Self-collimation effects improvement in two dimensional photonic crystal based on opto-fluidic technology

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ABSTRACT:

We propose an optofluidic based on two dimensional (2D) rod-type silicon photonic crystal (PhC) waveguide that support self-collimation effect over a large frequency and angle range without any defect or nano-scale variation in the PhC geometry. By analyzing the Equi-Frequency contour (EFC) of a triangular rod PhC-bands, we verify the optimum band of the structure that is suitable for self-collimation of light beams. By varying the refractive index of fluid which is being infiltrated into the background of PhC, we perform a systematic study of optofluidic self-collimation of light beams to achieve a wide range of angles and low loss of light. By means of selective microfluidic infiltration, and remarkable dispersion properties we show it is possible to design, auto-collimator, and negative refraction devices based on self-collimation effect with high transmission. We use the plane wave method (PWM) for analyzing the EFC and the finite difference time domain (FDTD) method for simulating the transmission properties.

KEYWORDS: phonic crystal waveguide; self-collimation; Optofluidics; negative refraction; transmission

Introduction

Photonic crystals which were first introduced by E. Yablonovitch and S. John in1987 [1],[2], have natural advantages of controlling the propagation of light in the wavelength-scale. In recent years, there has been a growing interest in using PhCs to design different telecommunication devices such as switch [3]-[4], router [5], and all optical logic gates [6]. Most of the research works reported in designing of PhC devices are based on the photonic band gap (PBG) properties[7]-[9].The devices based on this method relied on the optimization of the PhC lattice geometry, where the high fabrication accuracy is essential, as even nanometre-scale deviations typically lead to a significant degradation in the desirable optical dispersion properties[10]-[13]. However, in recent years the devices based on self-collimation of light beams and negative refraction in PhC without geometry variation are proposed [14]-[18]. Self-collimation (SC) effect, by which an incident light can propagate with almost no diffraction and no engineered defect in PhCs, has attracted particular attention because of its potential for photonic integrated circuit (PIC) [19]-[20]. coupling light into narrow waveguide. To use these effects in practical device its essential that light can be coupled efficiently into and out of the PhC structure with The self-collimation effect relies on the special dispersion properties in PhC, where the curvature of equi-frequency counter (EFC) departed from the normally circular curvature in free space. This property achieved when this curvature becomes flat [21]-[23]. Also this curvature has the ability to generate the negative refractive index. In this paper, we propose a two dimensional (2D) triangular rod-type photonic crystal lattice waveguide that support self-collimation effect over a large frequency and angle range using the optofluidic approach. Optofluidics is a new branch of photonics and microfluidics [26]-[27]. In particular, combination of PhC structures and microfluids has attracted some attentions as a means to tune the optical properties of PhC [28]-[29]. It means that, background fluid infiltration offers free parameter which is independent on the fabrication. However the most important aspect of microfluidic is the potential for reconfigurable properties which could overcome these topological limitations [30-31].

In this paper, we show the optimization process of light coupling and transmission in the SC region by injecting fluids with various refractive indexes to background of photonic crystal rods. We also show that the self-collimated beams can be easily controlled by varying the refractive indexes of infiltrated fluid. In order to analyzing of the EFC calculations, we have performed the plane wave method (PWM). Then by employing the finite different time domain (FDTD) method with perfectly match layer boundary condition the transmission properties of rod-type photonic crystals has been studied.

The rest of this paper is organized as follow. In Section 2, we review the theoretical foundations of self-collimation phenomenon and its corresponding EFC map. After that the suitable structure, by analyzing and calculating different parameters is achieved. The procedure to optimize and reconfiguration of self-collimation and negative refraction properties by means of selective optofluidic background infiltration through precision simulation techniques is presented in Section 3. Finally we conclude the paper in Section4.

2. STRUCTRE DESIGN AND ANALYSIS

2.1. Self-Collimation Effect in Photonic Crystal Structures

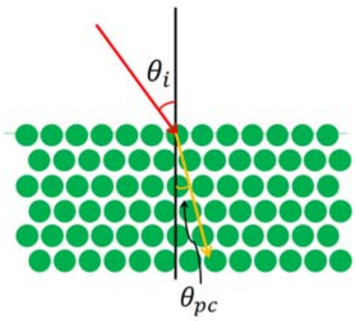
Photonic crystal structures provide the mechanism to control and confine the light .The existence of a bandgap in PhC help the majority of applications to confine light in space. However, by exciting the modes of photonic crystal with frequencies outside the photonic bandgap, light can propagate in the PhC. Then, due to the complex spatial dispersion properties of planar photonic crystals, phenomena associated with anomalous refraction of light such as a super-prism or self-collimation can be occurred.

Self-collimation or self guiding of light in a perfectly periodic photonic crystal is a process, in which a narrow beam of electromagnetic wave can be propagate without any significant broadening or diverging in beam profile. It has been demonstrated that PhCs designed for collimation properties, is based on in-band application, which do not need to exhibit bandgap. In this application the property of guiding mechanism relies on the shape of band, rather than bandgap.

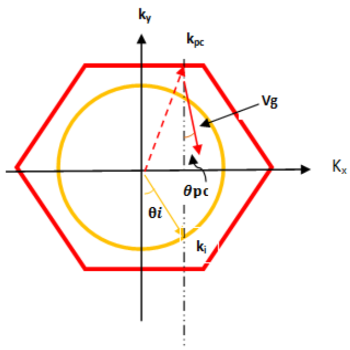
It is known that, in an in-homogeneous medium such as photonic crystals, the light propagation can be controlled by the direction of its group velocity given by $v_g=\nabla_k\omega(k)$, which is perpendicular to the equi-frequency contour [15]. Also the SC effect is achieved when the equi-frequency contours are as flat as possible, because the group velocity of light is always normal to the equi-frequency contours.

The schematic of the light coupling according to snell's law is presented in Fig. 1a. In this figure, θ_i and θ_{pc} represent the incident and transmitted light angles in a homogeneous dielectric and a PhC media respectively. Figure 1a shows that when the plane wave passes from the air to the PhC, it bends according to snell's law. The bending angle depends on refractive index of each medium. In order to find the frequency range in which the self-collimation effect take place, the EFCs calculation as a function of in-plane k vector, is essential.

A plane wave of frequency ω propagating in a homogeneous dielectric medium with refractive index n, is characterized in space by a wavevector of magnitude $k=n\omega/c$ and its propagation direction. The set of all possible wavevectors at this frequency illustrated by circle of radius k, as a result by considering various frequencies existence, leads to creation of different circles. These circles are EFCs of conical band surface related to homogeneous dielectric. As mentioned earlier, An EFC provides a valuable representation of light dispersion in any homogeneous or in-homogenous media. The schematic of this behaviour illustrated in Fig. 1b. The yellow circle and arrow indicate air medium EFC and incident wavevector, ki, respectively, at the incident frequency. The red curve and dashed arrow are the EFC counter of PhC and refractive wavevector, kpc, respectively, and the group velocity vector of refracted wave, vg, indicated by solid red arrow. It should be noted that in the self collimation of light beams, the group velocity and phase velocity has a same direction; meanwhile in the case of negative refraction their directions become opposite. In this case the phase velocity is opposite to the group velocity and it happens at angular convex EFC map.



(a)



(b)

Figure 1. (a) Geometry showing the creation of incident and transmitted light at the boundary of a homogenous dielectric and a PhC media according to snell law. (b) The equifrequency contour of two homogeneous isotropic dielectrics and a PhC.

2.2. Structure design

Our paper basic structure is hexagonal lattice with refractive index of 3.5 and 1 for silicon rods and background respectively. We restrict our calculations to transverse-electric (TE) polarization states, i.e. with the magnetic field being parallel to the rod axes. The EFC plot of the three bands with TE polarization states are presented in Fig 2. The flat part of the EFC which is perpendicular to the Γ−M direction, shows that the self-collimation phenomenon occur along this direction, if a TE polarized beam propagates in the PhC at a frequency of a/λ=0.2872, where *a* is lattice constant and *λ* indicates incident light wavelength. Thus we choose dash green line in figure 2 to indicate this frequency, as the working frequency. We have limitation on working frequency range in self-collimation region. It is also difficult to obtain a large flat dispersion contour by a high symmetrical PhC. Some structures with less symmetric lattice geometries have been proposed in order to improve the performance of self-collimation. For broadening and tuning this band width range, it is possible to control or change the rods size during fabrication but the complicated technological process is necessary. In this paper, we propose a remedy to these disadvantages by adopting a technique based on the background infiltration of the PhC lattice rather than careful nanometer-scale modification of the PhC geometry.

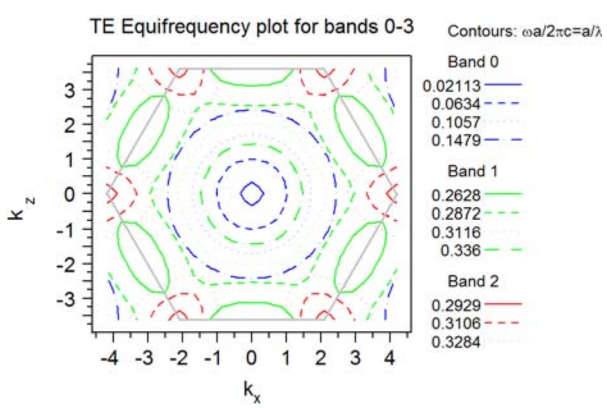


Figure 2. The EFC plot of three bands related to paper structure of a rod hexagonal PhC.

3. NUMERICAL SIMULATION OF OPTOFLUIDIC SC

3.1. Comparative analysis of self-collimation transmission for different fluids and frequencies

The simulation results, which represented in Section 2, show that the conventional rod-type PhC with the air background (no fluid infiltration) and the rod radius, r=0.35a is optimum structure. This occurs due to the lowest back-reflectance. As a result a reasonable self-collimation property is belonged to the second band. Based on this structure, we examine the bandwidth tuneability and transmission variation of lattice with fluid infiltration to optimize the device performance. To see the fluid infiltration effects, as an example for this paper the self-collimation effect with high transmission pattern is achieved by optical fluid of refractive index nf =1.6 in the PhC background with θi =0° in Fig.3. Temporal transmission diagram for TE polarization is shown by Blue and green lines as input and output of phC waveguide receptively in the lower part of the Figure.3. Obviously, with no structural defect we have complete transmission pattern for waveguiding.

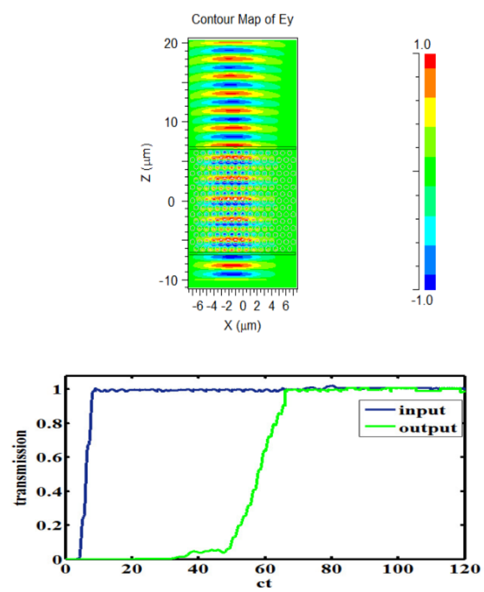


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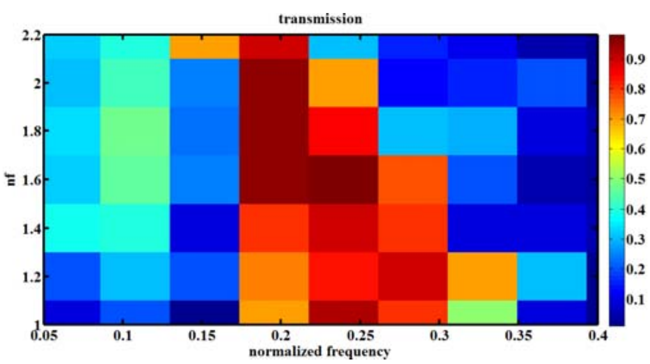
Figure 3. Self- collimation simulation for TE polarization in rod hexagonal PhC with nf =1.6. Blue and green lines are transmission amplitude at input and output of phC waveguide receptively and light coupling for incident light angle of θi =0°

Negative refraction of electromagnetic waves (EM) is a phenomenon that light rays are refracted at an interface in the reverse sense to that normally expected. Before that, it was predicted that negative refraction is characterized by simultaneous negative permittivity and permeability but recently it has been achieved in photonic crystal with positive index to make super lenses with resolution far beyond the diffraction limit [24]-[25]. Here we show the potential for generating negative refraction by using the optofluidic infiltration method. We have simulated light coupling with incident angle near θi =10°into bands, which have the desired dispersion properties. By focusing on above structure, the effect of the background fluid infiltration, on transmission for various fluids versus the normalized frequency is shown in figure 4(a). The fluid refractive indices range, nf, is chosen between 1.1 to 2.2. The figure obviously shows the second band frequency changing by nf conversion. To prove our claim one can observe the frequency variation which is shown by straight dashed green lines in EFCs plot; according to selective fluid infiltration Figure 4 (b) and (c) show the EFC plot as a sample for two arbitrary point, nf=1.4 and 1.6. The dashed green lines in EFC specifies the best SC normalized frequency which is a/λ=.258 and a/λ=.234 for nf =1.4 and 1.6 respectively. It can be seen that when the fluid refractive index increases, the normalized frequency associated to counter map decreases. But the basic point is here, we achieved both high transmission values (nearly 1) and large broadband width by injecting fluid refractive Index from 1.3 to 1.9. Thus in the related frequencies range, the structure can be used as virtual waveguide with no channel and without introducing dielectric waveguide or line defects. Consequently the beams of light can transport without scattering and broadening for TE polarization. And it also makes the effect of fluid on transmission values and tunability of PhC undeniable.



(a)

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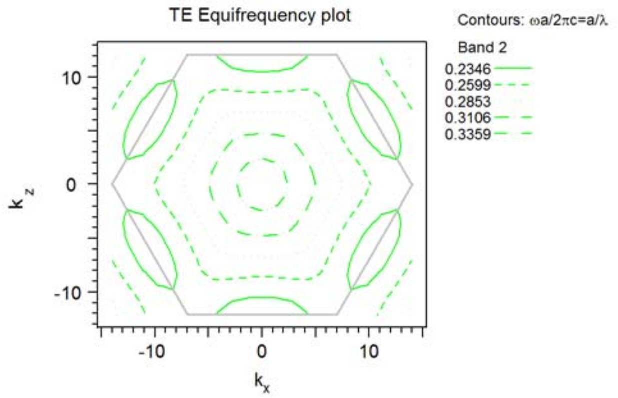

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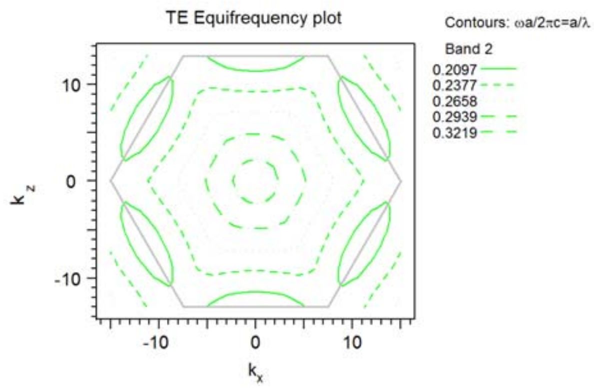

(c)

Figure 4. (a)Transmission color map for varying Normalized frequency a/λ and fluid refractive indices (nf) in incident angle θi =10°.EFCs plot: (b) nf=1.4 (c) nf =1.6.

3.2. Comparative analysis of self collimation and negative refraction transmission related to PhC background infiltration (*nf*) versus different incident angles

When a plane wave is incident to the PhC structure with period *a*, the number of propagation modes depend on both, normalized frequency (a/λ) and incident angle. In the previous section we showed that the SC effect for only a single angle θi =10° related to negative refraction. However, as it mentioned earlier, by fluid infiltration of the structure, the normalized frequency will be changed. In this case we developed the method for different angles and fluids. However it must be noted that the optimum SC frequency for the best transmission varied by different values of nf but in each situation the EFC plot helped us to find the related frequency value. All the simulation result illustrated in Figure 6, in which *x* axis is used for different incident angles from θi =0° to θi =50° and *y* axis refers to selective fluids. As it can be seen, simply by changing the background refractive index of fluid from 1.3 to 1.7 the complete transmission for incident angles between θi =0°to θi =50° is achieved. The numerical results presented here, so far, show that the approach based on the selective optofluidic infiltration method is very robust, and the problem with fabrication inaccuracies can be compensated by using a different fluid index. As a result beside system tenability, many of the properties that occur for lower refractive index contrast cause a larger range of materials become available for fabrication. Furthermore In figure 5 in which the incident angle increases and yet the transmission value is high (angles nearly between 10° to 30°) we have negative refraction phenomenon in normal structure with no negative index martial, which is suitable for perfect super lens. These effects lead us to realization integrated circuits. But for *θi* more than 30°, most of the coupled light, is reflected back. As a result the reasonable collimation regime in PhC is accessible by reconfigurable technique of infiltration for angles less than θi =25°. Figure 6 depicted transmission pattern related to nf =1.5 for two arbitrary angles caucusing negative refraction. In this manner in spite of beam angle enhancement, light coupling and guiding in the lattice have a convinced performance, without any dispersion or broadening in beam profile. Also it is apparent from Figure 6 that bending value of the output beam intensively depends on incident light angle. This relaxes the limitation on PhCs fabrication as compared to previous structural method such as waveguides defects or rods movement.

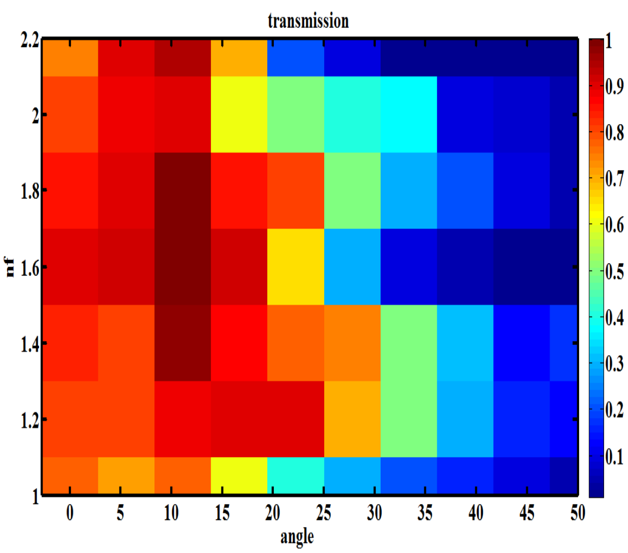

Figure 5. Transmittance contour plots for varying incident angles (*θi*) and fluid refractive indices (*nf*)

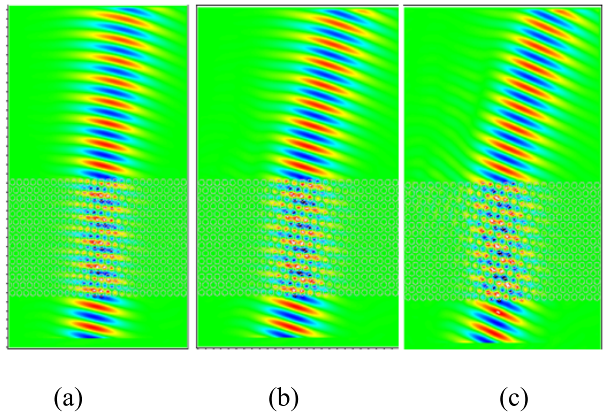

Figure 7. Negative refraction transmission pattern for different angles by selective infiltrated fluid with nf =1.5and normalized frequencies, f=.24a/λ: (a) θi =10°; (b) θi =15°; (c) θi =20°;

CONCLUSION

In this paper, the effect of new technique based on selective background liquid infiltration on novel self-collimation phenomenon of 2D rod hexagonal lattice is discussed. The proposed structure, acts as virtual waveguide with no defect that can propagate light with no serious diffraction or broadening. The simulation result shows, by controlling refractive index of the fluids into the background of rod-type planar PhC it allows to create a refractive index difference, which can lead us to make reconfigurable PhC self-collimation device with high transmission. For instance, the high transmission (nearly equal to 1) can be achieved by infiltration fluid with refractive index from 1.4 to 1.6. The results also show that the EFC and SC frequency is affected notably by changing of the background refractive index of infiltrated fluids .In addition to SC waveguides, for particular incident angles, the structure exhibit negative refraction over long propagation length without any dispersion or broadening in beam pattern with high transmission. This optimization approach, the infiltration-based approach, offers an additional and free parameter (which is independent on the fabrication) for achieving a desired SC and negative refraction effect in the PhC of integrated optical circuits.

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