Photonic crystal based Mach-Zehnder interferometer

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Introduction

Mach-Zehnder Interferometers (MZIs) are used widely in optical systems with applications in filtering, switching and phase measurement. As such, they will be an essential component in future optical integrated circuits. Photonic crystals (PCs) are one of the key technologies proposed for the fabrication of such devices, and several experimental results of PC MZIs have been reported recently.[1–3]Although numerical calculations[1,4] and simple theoretical models[3] have been used to predict the properties of these structures, there has been no discussion in the literature regarding fundamental differences between PC-based and conventional dielectric (fibre or planar) MZIs. We present here a simple analysis of two-dimensional PC MZIs, and show that one of the basic properties of photonic crystals, namely that light inside the bandgap can not leak out of a waveguide with PC walls, results in significantly different behaviour. This feature places strict requirements on the performance of junctions in PC MZIs. We describe a Y-junction with the required properties and provide rigorous numerical results for a realistic 2D PC MZI to demonstrate the effects predicted by the simple model.

MZI modal analysis

Consider first the MZI illustrated in Fig. 1. A single input beam is split into two equal parts, $|\psi_1\rangle$, $|\psi_2\rangle$, that travel along two arms. A phase difference φ is introduced into one arm before the two beams are recombined, the resulting output being a function of φ. In active devices such as switches, φ is varied to control the output signal, whereas in sensing devices, measurement of the output signal is used to determine φ.

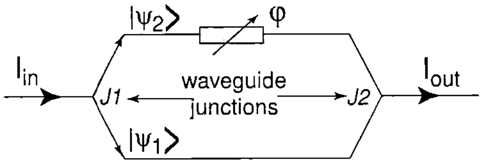

Figure 1. Schematic of a simple MZI consisting of an input, a beam splitter and a beam combiner and a phase element to introduce a phase difference φ.

The contrast between conventional and PC MZIs arises from the properties of the junctions used to split and combine the beams. Assume that each waveguide in the MZI is identical and only supports a single mode of even symmetry. At the input junction $J1$, the mode is split into $|\psi_1\rangle$ and $|\psi_2\rangle$, one in each guide (see Fig. 1). If the two output guides are arranged symmetrically with respect to the input guide, then the amplitude and phase of these modes must be equal. The combined field in the guides can also be expressed as even (+) and odd (−) superpositions of $|\psi_1\rangle$ and $|\psi_2\rangle$, $|\psi_\pm\rangle = (1/\sqrt{2})\,(|\psi_1\rangle \pm |\psi_2\rangle)$ respectively. In this notation, symmetry rules require that the input mode only couples to $|\psi_+\rangle$. Consider now the junction operating in reverse, as a beam combiner. In general, the modes in each arm have different phases and amplitudes, and the combined fields are a superposition of $|\psi_+\rangle$ and $|\psi_-\rangle$. However, only the $|\psi_+\rangle$ component of the field couples to the mode in the output guide. The remaining odd ($|\psi_-\rangle$) component of the field must either be reflected or radiated. Herein lies the essential difference between a dielectric waveguide junction and one formed in PC; in a dielectric junction, the odd field component is mostly radiated into the cladding, whereas in a PC junction, light can not leak through the walls, so any field that is not transmitted, must be reflected.

In light of this difference, consider the MZI in Fig. 1. Suppose that the first junction $J1$ splits the input mode equally into $|\psi_1\rangle$ and $|\psi_2\rangle$. If the arms are each of length L and the single propagating mode has propagation constant β, we can write the field at the output junction of the interferometer (J2) as

$$\begin{aligned}|\Psi(L)\rangle =& e^{i\beta L}\left(|\psi_1\rangle + e^{i\varphi}|\psi_2\rangle\right)\\ =& e^{i\chi}\left(\cos(\varphi/2)|\psi_+\rangle + i\sin(\varphi/2)|\psi_-\rangle\right),\end{aligned}$$

where $\chi = \beta L + \varphi/2$. In the case of a dielectric waveguide, the transmission of the interferometer is given by

$$T = I_{\text{out}}/I_{\text{in}} = \cos^2(\varphi/2) \qquad (1)$$

For the PC MZI however, the transmission is more complicated. The odd mode is reflected back into the interferometer, and propagates back to $J1$, accumulating a second φ phase difference in arm 2. At $J1$, the even component of the field is transmitted back into the input guide, and the odd component is reflected once more into the two arms. These multiple passes through the interferometer result in resonant behaviour, much like that in a Fabry-Perot cavity. When the transmitted field contributions from each pass through the interferometer are added as a geometric series, the transmitted intensity is found to be

$$T = \frac{4\sin^2(\chi)\cos^2(\varphi/2)/\sin^4(\varphi/2)}{1 + 4\sin^2(\chi)\cos^2(\varphi/2)/\sin^4(\varphi/2)}. \qquad (2)$$

For a fixed φ, Eq. (2) is equivalent to the reflectance of a Fabry-Perot etalon[5] with finesse given by $\mathcal{F} = \pi\cos(\varphi/2)/(1-\cos(\varphi/2))$. Thus the reflection spectrum of the MZI is similar to the transmission of a Fabry-Perot. This property could lead to novel tunable filter devices, for which both the resonant frequency and finesse could be tuned independently. One way of achieving this would be to use thermo-optic effects as in Ref [1]. Heating to both arms equally would vary β, and hence the resonant frequencies, while differential heating would change $\Delta\beta$ and hence the finesse. At a fixed wavelength, the response of the PC MZI as a function of φ somewhat resembles that of a conventional MZI (1), however resonant features appear due to the Fabry-Perot effects.

In the following two sections, we describe a realistic PC MZI design with the above transmission properties, and compare the predictions of the semi-analytic result (2) to a full numerical calculation of the PC structure.

Y-junction

The waveguide junctions in an MZI have two main requirements. First, they must split the input beam equally between the two arms, and second, they must have very low back reflection. As we have shown, the back reflection of the antisymmetric field components is unavoidable in a PC junction when the output guide only supports a single mode of even symmetry. However, further undesired effects occur if part of the symmetric field component is also reflected. In this case, Fabry-Perot effects result even if the interferometer is balanced ($\varphi = 0$), and the spectrum can become dominated by these resonances. This effect has been observed experimentally[1] and may explain why odd-mode resonance effects predicted by Eq.(2) have not yet been demonstrated. It is thus important to use a junction design that has very high transmission of the even symmetry mode.

Most PC MZI designs to date have used standard Y-junction designs, that have been optimized to provide maximum transmissions at the required wavelength. Junctions with calculated transmissions up to 99% have been designed in this manner,[1,6] however in most cases, the transmission bandwidth decreases rapidly as the peak transmission approaches 100%. Typical 95% transmission bandwidths for the optimized junctions reported in the literature are on the order of 10 – 40 nm for triangular lattice PC structures with air holes. An alternative beam splitter design implemented in many conventional MZIs uses a directional coupler to couple half of the incident light into a second waveguide[3]. The main advantage of this design is the very low back reflection from the junction, with the main disadvantage being that small variations in coupling length can result in uneven splitting between the two output guides.

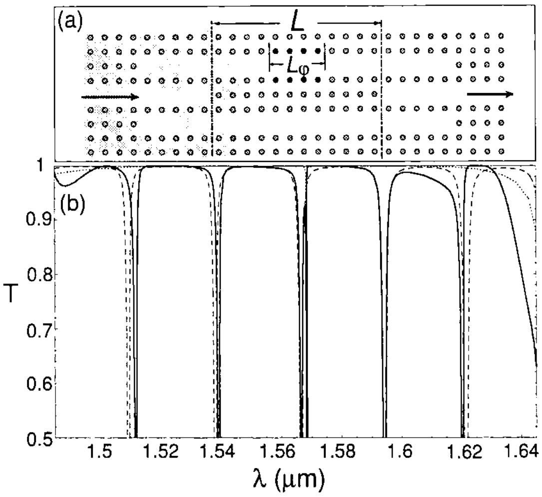

Figure 2. (a) Schematic of a PC MZI formed by joining two coupled Y-junctions (highlighted in grey) with two singlemode arms of length L. Changing the radius of L_φ pairs of cylinders along one arm introduces a phase change φ. (b) Transmission spectra of a single Y-junction (dotted curve), and the unbalanced MZI with $L = 26d$, $L_\varphi = 8d$ (solid: full numerical calculation, dashed: semi-analytic result).

We demonstrate here a coupled Y-junction design that uses the mode coupling properties of a directional coupler, but is symmetric with respect to the input guide, to ensure equal splitting of the mode. The geometry of the junction is shown in Fig. 2(a), highlighted in grey. A similar structure was proposed as an alternative to conventional Y-junctions in Ref [7], but to our knowledge has not been studied in a PC structure. We find that the coupled Y-junction can provide superior transmission bandwidths to standard optimized PC Y-junctions. The transmission of the junction is shown in Fig. 2(b) as a dotted curve. The photonic crystal is a square lattice of dielectric cylinders with refractive index $n = 3.4$ in air ($n = 1$). The radius of the cylinders is $a = 0.18d$, where d is the lattice period. The junction has a 95% transmission bandwidth of approximately 175 nm at $\lambda = 1.568\,\mu\mathrm{m}$, although this includes a narrow resonance dip at $\lambda \sim 1.58\,\mu\mathrm{m}$. To avoid this, the junction could be operated either side of the dip, which still gives bandwidths up to 112 nm at 95% transmission or 85 nm at 99%. These bandwidths are considerably higher than those achieved in the optimized Y-junctions formed in triangular PC lattices of air holes.

PC Mach-Zehnder

A realistic PC MZI is formed by joining two of the coupled Y-junctions of the previous section by singlemode waveguides, as shown in Fig. 2 (b). We introduce a small phase difference in one arm of the PC MZI by changing the radius of 8 pairs of cylinders lining one arm to $a = 0.20d$. This changes the propagation constant over a length of $L_\varphi = 8d$ by $\Delta\beta(\lambda)$, to give a phase difference of $\varphi(\lambda) = \Delta\beta(\lambda)L_\varphi$. The solid curve in Fig. 2(b) shows the transmission for a MZI of length $L = 26d$, calculated using a recently developed Bloch mode scattering matrix technique[8]. The dashed curve is the semi-analytic result (2) with numerical input of β and $\Delta\beta$. The location and width of the resonances are in excellent agreement across most of the bandwidth, with the finesse lying in the range $\mathcal{F} = 50 - 80$.

Conclusion

We have described a unique resonant behaviour in PC MZIs, caused by anti-symmetric mode rejection at the waveguide junctions. This property is predicted by a simple modal analysis, and has been verified numerically in a realistic PC structure. MZIs demonstrating these transmission properties may be useful in novel switching or filtering devices due to the tunable finesse and strong wavelength selectivity.

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