A new photonic crystal directional coupler switch based on slow light in coupled-cavity waveguides

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Abstract
Optical switch is one of the most important components in optical communication systems. In this paper, a new photonic crystal (PhC) directional coupler switch based on slow light in coupled-cavity waveguides is proposed. Slow light phenomenon is usually applied in nonlinear optics and can be estimated by slope of dispersion curve of the PhC waveguides. By introducing this structure, the group velocity of light at the wavelength of 1550nm is obtained as low as 36 times slower than the velocity of light in vacuum. As a consequence, a short switching length of $13.6\mu m$ *is achieved for a refractive index change of 0.02 in the coupling region. The device is simulated by finite-difference time-domain (FDTD) method and the results show that the available bandwidth of the switch is approximately* $9nm$. *Maximum transmission of 80% is also achieved in both linear and nonlinear cases at cross and bar ports, respectively.*

Keywords: *Coupled-cavity waveguide, Directional coupler, Photonic Crystal, Slow light*

1. Introduction

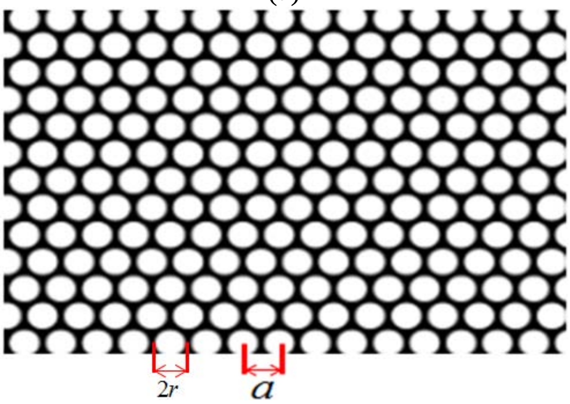
Photonic crystals (PhCs) are artificial crystals in which the refractive index changes periodically in one, two or three dimensions [1]. Similar to semiconductor crystals which show electronic energy band diagram and bandgap, photonic crystals show photonic energy diagram and photonic bandgap. Photonic bandgap is a range of frequencies for which PhC acts like a perfect mirror. Therefore, light with the frequencies within the photonic bandgap cannot propagate inside the PhC [2]. A waveguide which is one of the basic elements of photonic devices can be created by introducing a line defect to the perfect PhC. Thus, light wave at the wavelength within the photonic bandgap can propagate along the waveguide with very low attenuation loss [3].
Slow light phenomenon is a good approach to control the propagation of light in photonic circuits [1]. Guided modes in PhC waveguides can have the slow light property at the edge of the brillouin zone. In fact, near the edge of the brillouin zone the slopes of the dispersion curves of guided modes which indicate the group velocities are significantly small [4, 5]. The advantages of slow light phenomenon are as follows: increase in light-matter interaction, decrease in power consumption and miniaturization of optical devices like optical switches, modulators, lasers and amplifiers [5, 6].
Guided modes with the slow light property away from the edge of the brillouin zone can be obtained in PhC coupled-cavity waveguides (CCWs) [7, 8]. In such waveguides, light wave can propagate along the waveguide via tunnelling from one cavity to the neighbouring ones. Hence, the group velocities of guided modes in PhC-CCWs are much smaller than those in conventional ones [1].
Directional coupler is an important key component in optical wavelength division multiplexing (WDM) networks that can be utilized for various applications such as optical switches and modulators [9,10]. Propagation of slow light modes in PhC-CCWs can reduce the coupling length of the directional couplers significantly.

This paper is organized as follows: we first introduce the structure of the new PhC directional coupler and find the dispersion curves of its guided modes. In section 3, the directional coupler switch is analyzed, the group velocity of the propagating modes (supermodes) and the switching length is calculated. We design and simulate the directional coupler and show the results in section 4. Section 5 gives the conclusion.

2. Structure of directional coupler

Fig. 1(a) shows a 2D-PhC structure consisting of triangular lattice of air holes in dielectric background with refractive index of 3.5. Lattice constant "*a*" is equal to 406nm and the radius of holes "*r*" is equal to 0.4*a*. The photonic bandgap of the structure for TM modes which is in the normalized frequency range of 0.246 to 0.4 is plotted in Fig. 1(b).

(a)



(b)

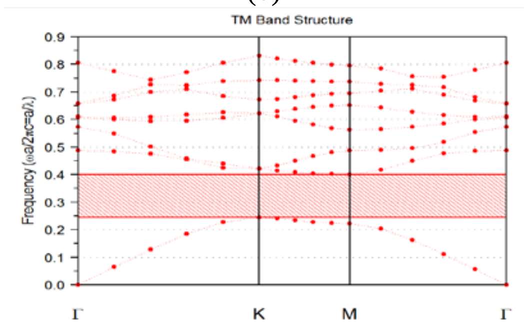
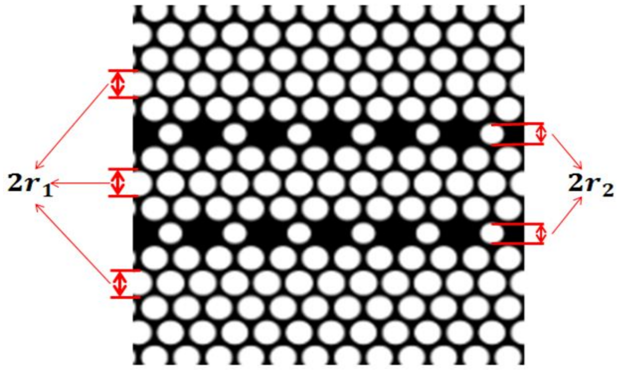


Fig. 1. (a) The schematic diagram of a 2D triangular lattice PhC. (b) Band structure for TM modes that shows a photonic bandgap.

Our proposed directional coupler based on CCWs is created by periodically filling air holes of two rows (separated by $2\sqrt{3}a$), where the distance between the neighbouring two cavities is Λ=2*a*, as shown in Fig. 2(a). Some other geometrical modifications are also applied to excite the desired modes. The holes in the center row have the radius of $r_1 = 0.416a$, and the holes in the waveguides have a radius of $r_2 = 0.35a$. As shown in Fig. 2(a), the holes at the second next rows of each waveguide also have radius of r_1. The odd and even modes of the structure are calculated and illustrated in Fig. 2(b).

(a)



(b)

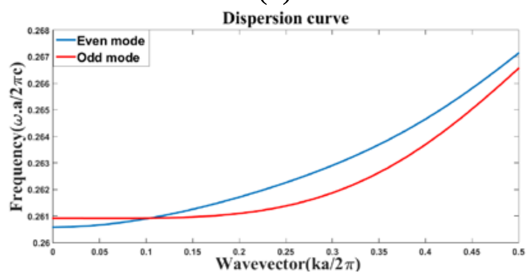


Fig. 2. (a) Schematic diagram of CCW directional coupler ($\Lambda = 2a$). (b) The dispersion curves of guided modes.

3. Analysis of directional coupler switch

To illustrate that the supported guided modes shown in Fig. 2(b) have the slow light behaviour, the following equation is used to calculate the group velocity [11]:

$$V_g = \frac{d\omega}{dk} \tag{1}$$

According to Eq. 1, the slope of the dispersion curve of each mode at any frequency gives the group velocity at that frequency. Thus, using the curves in Fig. 2(b), the group velocity at the wavelength of 1550nm is obtained approximately 36 times slower than the velocity of light in vacuum. This group velocity can also be reduced further by increasing the distance between the cavities. However, it should be noted that there is an intrinsic trade-off between the available bandwidth and the group velocity so that decreasing the group velocity reduces the accessible bandwidth [12].

Based on the dispersion curves of odd and even modes the coupling length of the directional coupler can be calculated by the following relation [13]:

$$L_c = \frac{(2n+1)\pi}{|k_{even} - k_{odd}|} \tag{2}$$

where n is an integer number and k_{even} and k_{odd} are the wave-numbers of the even and odd modes, respectively. By applying an external electric field in coupling region, the refractive index of the background material (n) changes by a small value due to a nonlinear effect. Thus, by adjusting the strength of the electric field, a desired value of Δn and a shift in the dispersion curve of the propagating modes is obtained. We take a refractive index change of 0.02 and plot the expected shift in the dispersion curves as shown in Fig. 3.

Now, the switching length of the coupler is determined by [13]:

$$L_{sw} = \frac{(2n+1)\pi}{|k_{e,lin} - k_{o,lin}| - |k_{e,nlin} - k_{o,nlin}|} \tag{3}$$

where $k_{e,lin}$ and $k_{o,lin}$ are the wave numbers of the even and odd modes in the linear case. Also $k_{e,nlin}$ and $k_{o,nlin}$ are those of the nonlinear case, respectively.

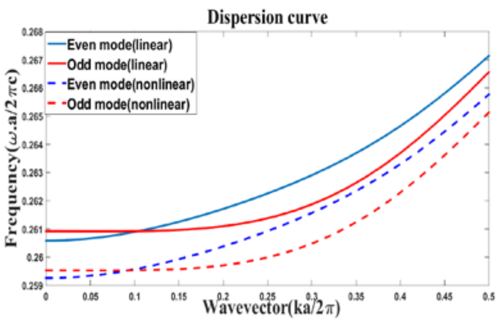


Fig. 3. Dispersion curves of even and odd modes of the directional coupler for the linear (n=3.5) (solid lines) and nonlinear cases (n=3.52) (dashed lines).

4. Simulation and results

In order to determine the switching length of the coupler at the wavelength of 1550nm (normalized frequency of 0.262), we find $k_{e,lin}$, $k_{o,lin}$, $k_{e,nlin}$ and $k_{o,nlin}$ from the curves given in Fig. 3. Using Eq. 3, the switching length at that wavelength is obtained as $13.6\mu m$, that is several times shorter than the proposed device by B. Vakili *et al*. [13]. Table 1, presents the switching lengths at different wavelengths.

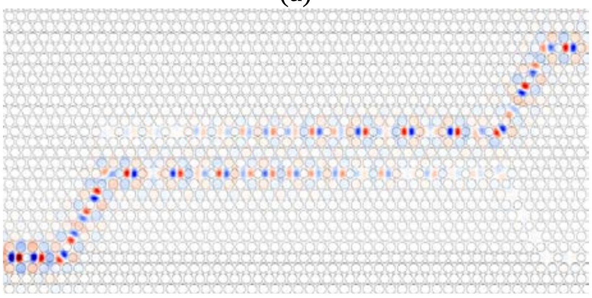
Figs. 4(a) and 5(a) show the operation of the directional coupler switch of length $13.6\mu m$ in the linear and nonlinear cases.

Table 1. The switching lengths (μm) at different wavelengths

Wavelength (μm)	Switching length (μm)
1.554	19.2
1.552	13.7
1.55	13.6
1.548	15
1.546	18
1.544	21.1

In the linear case, the signal is coupled to the cross port as illustrated in Fig. 4(a). However, as depicted in Fig. 5(a), in the nonlinear case the signal is coupled to the bar port. Figs. 4(b) and 5(b) are showing power transmission in the linear and nonlinear cases, respectively. The results in Fig 4(b) and 5(b) show that a very good symmetry of operation is realized in this switch.

(a)



(b)

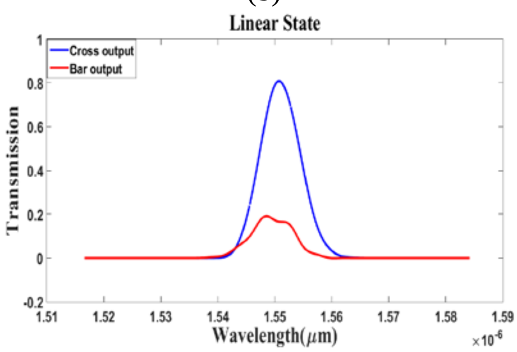
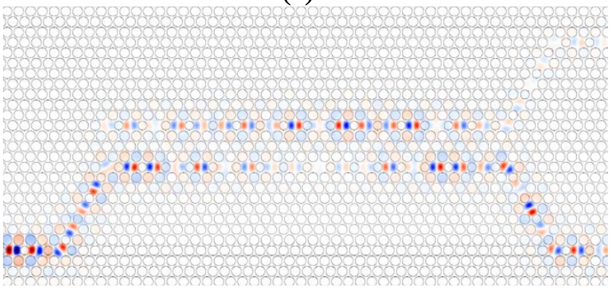


Fig. 4. (a) Snapshot of light propagation in directional coupler (linear case). (b) Transmission spectrum of the directional coupler in linear case.

(a)



(b)

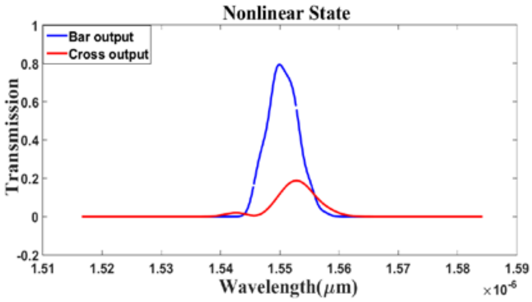


Fig. 5. (a) Snapshot of light propagation in directional coupler (nonlinear case). (b) Transmission spectrum of the directional coupler in nonlinear case.

5. Conclusion

In summary, modifying the radius of holes and the distance between cavities, we demonstrated a new directional coupler optical switch based on PhC-CCWs which can support slow light modes. By analysis of the guided modes the switching length for $\Delta n = 0.02$ is obtained as short as $13.6\mu m$ with the bandwidth of approximately $9nm$, and we achieve almost 80% power transmission in both linear and nonlinear cases.

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