Self-collimation and subwavelength imaging in two-dimensional photonic crystal

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Self-collimation and near-field subwavelength imaging in 2D air-cylinder photonic crystals are dicussed by finited-difference time-domain (FDTD) method. The investigation shows using the equal-frequency surface, self-collimation frequency range can be confirmed and self-collimation phenomenon of point source along different axis is simulated. It is also able to reproduce the details of subwavelength in the image plane by virtue of self-collimation rather than negative refraction. The resolution of 0.416 λ is obtained for single pointed source and decrease as the light gradually away from near field.

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1. Introduction

Photonic crystal(PC), which can control and manipulate the spread of electromagnetic waves, is an artificial dielectric structure and depending its complex and wonderful band-gap feature, we know Super Prism, Negative Refraction, Self-Collimation and so on[1-5]. Assuming Gaussian beam emits to PC, self-collimation effect means that the original divergent beam in space turns into a parallel light, divergent angle is suppressed in PC. Chgrin [6] dicussed self-collimation in a square grid structure of 2DPC arranged by dielectric cylinders, then Chen and his co-workers [7] proposed deflection of 90 degrees for self-collimated beam in PC. The seminal works of Lin[8] show that the high quality of near-field lensing can be achieved taking advantage of self collimation and scattered radiation effects of PC. First experiment was carried out to explore and paragraph progress has been made by Belov[9] at microwave frequencies.

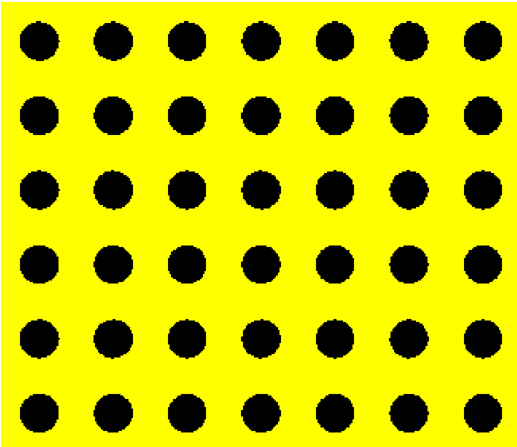
In this paper, we will present self-collimation phenomenon of a point source in 2D air-cylinder photonic crystals and study diferent splitting beam by changing the position of point source and cutting 2DPC.

Then we make an analysis of self-collimation imaging of 2DPC which Almost all spatial spectral component of light source are changed into spreading eigen-modes with the same group velocity in specific PC and these spread modes can well pass near-field electromagnetic information of optical object from the front surface of PC to the back-end and to reproduce the field distribution within the rear near-field of PC.

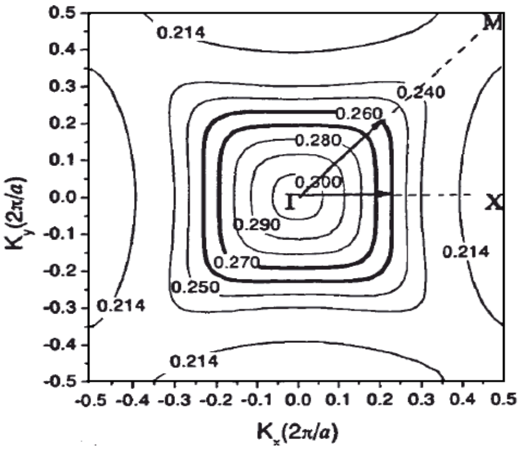
We come to a conclusion that imaging of a single point source can break well-known scattering limit and achieve super resolution but one important constraint is that point source or optical object must be in the very near field of the front surface for PC.

2. Self-collimation

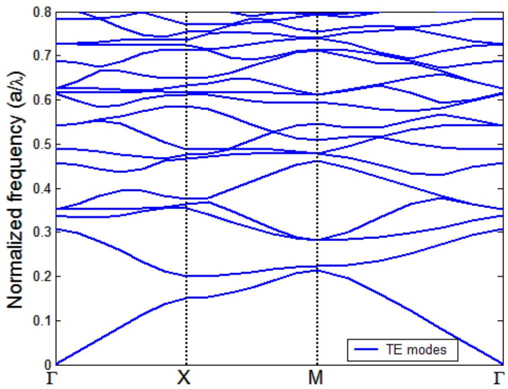
As seen in Fig. 1 (a), we consider a 2DPC compose of square lattice of cylindric air holes in silicon layer with *n*= 3.5, where the radius of the air holes is 0.26*a* (*a* is lattice constant). The propagation behavior of TE mode that magnetic field parallel to the axis of air holes is studied in this paper, thus we can get equal frequency contours(EFCs) for second band(Fig.1(b)) in the wave-vector space and photonic band gap of 2D air-cylinder photonic crystals(Fig.1(c)) relative to TE mode by plane wave expansion method .



(a)



(b)



(c)

Fig. 1. (a) Square lattice of cylindric air holes of 2DPC (b) Equal frequency contours for the second band of TE mode in the wave-vector space (c) Normalized photonic band gap of 2D air-cylinder photonic crystal

According to classical Maxwell electromagnetic theory, it is inferred that the direction of light energy propagation determined by $V_g = \nabla_k \omega_k$ perpendicular to the EFCs. Thus it can be seen from Fig.1(b) that near square will be shaped when frequency range between 0.260*c/a* and 0.270*c/a* which means light beam can spread toword ΓX or XM without spatial divergence result from owning the same group velocity, namely self-collimation effect. In order to simulate self-collimation phenomenon, when lattice constant *a* is 100nm; frequency of incident light (point source) is 0.261*c/a* (λ=3.83*a*) and point source is placed at 0.5*a* from the front of 2DPC, self-collimation phenomenon of a point source occurs in 2DPC by FDTD method where it should be noted that its background is air and the dimension of 2D air-cylinder photonic crystal is 31*a*x31*a*, at the same time, the FDTD size is 50*a*x50*a* with PML boundary.

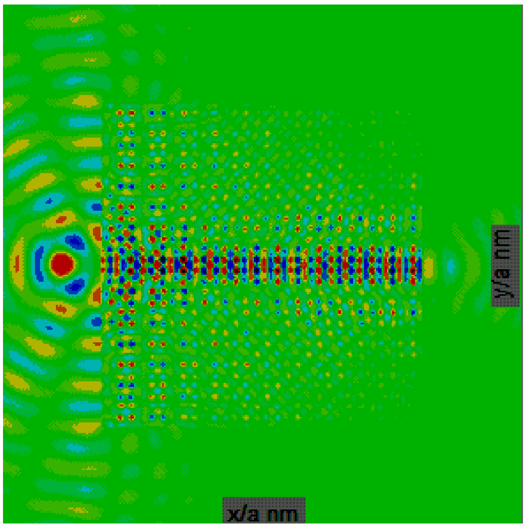


Fig.2 Transient field(H_z) distribution of a single point source in 2DPC

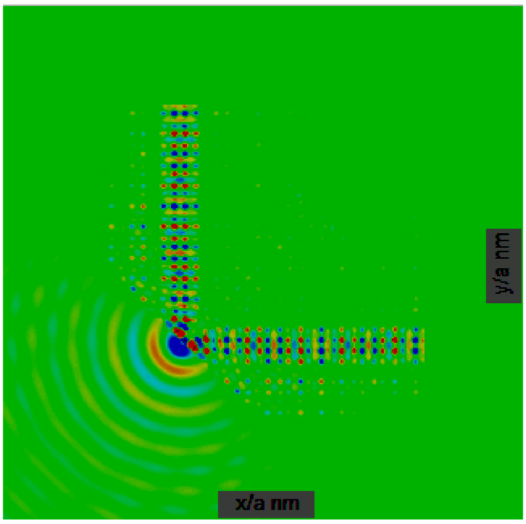


Fig. 3. Magnitic field distribution of splitted beam

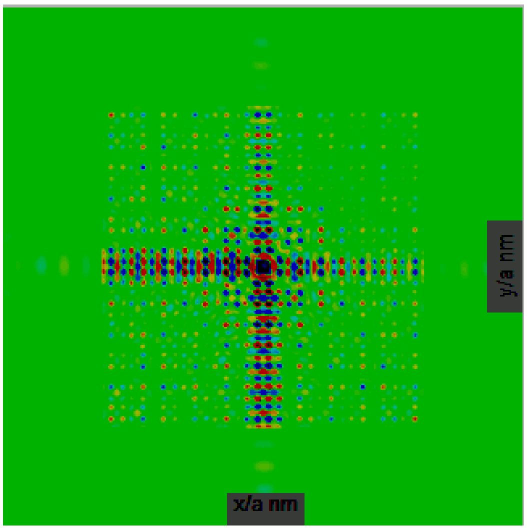
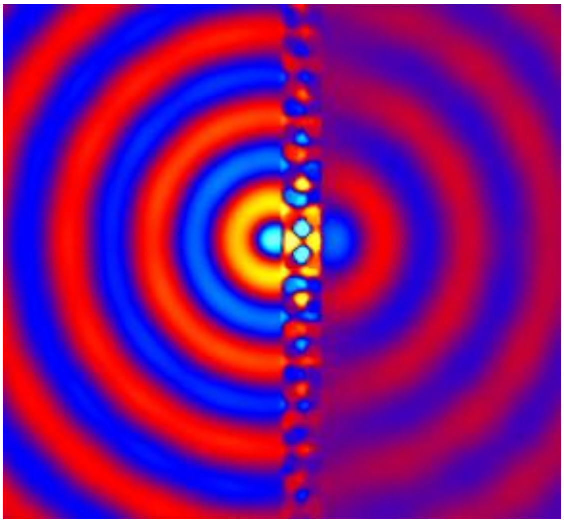


Fig. 4. Four splitted beam for central point resource.

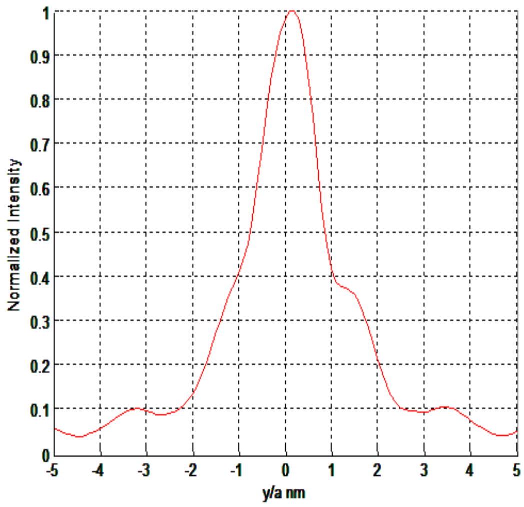
As the fig.2 shown, it is clear that one straight beam spread along x axis because half light of point source is restricted by direction XM of EFCs and collimated in PC, which of great significance that light pulse can be independent of time and space and propagate along a line without distortion in the waveguide. In fact , we may use the collimation character of XM and ΓX at the same time. If the lower left corner of original PC described by fig.2 is cuted and point source is placed at midpoint of cut line which means that a half of PC light (quarter point source light) is restricted by direction XM of EFCs but the other half PC light or quarter point source light is restricted by direction ΓX of EFCs .Thus it can be seen from fig.3 that light of point source in PC is collimated into two beam that perpendicular to each other. At the moment, 2DPC with square lattice of cylindric air holes become beam splitter. Due that EFCs for second band of 2D air-cylinder PC is square, when small center area of PC hollowed out and point resouce replaced, four beams are formed in fig.4.

3.Subwavelength Imaging

Unlike Luo and his colleagues[10] proposed negative refraction imaging, in fact, self-collimation imaging is that all spread modes and some evanescent components is forcibly converted into collimated transmission mode in PC. Thus it is able to reproduce subwavelength details of optical object in the image plane. Now, we still use FDTD method to simulate self-collimation imaging of 2D air-cylinder photonic crystal and a series of parameters will be adopted which λ is still 3.83*a*; the thickness of PC in x axis direction is 2*a* equal to 0.52λ, the length in y axis direction is 31*a* and the position of centrosymmetric point for 2DPC is (1.5*a* , 0); the coordinate of the point source is (0,0) that is 0.5*a* from the front surface of PC and means it belongs in near-field; the FDTD calculated areasize is also 50*a*x50*a* with PML boundary.



(a)



(b)

Fig.5(a) partial zoom of self-collimation imaging (b) The dependence of normalized light intensity at 0.5a from the back-end surface with y axis

It can be seen from Fig.5 that a point image is formed in the back surface of 2DPC. Point image will have better image quality and ultra-high resolution at 0.5*a* from the back-end surface, the FWHM of light intensity is 1.6*a* (0.416λ) achieving subwavelength imaging resolution. In fact, object distance can damage imaging resolution.

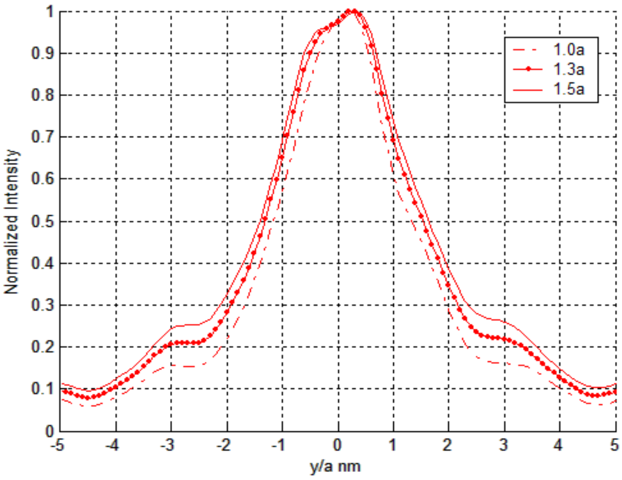


Fig. 6. The dependence of normalized light intensity at 0.5a from the back-end surface with the position of a single point source (1a , 2a , 3a)

When object distance that less than one wavelength is adopted from *a* , 1.3*a* , 1.5*a* and point image is viewed at 0.5*a* from the back-end surface of PC ; as fig.6 shown, secondary peaks are growing and closing to the top peak then integrate into it. due to secondary peaks couple and resonate with top peak, series of peaks occur and replace original sharp top peak which FWHM of light intensity is growing dramatically and breakthrough above one wavelength that means an area of the bright spot gradually expand in the back of PC and the point image is fading for high secondary peaks. Thus one important condition of self-collimation imaging is that light source must be stay at very near-field. We aslo find when point light changes, the image distance remains unchanged and always stay near the back surface of 2DPC .

4. Conclusions

Self collimation is the basis for the future of integrated photonic path and subwavelength imaging, having more and more attention. Based on this demand, we analyzed self collimation of point source for all direction in the second Brillouin zone and self collimation imaging in 2DPC with square lattice of cylindric air holes. By FDTD method, it shows that finite periodic structure can also reflect features of infinite periodic structure. using self-collimation, 2D air-cylinder PC can achieve self-collimation subwavelength imaging, but requires that light is close to PC as much as possible. the location of the point is always limited to near-field range the opposite side of light source. What's more, dielectric absorption and dispersion issues are not mentioned here, they are our future study.

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