Mach–Zehnder Interferometer Based on Coupled Dielectric Pillars *

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We propose a Mach–Zehnder interferometer (MZI) based on coupled dielectric pillars. It is composed of single-row pillar coupled waveguide modulating arms and three-row pillar waveguide 3 dB couplers. The slow light property and transmission loss of the single-row pillar modulating arm are optimized by the plane wave expansion method. A short 3 dB coupler is designed based on the modes transformation in three-row pillar waveguide. Finite difference time domain simulations prove the validity of this MZI and show that it has low insertion loss of < 1.1 *dB and high extinction ratio of* > 12 *dB.*

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In the past twenty years, photonic crystals (PCs) have attracted much of interest due to their potential applications for manipulating light at about wavelength scale.[1,2] Among the applications of PCs, photonic crystal waveguide (PCW) based devices such as straight and bending waveguide,[3,4] beam splitters,[5,6] multimode interferometers,[7,8] Mach–Zehnder interferometers (MZI),[9−11] have been designed and fabricated and have much smaller size compared with the conventional counterparts. However, PCW based devices also have several disadvantages. For example, the path of waveguide must follow the definite crystal lattice orientations, which induces large loss at sharp waveguide bend. The PCW must be sandwiched between two wide PC regions to avoid the propagation loss. These may bring negative impacts to the fabrications and applications of PC devices.

Recently, a novel kind of waveguide based on coupled dielectric pillars was proposed by Luan and Chang.[12] The light can hop between every two adjacent pillars to propagate along a straight or curved row of pillars. A 1.2 beam splitter is realized by coupling between different modes in a three-row pillar waveguide, which has high transmission of above 95%. Thus this coupled pillar waveguide (CPW) can overcome the above-mentioned weakness of conventional PCWs. Another important feature of the CPW is that it is a coupled resonator optical waveguide (CROW) and can support slow light. This makes the CPW has much stronger phase modulation efficiency and smaller modulating length compared to normal dielectric waveguides. If it is used as modulating arm of the MZI, the modulating arm length can be reduced about 100 times. Because of this length reduction, smaller active control region (for example, thermal-optic heater) will be needed and the power assumption will be reduced as well.

In this Letter, we combine the high transmission and slow light property of the CPW together to design a compact MZI. First, the slow light property and propagation loss of CPW are studied and optimized by the plane wave expansion (PWE) method. Then an MZI is constructed by the optimized CPW and three-row pillar splitter and combiner. Lastly, the light propagation properties of the MZI are simulated and analysed by the finite difference time domain (FDTD) method to validate its feasibility.

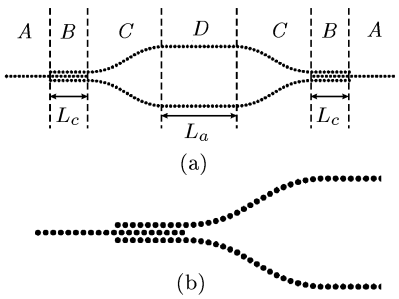


Fig. 1. Structure of the CPW-MZI: (a) whole view, (b) magnified view of the left half of the structure. A: input/output waveguides, B: 3 dB coupler, C: S-shaped branch, D: modulation arm.

The structure of the CPW-MZI is shown in Fig. 1(a). The structure can be divided into four regions labelled A, B, C and D, which are the input/output waveguide, 3 dB coupler, S-shaped branch and modulating arm, respectively. The lengths of the 3 dB coupler and the modulating arm are L_c and L_a, respectively. Figure 1(b) shows the magnified diagram of the left half of the structure. The distance between every two pillars along light path is a. The input/output waveguides and modulating arms are single row pillar waveguides, the 3 dB coupler is a three-row pillar waveguide. At the output of the 3 dB coupler, an S-shaped waveguide composed by two arcs

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and one straight line is used to send the light to the straight modulating arm with low loss. The radii of the two arcs are both $15a$, and the branch angle is $60°$. The dielectric constants of the pillar and background are 12 and 1, respectively. The radius of the pillar is R.

Because the slow light efficiency and propagating loss of modulating arm waveguide are most important for the MZI properties, they should be first studied and optimized. The dispersion curves for different modes of single-row CPWs with different radii are calculated by the PWE method and supercell technology,[13] which is shown in Fig. 2. Only TM polarization is considered in this study. The region above the dashed line is the light cone, where the light mode will become leaky mode and diffuse from the pillar into the surrounding air. As we know, the slow light capability is inverse to the slope of the dispersion curve. From Fig. 2, the slopes of the dispersion curves drop to 0 at the edge of Brillouin zone where $ka/2\pi = 0.5$, so there is strong slow light effect at the edge of Brillouin zone. When R increases from $0.2a$ to $0.45a$, the slope of the dispersion curve decreases gradually, which means that the slow light ability of the waveguide is enhanced gradually. Moreover, the propagation loss of this CPW is mainly due to the field radiating from the pillar out to surrounding air at some mode near the light cone. From Fig. 2, with the increase of R, the dispersion curve departs from the light cone, which means that the light field will be more concentrate in the pillar and the propagating loss is reduced. Thus R should be set as large as possible, as long as the fabrication process permits. Here we set R to be $0.4a$ and the normalized frequency to be 0.165.

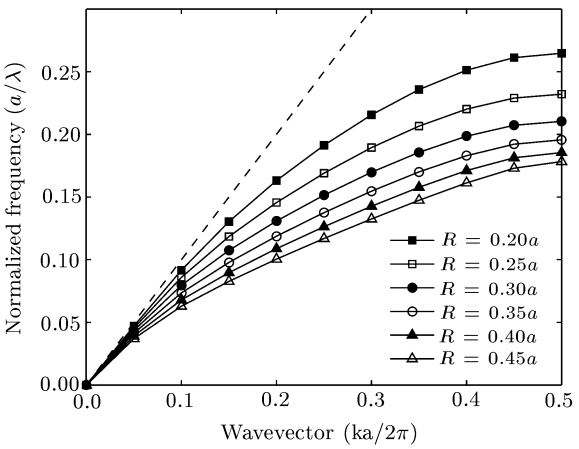


Fig. 2. Dispersion curves for different modes of single-row CPWs with different radii.

In order to introduce π phase shift on one modulating arm with length L_a, index change Δn should be introduced onto the pillars to bring wavevector difference $\Delta\beta_a$ between the two arm waveguides. Here $\Delta\beta_a \cdot L_a = \pi$. Because of the memory limit of our computer, we set L_a to be only $18a$ in order to save the calculation memory and time. By band structure calculation, Δn can be determined to be 0.15 at the normalized frequency of 0.165.

The three-row pillar waveguide splitter is another important component for the MZI. Although its principle and design method have been mentioned in Ref. [12], here they are worthwhile to be described in more detail. Figure 3 shows the band structure of the three-row pillar waveguide calculated by the PWE method and supercell technology. The width W between the centre of the first and third rows is set to $2a$. The grey area in Fig. 3 is the light cone. The field distributions of these three modes are also shown in the sect of Fig. 3. We can see that the zeroth mode is located at the central row of pillars, which is similar to the mode in single-row pillar waveguide.[12] The first mode is located at the two adjacent side rows symmetrically and the second mode is located at the two adjacent side rows asymmetrically. The fields of the fist and zeroth modes have both even symmetry with the waveguide central axis, but the second mode has odd symmetry with the waveguide central axis. From mode coupling theory, normally only modes with matched space symmetries can transform each other. Thus in our case, only the zeroth and first modes have matched symmetries and can transform each other periodically in the three-row pillar waveguide with the light propagating length changes. According to the coupled mode theory, the coupling length L_c between zeroth and first modes can be determined by

$$L_c = \frac{\pi}{\Delta\beta_{01}}, \tag{1}$$

where $\Delta\beta_{01}$ is the difference of the wavevectors between the zeroth and first modes. From Fig. 3, at the normalized frequency of 0.165, $\Delta\beta_{01} = 0.11\pi/a$, so $L_c = 9a$. It should be noted that width W must be carefully chosen to let L_c be integral times of period a.

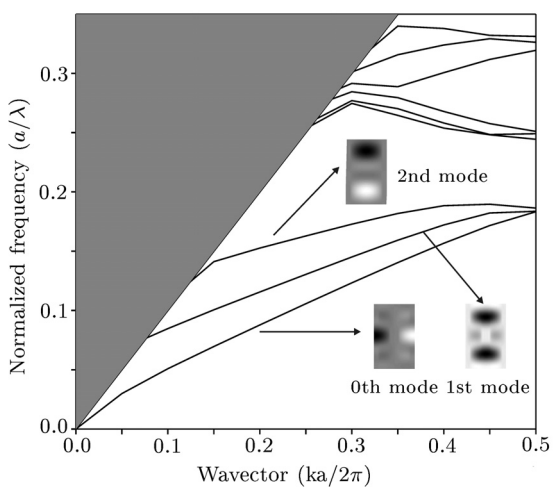


Fig. 3. Band structure and field distributions for different modes of the three-row pillar waveguide.

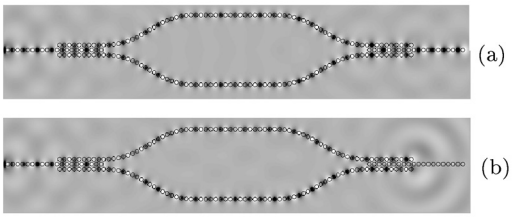


Fig. 4. Field diagrams of the CPW-MZI under cw source excitation: (a) before modulation, (b) after modulation.

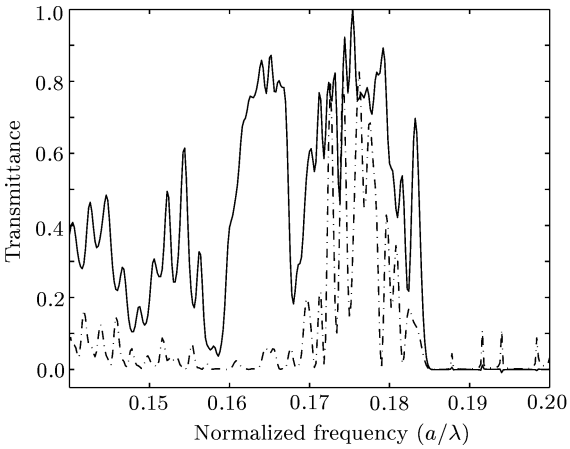


Fig. 5. Transmittance spectra of the CPW-MZI before modulation (solid line) and after modulation (dot-dashed line).

Now all the structure parameters have been determined, in the following the FDTD method[14] is used to validate the capability of the MZI and to analyse its transmittance spectra. Firstly, a cw Gaussian shaped source with half $1/e$ spread of pillar radius R and normalized frequency of 0.165 is introduced to examine the light field propagation along the MZI before and after modulation. The field diagrams are shown in Fig. 4. Before modulation, at the first 3 dB coupler, the light is transformed from the zeroth mode to the fist mode, so the light can be split and can transmit in the two modulating arms smoothly. The light phases in the two arms are always the same, so when they are recombined at the second 3 dB coupler, the mode is transformed from the first to the zeroth again and can be coupled to the output waveguide. However, when modulation is applied, due to the wavevector difference of the two arms, the phases in the two S-shaped waveguides behind the modulating arms become opposite, which proves that a π phase shift is successfully introduced by the index modulation. Thus at the end of the three-row pillar combiner, the mode field becomes odd symmetry with waveguide central axis and has big phase mismatch with the even-symmetry mode of the output single-row pillar waveguide. As a result, the light can not be coupled to the output waveguide and radiates into the surrounding air directly.

Then the transmittance spectra of the MZI are calculated by the FDTD method with a pulse source, which are shown in Fig. 5. Before modulation, the transmittance is nearly 80% at the frequency range 0.163–0.167, which means that the insertion loss is less than 1.1 dB within 37 nm bandwidth when the central wavelength is 1550 nm. When modulation is applied, the transmission drops to below 6% enormously in the above-mentioned frequency range. It can be calculated that the extinction ratio is larger than 12 dB.

In summary, we have proposed an MZI by pillar coupled slow light waveguides and 3 dB couplers. The slow light property is enhanced and transmission loss can be reduced by increasing the pillar radius. Taking advantage of modes transformation of three-row pillar waveguide, a short 3 dB coupler is designed to split and combine light. The functionary of the MZI is verified by checking field distributions before and after modulation with FDTD modulations. The transmittance spectra calculated by the FDTD method show that the insertion loss of the MZI is below 1.1 dB and the extinction ratio is higher than 12 dB. In order to fabricate this kind of MZIs, some thermal-optic or electro-optic polymer (or liquid crystal) may be filled as background material surrounding pillars at one modulating arm and so index modulation can be applied to the modulating arm. This pillar coupled MZI may have great potential in future compact optical interconnection and high density optical integration.

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