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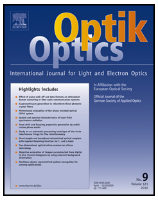

Wavelength-division-multiplexing system with photonic crystal self-collimation and co-directional coupling effect

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ABSTRACT

A wavelength-division-multiplexing system with high compactness and extremely simple structures is designed and analyzed theoretically for optical communication wavelengths. The structure consists of a self-collimation region, a coupler, a coupling section, and two arbitrarily bent periodic dielectric waveguides (PDWGs). Operation principle of the devices is based on self-collimation and directional coupling mechanism. The equal-frequency contours (EFCs) are nearly flat from 0.17–0.22 ($2\pi c/a$), thus the self-collimation region acts as a multiplexer. Operation principle of the demultiplexer is based on directional coupling in two parallel periodic dielectric waveguides. The device performances have been evaluated by the finite-difference time-domain simulations coupled with perfectly matched layer (PML) boundary conditions.

1. Introduction

In recent years, there has been a growing interest in the realization of photonic crystals (PCs) as optical components and circuits. A common use for PCs in integrated optical applications is that of optical beam splitting or combining [1–12]. This allows for division of an optical beam into multiple signals for density routing. In communication system or fiber optic sensors application field, wavelength-division-multiplexing (WDM) system is useful for better bandwidth utilization of multiplexing technology. Over the last decades, a WDM employing the conventional directional couplers has been studied, but the device size still remains very large. This is because of the weak coupling in horizontally arranged couplers. Recently, different photonic crystal WDM systems based on channel drop filters have been proposed [13–21]. Among various PC wavelength selective filters, add–drop filters utilizing resonant coupling between microcavity modes produced by point defects and waveguide modes created by line defects have recently become the focus of much attention [18–21]. However, PC-based devices have an intrinsic disadvantage that the device structures must follow the PC lattice orientation and require a wide PC background (at least several lattice constants) and usually occupy much space in transverse dimension. These may cause inconvenience for highly integrated photonic integrated circuits (PICs) [12]. Periodic dielectric waveguide (PDWG) has the ability to provide high transmission in arbitrary shaped device with very little space is a good candidate for building ultracompact devices [12,22].

In this paper, we continue our previous work and adopt the advantages of the self-collimation and directional coupling mechanism to propose a new kind of WDM system consisting of a self-collimation region, a coupler, a coupling section and an arbitrarily bent PDWG (shown in Fig. 1), the numerical results by using the FDTD method with perfectly matched layers (PML) absorbing boundary conditions demonstrate the performances of the system for optical communication wavelengths.

2. Description of the self-collimation region and the coupler

Self-collimation region can be formed by dielectric cylinder array in air or air-hole array in dielectric. A 2D PC with size of $11a \times 37a$ composed of square lattice of dielectric cylinders in air is considered, in which the dielectric constant of dielectric cylinders $\varepsilon = 11.56$ and radius of dielectric cylinders $R = 0.33a$ (a is the lattice constant). Only H-polarization (magnetic field along the cylinder axis) is studied in this paper. The dispersion and the equal-frequency contours (EFCs) diagram of this 2D-PC in the first Brillouin zone (BZ) are calculated by the plane wave expansion (PWE) method [23], the number of plane waves employed in the calculation is 961, the results are shown in Fig. 1. Within a range of **k**-vectors and normalized frequencies $f = 0.17–0.22$ ($2\pi c/a$) (c is the speed of light in vacuum), near the **M** point, the EFCs are nearly

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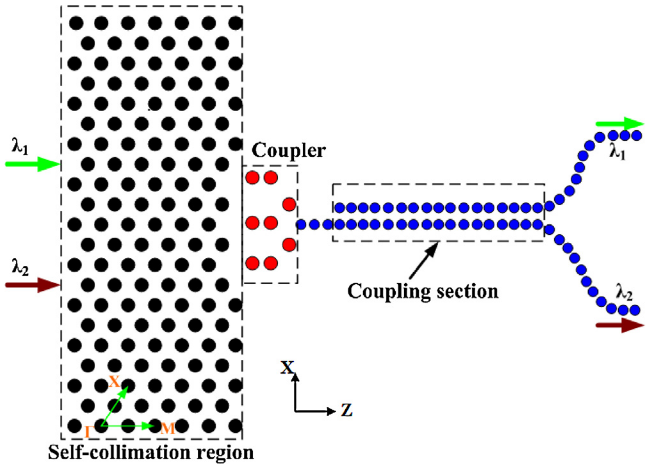

Fig. 1. The structure of the proposed WDM system. It consists of a self-collimation region, a coupler, a coupling section, and two bent arms.

flat and perpendicular to the ΓM direction, which means that self-collimation phenomena may occur, thus the self-collimation region can act as a multiplexer. The energy flow of light propagation, which is defined by the group velocity, $V_g = \nabla_k \omega(k)$, coincides with the direction of steepest ascent of the dispersion surface, and is therefore perpendicular to the EFCs. As indicated in Fig. 1(b), the light wave with **k**-vectors and normalized frequencies within such flat EFCs region has the group velocity v_g predominantly pointing toward the ΓM direction.

For photonic crystals self-collimated waveguides, properties of the surface layer or terminated surface provide a key physical mechanism for the excitation of surface modes, their constructive interference, and subsequent the highly directed emission. Here the coupler is introduced to form the directional emission and thus enhance the transmission of light to the coupling section.

3. Dispersion relations of the modes in the coupling section

To perform a function of WDM system, a directional coupling model is formed by arranging two parallel single-row PDWGs with a distance d, as shown in Fig. 2(a). The radius and the dielectric constant of the rods are taken as $0.35a$ and 9. By the PWE calculation, $d = 2a$ is chosen for the directional coupling model. Fig. 2(b) shows the band structure for the $a \times 14a$ supercell shown by the dashed frame in Fig. 2(a). It can be seen from Fig. 2(b) that there are two modes with different wave vectors and mode patterns. For operating at optical communication wavelengths, a is specified as $a = 270$ nm. Two normalized frequencies of 0.210 (a/λ) and 0.174 (a/λ) can be obtained for the wavelengths of $\lambda = 1.31$ and 1.55 µm, respectively.

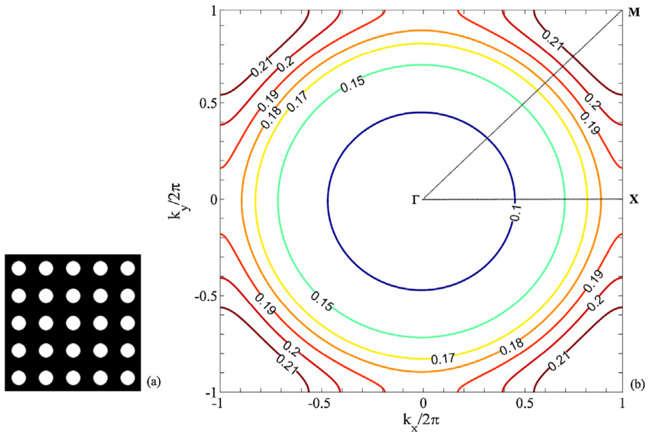

Fig. 2. (a) 2D photonic crystal consisting of a square lattice of cylindric air holes in silicon. (b) Equal frequency contours of the first band in the wave-vector space for TM modes.

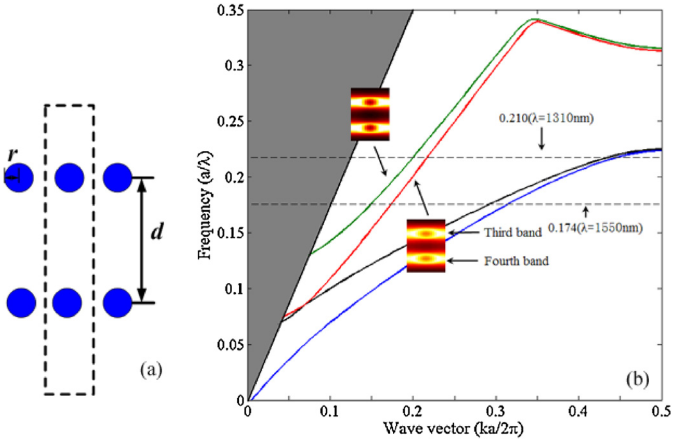

Fig. 3. (a) Directional coupling model. The dashed frame shows the supercell for the PWE calculation. The size of the supercells for calculating the band structures is $a \times 14a$. (b) Band structure of the model (choosing $d = 2a$). The mode patterns of the third and fourth band are shown in the insets.

The E-fields of the two PDWGs A and B fulfill:

$$\begin{cases} \dfrac{dE_A}{dz} = -j\beta E_A - j\kappa E_B \\ \dfrac{dE_B}{dz} = -j\beta E_B - j\kappa E_A \end{cases}$$

and

$$\begin{cases} E_A(0) = 0 \\ E_B(0) = 1 \end{cases},$$

where κ is the coupling coefficient. The solutions of the coupled mode equations are $E_A(z) = \cos(\kappa z)e^{-j\beta z}$ and $E_B(z) = -j\sin(\kappa z)e^{-j\beta z}$, respectively. And the coupling length is $L_c = \pi/2\kappa$. While the wave guiding mode traverses a distance of odd multiple of the coupling length (L_c, $3L_c$, $5L_c$, ..., etc.), the optical power is completely transferred into the other waveguide. But it is back after a distance of even multiple of the coupling lengths ($2L_c$, $4L_c$, $6L_c$, ..., etc.). If the wave guiding mode traverses a distance of odd multiple of the half coupling length ($L_c/2$, $3L_c/2$, $5L_c/2$, ..., etc.), the optical power is equally distributed in the two guides. If the two coupling lengths L_{c1} (for λ_1) and L_{c2} (for λ_2) satisfy $(2N - 1) \times L_{c1} = 2N \times L_{c2}$, where N is a natural number, we can route λ_1 and λ_2 to different output waveguides.

For 1.31 µm (0.210 a/λ) and 1.55 µm (0.174 a/λ), the respective coupling lengths $L_{c1} = 44.4a$ and $L_{c2} = 22.19a$ can be calculated by taking k_1 and k_2 from Fig. 2(b). The results satisfy $L_{c1} \approx 2L_{c2}$. Therefore, if the coupling region length L is set to be $L = 45a$, 1.31 µm can be totally coupled from one PDWG to the other while 1.55 µm will be totally coupled back into the original PDWG after twice coupling (Fig. 3).

4. Numerical results and the analysis

In order to verify our above conjecture, we perform a numerical simulation based on the finite-difference time-domain (FDTD) method which is a very powerful method to analyze electromagnetic problem due to its simplicity and accuracy. The FDTD method for solving Maxwell's equations has been the workhorse of computational electromagnetic in the time domain, due to its simplicity.