Self collimation in square lattice two dimensional photonic crystals with dielectric ring

QUAN XU*, KANG XIE, HUAJUN YANG[a], ZHIBO LI[a]
College of Optoelectronic Information, University of Electronic Science and Technology of China, Sichuan Province, 610054, China
[a]*College of Physical Electronics, University of Electronic Science and Technology of China, Sichuan Province, 610054, China*

The self collimation phenomena based on a new type of photonic crystals made of square lattice with dielectric ring is demonstrated. The plane wave expansion (PWE) method is used to get the three dimensional band diagram and equi-frequency of the second band which displays the self collimation phenomena for the structure we proposed in this paper. The collimation angle is mainly depending on the maximum flatness half width (MFHW) of the equi-frequency. Latterly, we investigated the relation of the MFHW, radius R and the width r for TM modes (only TM mode is referred in this paper) with the ring shaped holes structure. By further investigation, we know that with every r, the MFHW would get a maximum value for different R. Lastly, the FDTD method is employed to demonstrate the electric field amplitude distributions for the collimation phenomena. Partly, in order to achieve high efficient coupling of the input and output port, we modify both surface structures to modulate the wave-front to obtain desired effect. The parameter of the input surface is modified which will prevent the production of surface modes which takes away the EM power and enhance the transmittance. For a square lattice with the modified parameters at each side of the input surface, the surface modes are suppressed to couple with the continuum of the air modes. The parameters are $R' = 0.384R$ and $r' = 0.384r$ in the modified zone at the input and output. These self collimation based devices can be used to enhance the light coupling efficiency, narrow the beam divergence of micro-cavity laser over a large frequency range. More importantly, they might have potential application in integrated optical circuits.

(Received April 14, 2010; accepted after revision November 10, 2010)

*Keywords: (*9999.9999) Photonic crystals, (250.5300) Photonic integrated circuits, (130.3120) Integrated optics devices

1. Introduction

Photonic crystals (PCs) have very different dispersion properties compared to conventional dielectric due to their periodic boundaries. Since last decade, photonic crystals (PCs) have been paid a great deal of attention due to their unique properties in photonic crystal integrated circuits [1-4].Particularly, great efforts have been put into the development of self collimation [3,4]. Self collimation have enabled exiting new ways to control light and construct integrated optical devices is a linear effect [5], totally independent of the light intensity. Unlike spatial solitons, there is no beam focusing (diffraction compensation) due to nonlinearities. Instead, PCs can be designed to have dispersion properties that allow incident waves to naturally collimation in certain directions and propagation [6]. The most commonly used PCs lattice for collimation is square lattice of circular holes or dielectric rods. However, such patterns offer only two parameters: the radius of the holes and the dielectric background. For fine tuning of the dispersion properties and maximum flatness half width (MFHW), we study collimation based on a PCs with ring-shaped dielectric [7-10]. This structure offer us one extra parameter (the ring width) to engineering the collimate properties.

2. Description of the structure and theory

A square lattice of dielectric rings in 2D PCs is considered, in which the dielectric constant of the background is $\varepsilon_r = 11.56$ (e.g. in InGaAsP-InP at a wavelength of $1.55\mu m$) and the parameters are shown in Fig. 1, where a is the lattice constant of the PCs. The principle for TE and TM modes are analogous, so only TM polarization (magnetic field parallel to the axis of the cylinders) is studied in this paper.

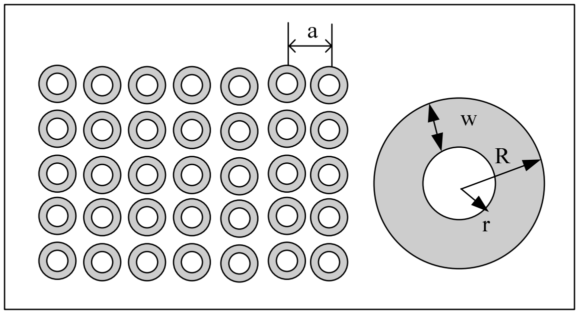


Fig. 1. Schematic of a photonic crystal with dielectric rings. R is the radius of air holes, r is the filling dielectric and w is the ring width.

First the computation used in this paper is introduced firstly. The plane wave expansion (PWE) method is used to get the band diagram and equi-frequency contours for the structure we proposed. In this paper, we only need to change the $f(G)$ in the literature of PWE method.

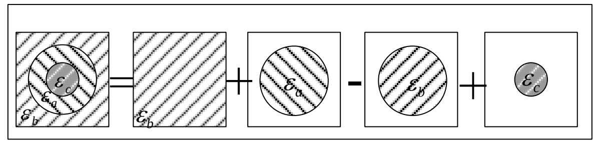


Fig. 2. Schematic illustration of the unit cell construction for the 2D square lattice of the structure.

Summarizing, we have,

$$f(G)=\begin{cases} \dfrac{1}{\varepsilon_b}+SR*(\dfrac{1}{\varepsilon_a}-\dfrac{1}{\varepsilon_b})+Sr*\dfrac{1}{\varepsilon_c} & G=0 \\ 2*SR*(\dfrac{1}{\varepsilon_a}-\dfrac{1}{\varepsilon_b})*\dfrac{J_1(GR)}{GR}+2*SR*\dfrac{1}{\varepsilon_c}*\dfrac{J_1(Gr)}{Gr} & G\neq 0 \end{cases} \quad (1)$$

Where $SR=\pi R^2/Au$, $Sr=\pi r^2/Au$, and Au is the area of the unit cell.

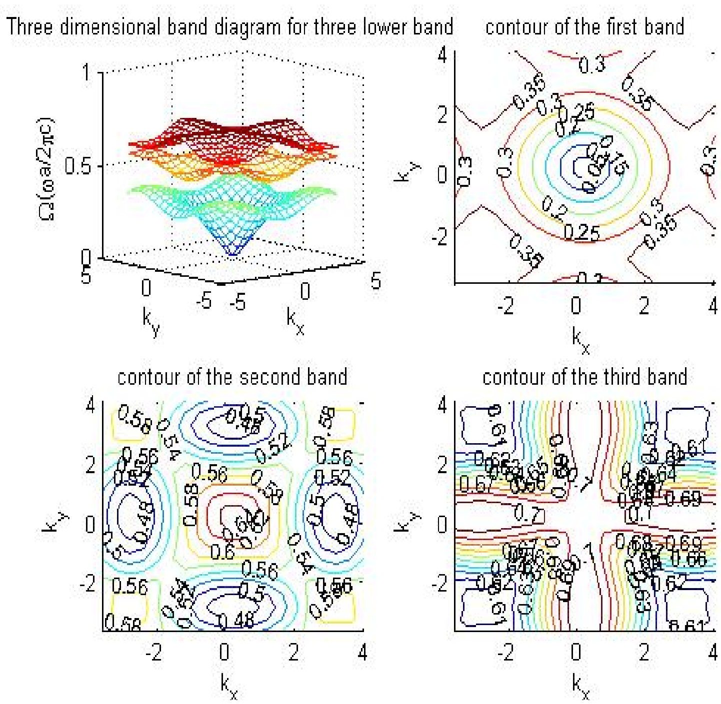


Fig. 3. (a) Dispersion diagram for TM three lower bands for the structure shown in Fig. 1 with $R=0.2a, r=0.1a, w=0.1a$. (b) Equi-frequency contours for the first band diagram. (c) Equi-frequency contours for the second band diagram. (d) Equi-frequency contours for the third band diagram.

Fig. 3 (a) shows the dispersion diagram for TM modes three lower bands for the structure shown in Fig. 1. (b), (c), (d) show the equi-frequency contours for them. We can clear know that for the structure we proposed, the collimation propagation behavior appear in the second band diagram. Next, we mainly investigate the properties of the second band diagram which would be useful for us to design collimator.

Compared to the circular contour of isotropic materials, square like shapes are observed for the second band diagram contour. The flat contour can be used to laterally confine the light. The fact, for a range of incident wave-vectors, the propagation will be normal to the equi-frequency contour, since the energy of the modes will propagate with a group velocity given by

$$\bar{v}_g = \nabla_{\bar{k}}\omega(\bar{k}) \tag{2}$$

This effect will be observed for incident angles smaller than α :

$$\alpha \le \sin^{-1}(k_L a / 2\pi\Omega) \tag{3}$$

Where k_L is MFHW, Ω is the normalized frequency.

Any incident beam can potentially be collimated propagation. In practice, the MFHW may limit the maximum size of the beam. Also, if the dispersion surface is not exactly flat, beating patterns can appear. Next we focus on investigate the effect of R and r on the MFHW, in order to design high quality collimation structure.

3. Simulation result and discussion

From previous section, we know that if we want to get the maximum collimation angle, the MFHW would be as large as possible. This can be achieved by appropriate structure design. Next we give the relation of the MFHW, radius R and the width r for TM modes with the structure we reference before.

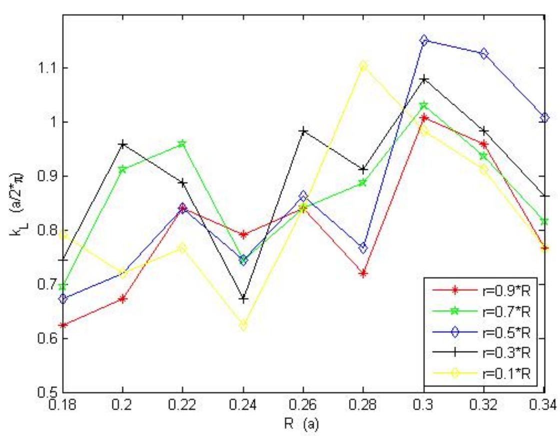


Fig. 4. The relation between the maximum flatness half width and radius R are given for TM modes with different r .

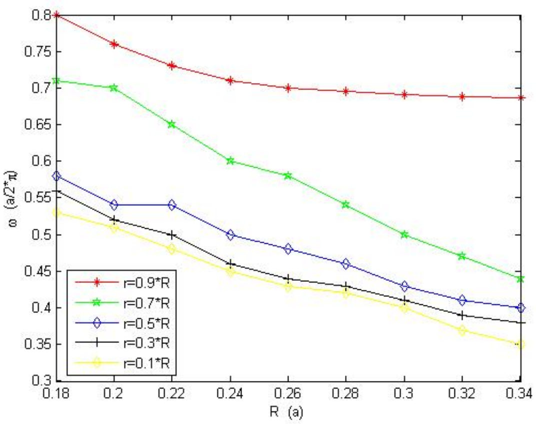


Fig. 5. The correspondence center normalized frequency of the MFHM.

By define a series of arbitrary parameters, the tendency of the MFHW with the difference radius R and r were given. From Fig. 4 we know that with every r , the MFHW would get a maximum value with different R . We would get a maximum value at $R \in (0.28a, 0.32a)$ for each r with the structure which considered in this paper. The correspondence center normalized frequency (the equi-frequency which has maximum MFHW and most flatness) is shown in Fig. 5. Those vales were gotten from the band diagram for the second by PWE method by trial and simulation experiment. By the origin with that most energy of the propagation beam is concentrated at low $|k|$ components, better self collimation modes are expected to be excited at the flat dispersion band region of the second band.

In view of the results obtained, the structures we referenced can be used for directing the design of efficient collimation, and in other application to achieve highly efficient optical transmission in integrated optics.

To quantify the efficiency of such collimation structure, we consider a PCs structure with large size of $29a \times 11a$ which is show in Fig. 6. The Gaussian waveguide source is used with the width of $2.6a$ and $L = 3a$ .Using the FDTD method with the perfectly matched layers which are absorption boundaries [11], the propagation properties of the structure are investigated quantitatively. Fig. 7 (a) displays the electric field amplitude distributions obtained for the corresponding PCs structures which we proposed before. The spatial resolution in the computational zone is set to classical value $a/20$ and the time step coefficient is given by 0.95, in order for the FDTD method to be stable. The simulation parameters are $R = 0.3a, r = 0.5R$ and normalized frequency $f = 0.43$.

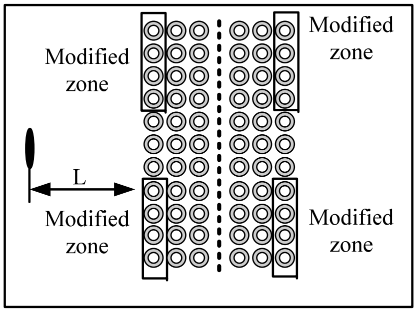
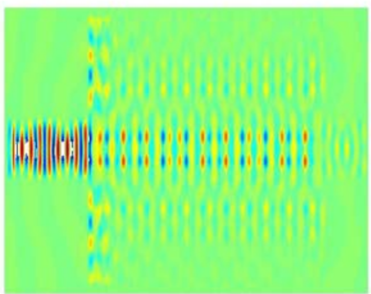
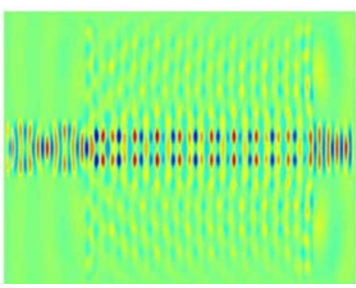


Fig. 6. The 2D PCs structure with the size of $29a \times 11a$ *which is simulated with.*



(a)



(b)

Fig. 7. The spatial distribution of the Poynting vector (a) unchanged surface; (b) the input and output surface of the PCs structure are modifies as $R' = 0.384R$ *and* $r' = 0.384r$.

4. Conclusions

In conclusion, we showed that self collimation can be achieved by dielectric ring photonic crystals with square lattice. The plane wave expansion method is used to get the band diagram and equi-frequency. The effect of R and r on the MFHW is investigated by search the three dimensional band diagram and equi-frequency. The R and r are fiercely effect on the MFHM which is used to weigh the collimation properties. Lastly, the FDTD method is employed to demonstrate the electric field amplitude distributions for the collimation phenomena. These self collimation based devices can be used to enhance the light coupling efficiency, narrow the beam divergence of micro-cavity laser over a large frequency range. More importantly, they might have potential application in integrated optical circuits.

Acknowledgements

We would like to acknowledge the financial support by NSFC (project number 60588502).

Reference

[1] E. Yablonovitch, Phys. Rev. Lett. **58**, 2059 (1987).
[2] S. John, Phys. Rev. Lett. **58**, 2486 (1987).
[3] H. Koseka, T. Kawanshima, A. Tomita, M. Notomi, T. Tamamura, T. Sato, S, Kawakami, Appl. Phys. Lett. **74**(9), 1212 (1999).
[4] L. J. Wu, M. Mazilu, T. F. Krauss, J. Lightwave Technol. **21**(2), 561 (2003).
[5] L. J. Wu, M. Mazilu, T. Karle, T. F. Krauss, IEEE J. Quantum Electron. **38**(7), 915 (2002).
[6] D. W. Prather, S. Y. Shi, D. M. Pustai, C. H. Chen, S. Venkataraman, A. Sharkawy, G. J. Schneider, J. Murakowski, Opt. Lett. **29**(1), 50 (2004).
[7] M. Mulot, A. S¨ayn¨atjoki, S. Arpiainen, H. Lipsanen J. Ahopelto, proceedings of the 3rd European Symposium on Photonic Crystals (ESPC 2005), Barcelona, Spain, 3-7 July, 2005.
[8] H. Kurt, D. S. Citrin, Opt. Express **13**, 10316 (2005).
[9] M. Mulot, A. S¨ayn¨atjoki, S. Arpiainen, H. Lipsanen, J. Ahopelto, accepted for publication in J. Opt. A: Pure and Appl. Opt.
[10] A. S¨ayn¨atjoki,M.Mulot, S. Arpiainen, J. Ahopelto, H. Lipsanen, PECS VII conference, Monterey, USA, 8-11 April, 2007.
[11] J. P. Berenger, J. Comput. Phys. **114**, 185 (1994).

*Corresponding author: xuquanwww@163.com