doi:10.3788/gzxb20124102.0154

Design of Silicon Hole Based Photonic Crystal Filter with High Selectivity

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Abstract: The band structures of triangular hole lattice photonic crystal are studied via plane wave expansion method, with radiation loss considered. The spectrum transmission characters of the designed structure are investigated through simulation of finite difference time-domain method (FDTD) for hexagonal ring resonant, and the parameters of lattice period and radius of the lattice hole are optimized. The drop efficiency rate of 98.8% and FWHM of 32.9 nm are reached through optimization of the designing in C-band. The samples are tentative fabricated through photolithography and reactive ion etching and the parameters are given. The transmission spectrum is measured and the reasons of differences from the theoretical result are analyzed. The schemes of slab based on ring resonant holes show a more stable character than the rod ones, and have potential future for filters, WDM devices and micro gyroscope.

Key words: Photonic crystal; Triangular lattice holes; Hexagonal ring resonant; Band structure; Transmission rate; Photolithography

CLCN: TN256 **Document Code**: A **Article ID**: 1004-4213(2012)02-0154-5

0 Introduction

Various optical components can now be fabricated in a small scale based on the unique features of photonic crystals (PCs) and high quality factor can be realized on PCs based resonators[1-3]. PCs based add-drop filters (ADFs) and coupled resonator optical waveguides (CROWs)[4-7] are some examples which have potential futures in photonic integrated circuits and WDM systems. Photonic crystal ring resonators (PCRRs), proposed for the first time during a research on ring laser[8], are now structures often utilized in PCs components and devices mentioned above. PCRRs are usually studied based on lattice of dielectric rods on a lower dielectric index background of material, for instance, air. However, photonic crystal slab, which is fabricated by drilling holes on the relative high dielectric material, has the advantage on the manufacturing process, and is easier to be realized by optical lithography or reactive-ion etching. This letter will discuss the band structures and the transmission characteristics of the photonic crystal ring resonator slabs based on the methods mentioned in the next session.

1 Computational method

Despite other methods, like inverse problem techniques[9], level set method [10] and swarm optimization method[11] are developed to optimize the design of PCs in recent years, two methods that are most often utilized in analyzing issues associated with photonic crystals are plane wave expansion (PWE) method[12] and the finite-difference time-domain (FDTD) method, which is often combined with the usage of perfect matched layers and now known as one of the most important method in computational electrodynamics[13]. The PWE method, which expresses the periodic structures of the PCs as a series of plane waves on the basis that the electromagnetic waves inside the periodic structure will follow the Helmholtz equation in the photonic crystals[14].

Foundation item: The National Natural Science Foundation of China (No. 50875015) and Ministerio de Ciencia e Innovación project of Spain (No. TEC2010-19511)

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Received date: 2011-08-25 **Revised date**: 2011-10-18

2 Structures: design and optimization

In our previous research of PCs mirrors[15], we designed the PCs based on structures of dielectric rods, which were more often used in theoretical studies, partly because that kind of lattice could have a better single mode characteristic. The forests of rods have relative wide band gaps for TE modes (sometimes differs from the definition of TE and TM modes). During our process of fabrication however, the rods are more difficult and time consuming to fabricate than drilling holes on a slab and are more fragile and easy to break, thus made the structure useless. Fig. 1 illustrates one example that the dielectric rods that break in the process of the optical lithography during our previous research.

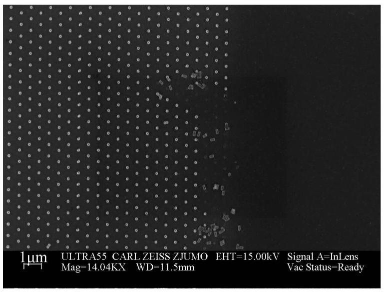
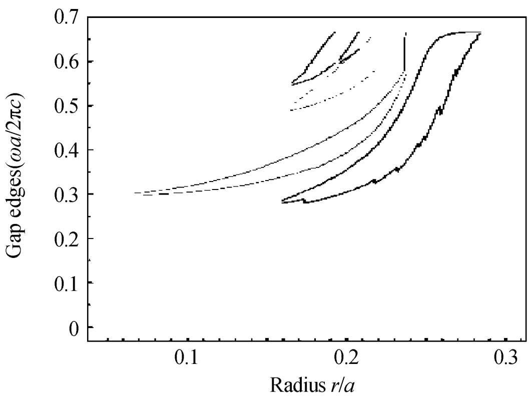


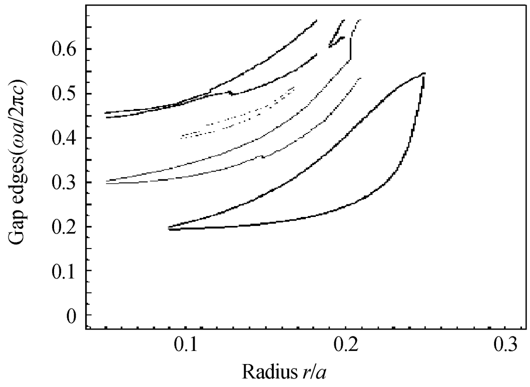
Fig. 1 The dielectric rods of photonic crystals which are partly break during fabrication process

2.1 Band gaps and ring resonant size

We design the new structure on a photonic crystal slab by drilling air holes on a dielectric material that has a refractive index of 3.48, which is the index of silicon. And the lattice type is triangular, which has a relative larger band gap than square lattice. Then the band edge frequency curves of ($\omega a/2\pi c$) are calculated via PWE method with the radius as a variation, thus we have the band edges and the band gap structures for both TE and TM modes.



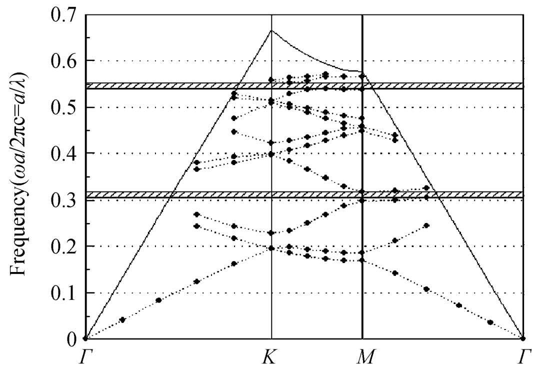
(a) TE



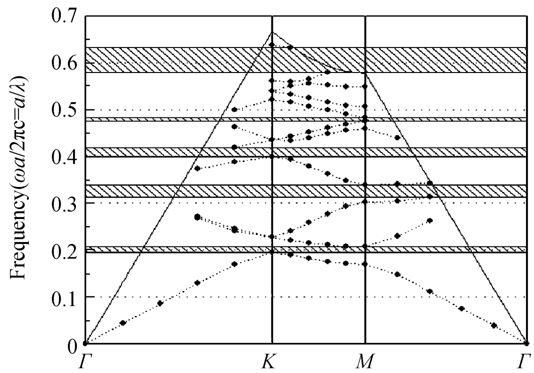
(b) TM

Fig. 2 The band edges of TE and TM modes with the radius of the lattice hole as a variation

Define the gap-mid gap ratio as $\frac{\Delta\omega}{\omega_m}=\frac{\Delta\varepsilon}{\varepsilon}\cdot\frac{\sin(\pi d/a)}{\pi}$, where ω_m is the frequency at the middle of the gap. We could conclude from the figure above that the TM mode will have a relative wider band gap when the radius of the hole is around $0.2a$, where a is the period of the lattice, whereas the TE mode, although there exit some band gaps for this mode, are not as wide as ones for TM mode. Next we calculate the band structures of the triangular lattice of the photonic crystal slabs with $0.2a$ as the radius of the holes and the following results are derived.



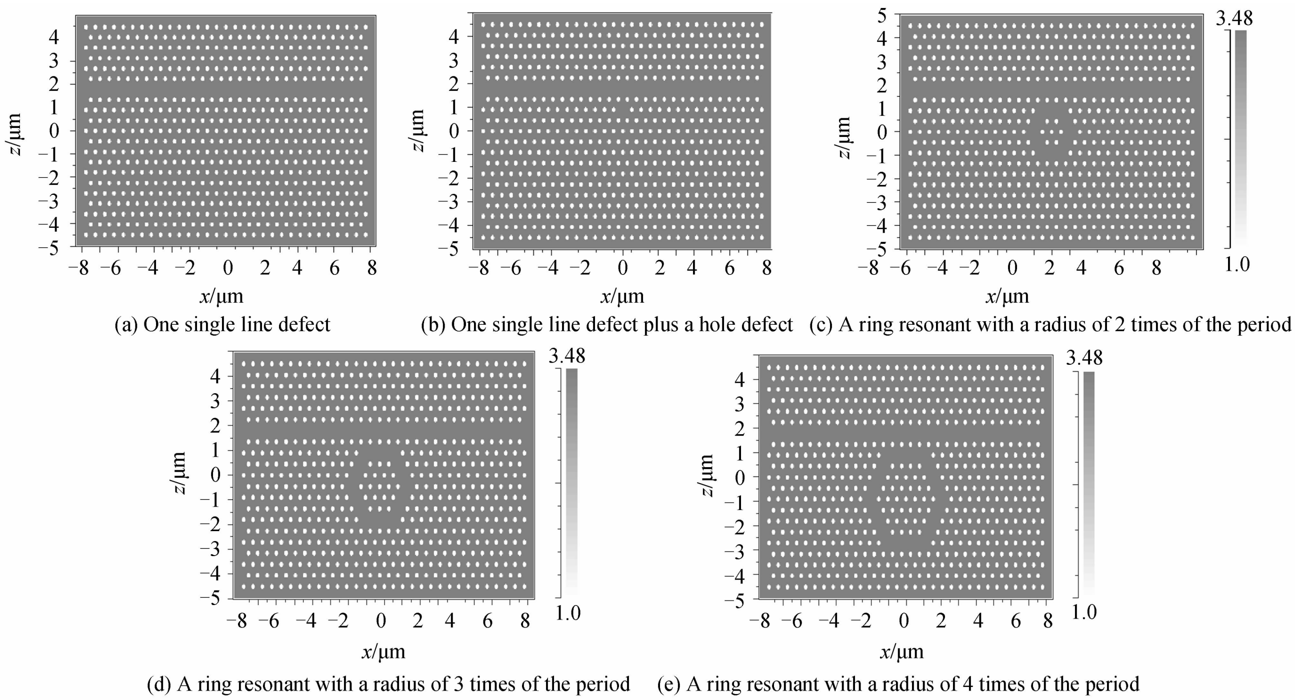
(a) TE



(b) TM

Fig. 3 TE and TM band structures of the triangular PC slabs with $0.2a$ as the radius of the hole

The band structures above are calculated with light line concerned, although many papers did not take this point into consideration, the fact is that only the corresponding band structures that below the light line could propagate inside the PC slabs. If not, the wave will radiate and exponential decay outside the slab and therefore should not be added to the final band gaps. It could be noticed that there are overlaps between the first gap region of the TE mode, which is $0.3050<a/\lambda<0.3183$, and the second gap region of the TM mode, which is $0.3127<a/\lambda<0.3394$. We choose $\lambda=1\ 550$ nm, which correspond to C band and some other light sources that often used in our research and the corresponding period would be $484.7\ \text{nm}<a<526.1\ \text{nm}$. And then make the adjustment of the parameters through FDTD simulation. The light source is TM mode and the detectors are put inside the line defect for theoretical calculation convenience. The simulation is under five schemes: one with a single line defect but has no ring resonant, one with a single hole defect, the other three with a ring resonant defect and the radius of the ring resonant are 2, 3, 4 times of the lattice period, respective(Fig. 4).



(a) One single line defect (b) One single line defect plus a hole defect (c) A ring resonant with a radius of 2 times of the period (d) A ring resonant with a radius of 3 times of the period (e) A ring resonant with a radius of 4 times of the period

Fig. 4 The index profile of the PC slabs

2.2 FDTD simulation and resonant spectrum

The slab is made of a 31 by 21 array and the one dimensional scanning FDTD computer program would change the lattice period from less than half of a micro to about two micros. Meanwhile, the radius of the lattice hole is kept as 0.2 times of the lattice period unchanged. Calculate the transmission characteristics using FDTD method, and drawing the curves of the transmission rate varying with the period of the slab lattice. Given the fabrication limitation, the step of the period changing is set to be 10 nm, ranging from less than 500 nm to over 2 000 nm. After the scanning program calculation, the transmission curves could be drawn as Fig. 5.

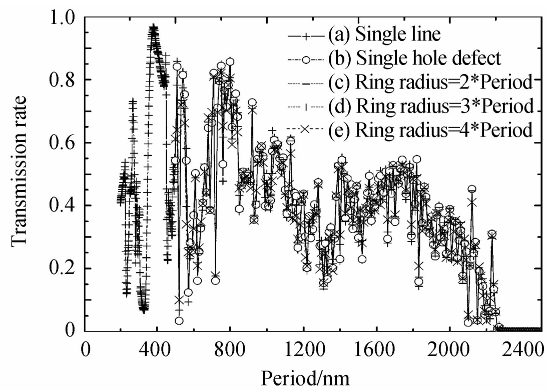


Fig. 5 Transmission rate with the change of the lattice period of photonics crystal slabs in Fig. 4

It is noticed that in most areas the transmission rate for different structures equal with others , but have differences around some specific wavelength because of the influence of the ring size. A minimum transmission rate, which also means a maximum drop efficiency is reached at around 520 nm, that lies within the range from 484.7 nm to 526.1 nm, and the drop efficiency at this wavelength for different ring size are shown in Table 1.

Table 1　The type of the slab defects and their drop efficiency when lattice period is 520 nm

Photonic crystal slab type	Drop efficiency
(a) single line defect	96.6%
(b) single hole defect	96.6%
(c) ring resonant with a radius of 2 * period	93.2%
(d) ring resonant with a radius of 3 * period	91.8%
(e) ring resonant with a radius of 4 * period	89.4%

To obtain higher drop efficiency, we choose the slab with a single hole defect to continue the FDTD simulation. We fix the period as 520 nm but change the wavelength of the light source around 1 550 nm. For faster and more accurate calculation, interval is divided unevenly: from 1 545 nm to 1 570 nm the wavelength step is set to be 0.1 nm, whereas from 1 500 nm to 1 545 nm and from 1 570 nm to 1 600 nm the step is 0.4 nm, and the step is 1.0 nm if the wavelength is shorter than 1 500 nm or longer than 1 600 nm. Through another one dimensional scanning computer program, a transmission rate of 1.22% is reached when wavelength is 1 557.8 nm, corresponding to drop efficiency as high as 98.8%. FWHM of the structure is about 32.9 nm for wavelength around 1 550 nm in C-band.

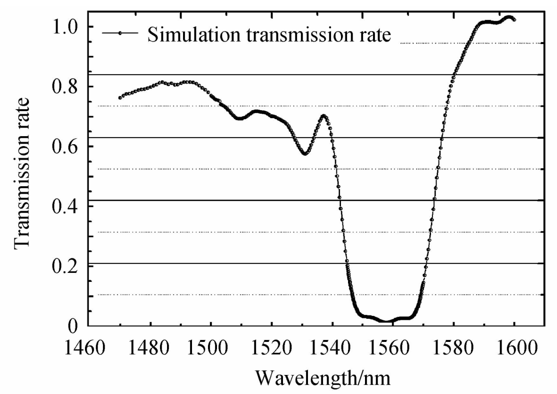


Fig. 6　Transmission rate changes with the wavelength for the single hole PC slab. 98.8% drop efficiency is achieved

3　Experimental approach & discussion

After the optimization of the parameters and structure designing, we fabricate the sample using photolithography and the reactive ion etching process. During reactive ion etching, the gas is CF_4 and power is 210 W with 500 V as DC bias. From the scanning electron microscope pictures, the sample based on slab holes are much more stable than the previous rod forests we made, which are easily to be broken. However, due to the fabrication limitation, a deviation of about 10 nm still exits on the lattice period, which if made perfectly, should be 520 nm. The scanning electron microscope pictures of the sample are given in Fig. 7.

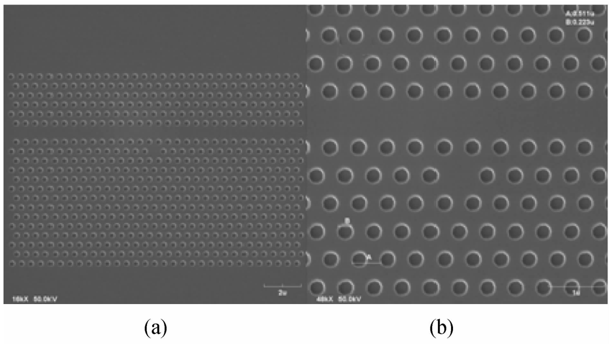


Fig. 7　SEM pictures of the fabricated PCs resonant samples

The sample is tested through a self-building system with the KOHERAS as the light source, Newport M-562 and Zolix APFP-FH as the adjusting platform and Agilent 86142B spectrometry to measure the output at the end.

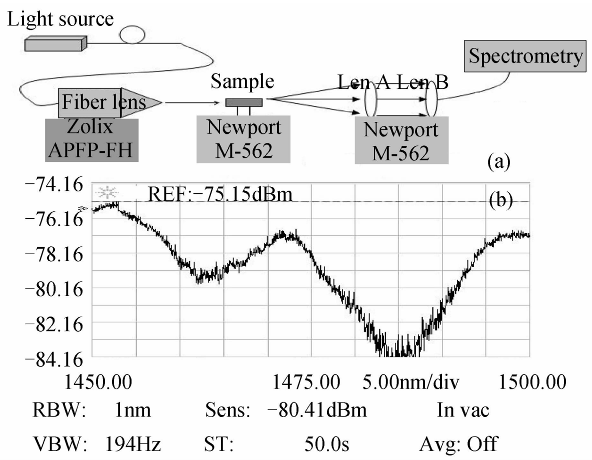


Fig. 8　(a) The measuring platform scheme and (b) the tested transmission spectrum of the sample

A minimum transmission rate could be found at around 1 477 nm, which is about 80 nm less than the theoretical result. The minimum value differs from maximum about −10 dB, which corresponds to 90% of selectivity. One main reason is that the simulation could use an ideal single wavelength light source whereas in practice, the source has a wide spectrum ranging from 500 nm to 1 750 nm with different amplitude. Another issue that should take into consideration is that there will be fabrication tolerances about 10 nm, and the limited depth of holes, which in simulation should be infinite. Moreover, the coupling between fiber, lens and slab waveguide will also have some energy loss and thus have different result from the previous simulation.

4 Conclusion

The band gaps of photonic crystal are calculated for TE and TM mode. The transmission spectrum of for ring resonant based on slab holes with different resonant size are simulated via FDTD method, achieving a drop efficiency of 98.8% and FWHM of 32.9 nm. Photolithography and reactive ion etching are used to fabricate the sample with a tolerance of 10 nm. The spectrum characteristic is measured and the issues that caused the differences with the theoretical results are given. The photonic crystal rings resonant has potential in applications of filters, WDM devices, gyroscopes etc.

Acknowledgement: *Thank Carlos Angulo Barrios and Fernando Calle Gómez for the advice on the structural designing. Thank David López-Romero Moraleda for the work on lithography and RIE process.*

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硅基孔状光子晶体高选择性滤波器设计

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摘 要:通过平面波展开法研究了三角孔状光子晶体晶格的能带结构,并考虑了该过程的辐射损耗.用时域有限差分的方法模拟计算了对应六边形环行腔结构的光谱透射特性,得出优化的晶格周期和占空比.在C波段上,优化的结构达到了98.8%的光学选择比和32.9 nm的半高全宽.用光刻和反应离子刻蚀的方法对样片的加工过程进行了尝试并给出加工参量.搭建相应的系统测试了样片的光谱性能,结果表明:实际样片孔状的样片较之柱状样片更为稳定,而基于环行谐振腔的结构在未来有应用于滤波器、波分复用系统、微陀螺等领域.

关键词:光子晶体;孔状三角晶格;六边形环行腔;能带结构;透过率;光刻