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Self-imaging effect of TM modes in photonic crystal multimode waveguides only exhibiting band gaps for TE modes

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Abstract

This Letter presents the properties of transverse-magnetic (TM) modes in multimode photonic crystal waveguides (PCWs), which only exhibit photonic band gaps for transverse-electric (TE) modes. A good equivalent model is applied to analysis the designed structures on the basis of multimode interference effect and self-imaging principle. The performance shows that the TM modes can also be propagated with high efficiency, and resemble index-guided modes owing to the combination of total internal reflection (TIR) and distribution Bragg reflection. It provides a novel way to realize the components for both TM and TE polarizations by combining PBG and TIR effect in PCWs. As one of potential applications, polarization-insensitive power splitter based on the proposed structures can be designed.

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Keywords: Photonic crystal waveguides; Self-imaging principle; Total internal reflection

1. Introduction

Photonic crystals (PCs), which are artificially fabricated periodic dielectric structures, have gained worldwide interest in the past twenty years. They provide a good way to control the propagation of electromagnetic (EM) waves due to the existence of photonic band gaps (PBG) and localization of EM waves in the irregular regions of PCs [1–4]. There has been much attention in study of PCs with defects. Photonic crystal waveguides (PCWs), which are one of the most promising components of PCs to be realized in photonic integrated circuits (PICs), may be constructed by introducing a line defect into perfect PCs and the EM waves can propagate along the line defect [5]. Generally, the EM waves are mainly guided by PBG effect in PCWs due to the existence of defect modes inside the PBG. However, both theoretical and experimental results have shown that the propagating modes may be guided by not only the PBG effect, but also total internal reflection (TIR) if the effective index of the guiding region is higher than that in the ambient area [6–9]. Thus they provided another mechanism to confine the EM waves in PCWs.

Multimode interference (MMI) devices are important components in PICs owing to their simple structure, low loss, and large optical bandwidth [10]. Recently, MMI structures based on PCs were presented [11–16]. It has been shown that the operation of those structures is also based on the self-imaging principle, i.e. the input field profile can be reproduced in single or multiple images at regular intervals along the propagating direction in the multimode waveguides [10]. And this property permits one to design wavelength de-multiplexer or multiplexer [11,12], power splitter [13–15], optics switch [16], and so on. All the propagating modes in those MMI structures were guided

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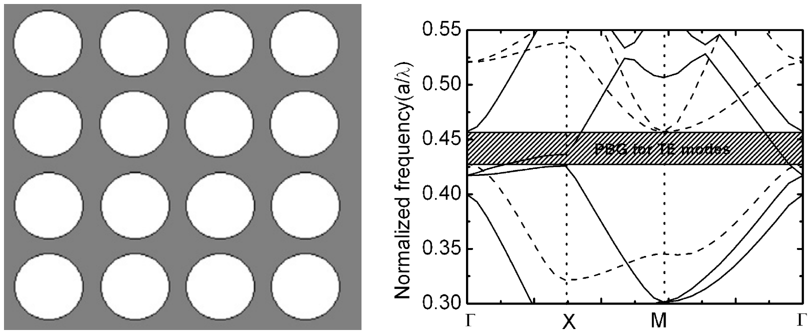

Fig. 1. (a) Air hole arrays with a square lattice in dielectric slab; (b) Band diagram for TM modes (solid lines) and TE modes (dash lines). The shadow indicates TE PBG.

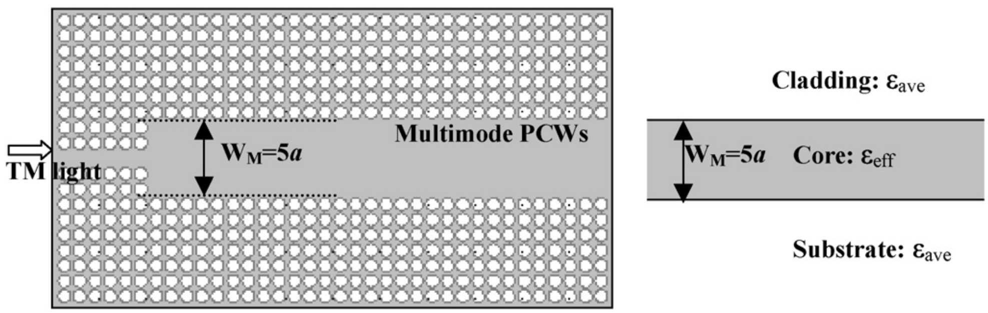

Fig. 2. (a) Schematic diagram of multimode PCWs; (b) the equivalent three layer dielectric waveguide composed of the core (multimode region), the cladding and the substrate (the PC mirrors located on both side of the core). The permittivity of the core is $\varepsilon_{\mathrm{eff}}$, the average permittivity of both the cladding and the substrate are $\varepsilon_{\mathrm{ave}}$.

by PBG effect other than TIR effect. However, we always need design functional devices for both TM and TE polarizations, thus the PCs having absolute PBG are necessary if only PBG effect is considered. Nevertheless, the absolute PBG is restricted to the structure parameters and always not wide enough.

In this Letter, we study another mechanism to guide the propagation field in multimode PCWs having no PBG. Both TIR and distributed Bragg reflection (DBR) determines the propagation of the guided modes. It provides a good model to analysis the proposed structures and a new way to design the components for all the polarizations using MMI effect in PCWs.

2. Model and analysis

The PCs, which are suitable for practical devices in PICs are in the form of a lattice of holes in a dielectric material such as Si or GaAs. The proposed structure is based on air hole arrays with a square lattice, which is realized in conventional slab waveguides, as shown in Fig. 1. The radius r of holes is set to $0.4a$, a being the lattice constant. The effective refractive index $\varepsilon_{\mathrm{eff}} = 2.95$ is used to replace the refractive index of the background dielectric slab to confine the light in the third dimension [17,18]. This method has proved to be a good approximation of the original 3D problem. Fig. 1(b) shows the band diagram for both TM and TE modes of the perfect PCs obtained by using the plane wave expansion method. There is a PBG for TE modes appearing at the normalized frequency of $a/\lambda = 0.428$ to 0.455, where λ is the wavelength. However, no PBG appears for the TM modes. This indicates that the input TM field cannot be guided by PBG effect along the PCWs. Fortunately, the EM waves can also be propagated through the index contrast due to the fact the index of the guiding region is higher than that in the surrounding area [6–9]. The propagation of TM modes is discussed as follows.

Fig. 2(a) shows a multimode PCWs formed by removing five rows of air holes. The waveguide consists of three parts: dielectric-core region (multimode region), two PCs mirrors on both sides of the core. The presence of the periodic structures along the guiding direction results in DBR. We equal the system as a conventional three layer dielectric waveguides composed of the core, the cladding, and the substrate, as shown in Fig. 2(b). The dielectric constant of the core is that of the slab. The width W_M of the multimode region can be considered as the multiplier of the number of the rows of the removed holes and lattice constant a. Accordingly, W_M is $5a$ in Fig. 2(a). The optical properties of the substrate and the cladding are characterized approximately as average permittivity [6,7]:

$$\varepsilon_{\mathrm{ave}} = \varepsilon_{\mathrm{eff}} - \pi (r/a)^2 (\varepsilon_{\mathrm{eff}} - 1). \tag{1}$$

It is observed that the distribution of the refractive index is satisfied with TIR in the equivalent dielectric structure. Thus this structure supports multiple index-like guided modes controlled by TIR effect. It can be deduced that the excited modes will couple with each other and then MMI effect behaves like a conventional dielectric multimode waveguide. For the case of