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Folded Mach-Zehnder Interferometer in a Hole-type Silicon Photonic Crystal*

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Abstract: A folded Mach-Zehnder interferometer in a hole-type silicon photonic crystal is proposed, which consists of one splitter and several mirrors. Light propagates between them employing self-collimation effect. Its performance is investigated based on finite-difference time-domain simulation technique. The two complementary transmission spectra at two output ports are both in the shape of sinusoidal curves in the frequency range from 0.255c/a to 0.270c/a. The peak spacing becomes smaller when the length difference between the two interfering branches is increased. This folded Mach-Zehnder interferometer with compact structure is much smaller than non-folded interference-type filters in photonic crystals. It may work as a wavelength division demultiplexer in high-density photonic integrated circuits.

Key words: Photonic crystal; Self-collimation; Mach-Zehnder interferometer

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0 Introduction

Photonic crystals (PhCs) are capable of constructing various dispersion relations[1-2]. One of interesting phenomena found in photonic crystals is self-collimation effect[3-4]. An equal frequency contour (EFC) is a cross section of a dispersion surface which characterizes all allowed wave vectors corresponding to the same frequency. For some frequencies, the EFCs take shape similar to square and thus have flat dispersion borders. With these frequencies and in the direction perpendicular to the flat dispersion borders of the EFCs, a narrow-width light beam can propagate without broadening in the photonic crystal, which is called self-collimation (SC) effect. This behavior has been utilized to efficiently guide electromagnetic waves within PhC slabs without the use of any structural waveguide[5-14]. Compared to its alternatives, namely dielectric waveguides and PhC line-defect waveguides, this type of waveguides does not need physical boundaries to confine light. So it releases the strict alignment requirements imposed by the coupling efficiency in the case of dielectric or PhC line-defect waveguides. Moreover, self-collimation light paths can intercross each other without any crosstalk, which is very important for high-density photonic integrated circuits (PICs) to achieve arbitrary routing. In this paper we demonstrated a folded Mach-Zehnder interferometer based on PhC self-collimation effect.

1 Design and calculations

1.1 Self-collimation frequency range in a photonic crystal

As shown in Fig. 1 inset , the perfect two-

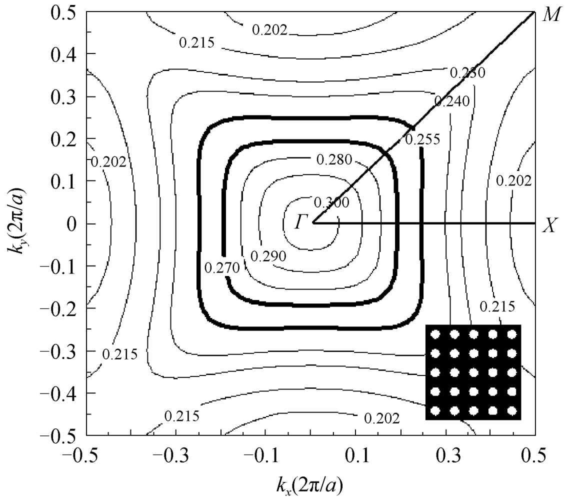

Fig. 1 Equal frequency contours of the second band in the wave-vector space for TE modes

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dimensional photonic crystal consists of a square lattice of cylindric air holes in silicon background with the dielectric constant $\varepsilon = 12.25$ (correspondingly the refractive index $n=3.5$). The radius of the air holes $r_1=0.26a$, where a is the lattice constant. Fig. 1 shows its equal frequency contours of the second band in the wave-vector space for transversal electric (TE) modes. The TE modes have the electric field perpendicular to the axis of air holes. It can be seen that the EFCs in the frequency range between $0.255c/a$ and $0.270c/a$ take shape similar to square. With these frequencies and in the direction perpendicular to the flat dispersion borders of the EFCs, a narrow-width light beam can propagate within the PhC without broadening, in dependence on self-collimation effect.

1.2 Structure of the folded Mach-Zehnder interferometer (FMZI)

As shown in Fig. 2, a FMZI is constructed in the PhC. It consists of one splitter and five mirrors. Light propagates between them employing self-collimation effect. As self-collimation light beams can propagate across each other without coupling, the two interfering branches with different path lengths are folded back in the FMZI so that the structure dimensions are decreased rapidly. The path length of the shorter branch along which light travels clockwise is $l_1 = 200a$, as shown by dash-dot lines in the figure. The path length of the longer branch along which light travels counterclockwise is $l_2=200a+2d$, as shown by solid lines. Here d represents the distance between mirror 2 and mirror 3, or between mirror 4 and mirror 5.

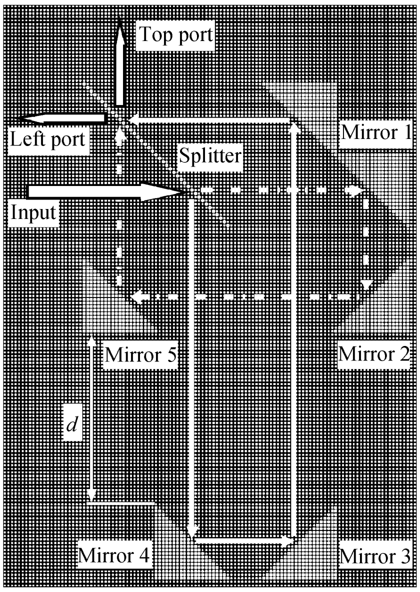


Fig. 2 Structure of the FMZI in a 2-D photonic crystal

Each of the five mirrors is formed with another silicon photonic crystal consisting of a square lattice of air holes whose radius $r_2 = 0.386a$. It has a TE photonic band gap (PBG) located between $0.2496c/a$ and $0.2716c/a$. So the mirrors own 100% reflectivity for incident self-collimation light with frequencies between $0.255c/a$ and $0.270c/a$. The beam splitter is a line defect introduced into the perfect PhC. The line defect is formed by enlarging the radius of a row of air holes in the ΓM direction to $r_3=0.429a$. Calculated with the finite-difference time-domain (FDTD) method, the splitter has about 50% reflectivity and 50% transmissivity for the self-collimation light with frequency between $0.255c/a$ and $0.270c/a$.

1.3 Transmission spectra of the FMZI

The FMZI structure shown in Fig. 2 has two output ports, i. e. the top port and the left port. The transmitted light from the longer branch and the reflected light from the shorter branch interfere at the left port, while the reflected light from the longer branch and the transmitted light from the shorter branch interfere at the top port. The two transmission spectra at the two output ports are calculated with the FDTD simulation method. Fig. 3 shows the transmission spectra when $d=50a$ (i. e. $l_2 = 300a$). It can be seen that both the transmission spectra are in the shape of sinusoidal curves in the frequency range between $0.255c/a$ and $0.270c/a$. Each of them has a uniform peak spacing $0.0026c/a$. The two curves are approximately complementary. In the transmission spectrum at the top port, the transmissivities of the peaks range between 78.4% and 92.6%. In the transmission spectrum at the left port, the transmissivities of the peaks range between 63.3% and 81.4%.

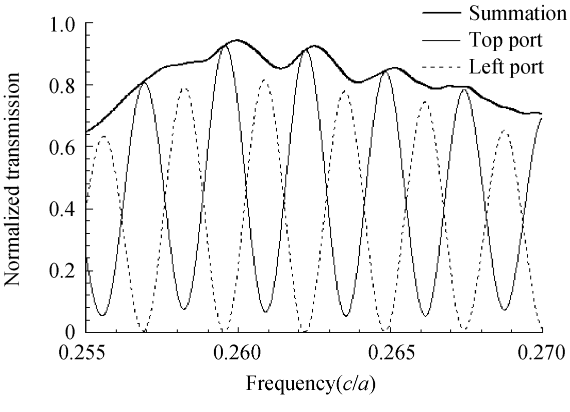


Fig. 3 Transmision spectra at the two output ports of the FMZI when $d=50a$

The transmission spectra for different d were also investigated. As shown in Fig. 4, the transmission peaks shift left to the lower frequency when the the path length of the longer branch increases. For instance, when d increases from $50.00a$ to $50.08a$, the frequency of the third transmission peak at the top port decreases from $0.2622c/a$ to $0.2613c/a$ as shown in Fig. 5. In addition, it can be seen from Fig. 6 that the peak spacing of the transmission spectrum decreases as d increases. The peak spacing for $d=30a$ is about twice as large as that for $d=75a$ as shown in Fig. 7.

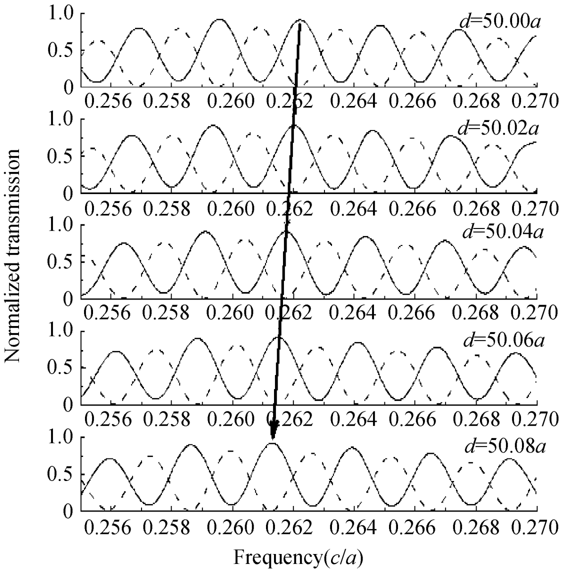


Fig. 4 Transmision spectra at the two ports of the FMZI for different d

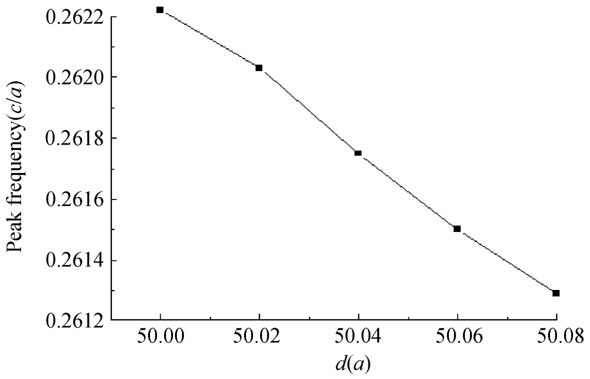


Fig. 5 A transmission peak frequency at the top port varies with d

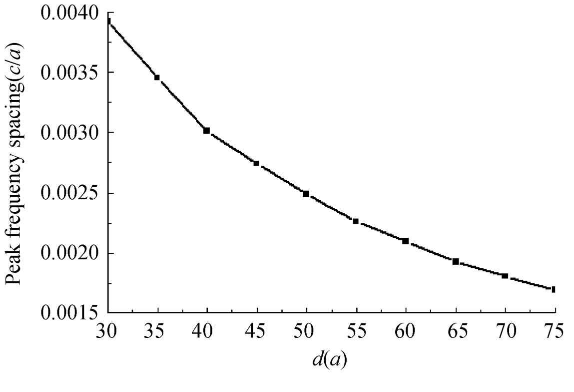


Fig. 6 Peak frequency spacing varies with d

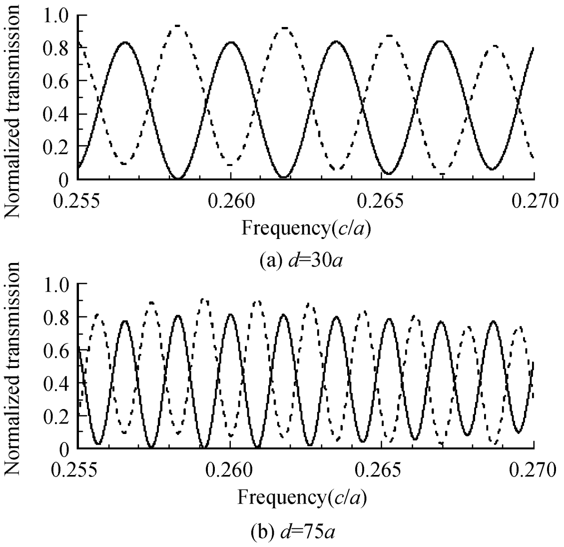
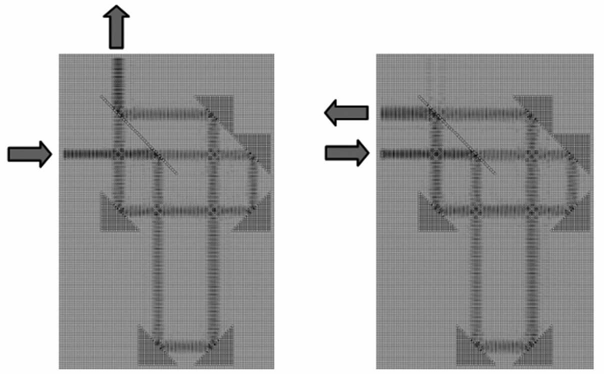


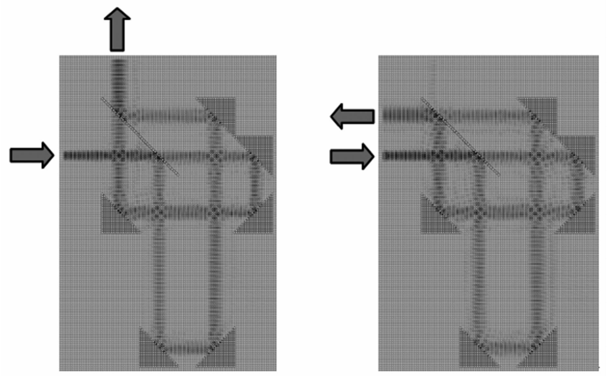
Fig. 7 Transmision spectra at the two output ports of the FMZI when $d=30a$ and $d=75a$

1.4 FMZI working as a wavelength division demultiplexer

As its two sinusoidal transmission spectra are complementary, the FMZI can work as a wavelength division demultiplexer. When a series of self-collimation light with equal-spacing frequencies are incident into the FMZI simultaneously, they can be separated into two groups that come out of the FMZI from the top port and the left port respectively. The frequency spacing in each group is twice as large as that in the incident light. For example, there are four transmission peaks $f_1=0.2596c/a$, $f_2=0.2609c/a$, $f_3=0.2622c/a$ and $f_4=0.2635c/a$ in the two transmission spectra as shown in Fig. 3. They have a uniform spacing $0.0013c/a$. By using FDTD method, magnetic-field distribution can be figured out when SC light is incident into the FMZI. As shown in Fig. 8 (a) and (c), SC light with frequency f_1 or f_3 come out from the top port. On the contrary, SC light with frequency f_2 or f_4 come out from the left port as shown in



(a) $f_1=0.2596c/a$ (b) $f_2=0.2609c/a$



(c) f_3 =0.2622c/a (d) f_4 = 0.2635c/a

Fig. 8 Magnetic-field distribution for self-collimation incident light with different frequencies

Fig. 8 (b) and (d). As a result, these equal-spacing input channels are separated into two groups that can go out from the two output ports respectively.

2 Conclusions

A folded Mach-Zehnder interferometer in a 2-D silicon photonic crystal with square-lattice air holes is proposed and numerically demonstrated. In dependence on the interference between self-collimation light beams, this FMZI has two sinusoidal transmission spectra in the frequency range from 0.255c/a to 0.270c/a at the top output port and the left output port respectively. As the two spectra are complementary and have uniform peak spacing, the FMZI can work as a wavelength division demultiplexer. The peak frequencies and their spacing decrease when the length difference between the two branches increases, which means that the transmission spectra can be designed to meet different application requirements by selecting a proper length difference between the two interfering branches. Moreover, as self-collimation light beams can cross each other without coupling loss, the FMZI is much smaller than non-folded interference-type filters in photonic crystals. Its dimensions are only tens of microns when the central operating wavelength is around 1 550 nm. So this FMZI can play an important role in high-density photonic integrated circuits.

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孔型硅光子晶体中折叠式马赫-曾德尔干涉仪

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摘　要：设计了基于孔型硅光子晶体的折叠式马赫-曾德尔干涉仪．它由一个光反射器和几个光分束器构成．在干涉仪中，窄光束依赖自准直效应进行传输．利用时域有限差分法研究了折叠式马赫-曾德尔干涉仪的特性．结果表明，在 0.255～0.270c/a 的归一化频率范围内，干涉仪的两个透射谱均为正弦形且强度互补，透射谱的透射峰间距随着干涉仪两臂的光程差的增大而减小．该折叠式干涉仪结构紧凑，尺寸比非折叠式光子晶体马赫-曾德尔干涉仪要小许多，有望作为信道解复用器应用于光子芯片中．

关键词：光子晶体；自准直；马赫-曾德尔干涉仪

CHEN Xi-yao　was born in 1964. He received the Ph. D. degree in physics from University of Science and Technology of China in 2004. Now he is an associate professor and his main research interests focus on novel optical devices based on photonic crystals.