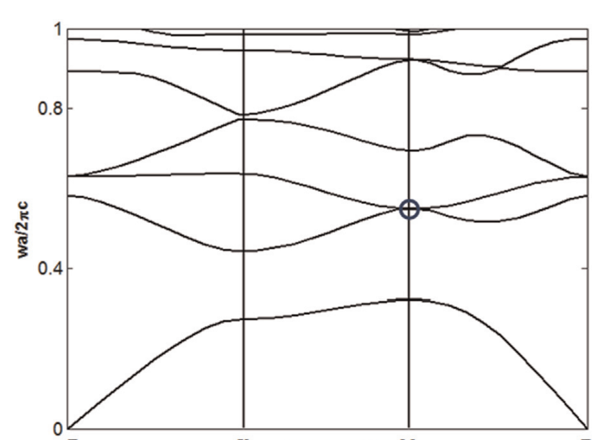

Fig. 4. TM band structure for a 2D square photonic crystal.