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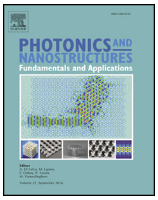

Investigation for ultra-shorten coupling length in woodpile structure

Zhifang Feng[a,*], Tingting Fu[a], Bin Yan[a], Rongjuan Liu[b,*]

[a] *Beijing University of Chemical Technology, Beijing, 100029, China*
[b] *Institute of Physics, Chinese Academy of Sciences, Beijing, 100080, China*

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ABSTRACT

An off-plane directional coupler in woodpile structure is investigated theoretically by finite-difference time-domain method. Our study shows that the coupling length can be adjusted effectively by controlling the refractive index in central region between input and coupling waveguides. And if the distance between rods is more than 1.5a, a coupling length less 2a can be also obtained, where a is the lattice constant. Also, we investigate the effect of the width of rods on the coupling length. The results show that the coupling length can be shortened further by decreasing the width of rods. All results we simulated are very important for the high-density integrated circuit.

1. Introduction

High-density photonic integration is an enabling technology for optical communication components that essentially depends on novel optical materials properties, both actives and passives, and utilizes photonic crystals. Woodpile structure has attracted a great deal of attention [1,2]. For example, it has a complete bandgap and can realize the omin-directional inhibition of light propagation. Since then, more and more reports about optical devices in woodpile structure have been proposed, such as 3 + 1 dimensional integrated optics [3], ultra-high-Q nano-resonators [4], high-Q microcavity [5], highly confined waveguides [6], planar and off-planar channel drop filter and so on [7,8].

It is known that the directional coupling is a key component for optical network. It can be used in many optical devices, such as optical fibers [9,10], optical switches [11,12], and wavelength demultiplexing [13,14]. However, coupling length in the directional coupler is a very important parameter to realize a high-density optical circuit. Therefore, it is very important to shorten effectively the coupling length. Now many researches both theoretically and experimentally concentrate on the two-dimensional photonic crystal (PC) slab [15–22]. For example, M. K. Moghaddam et al. [18] have proposed that the ultra-shorten coupling length less that 3a can be realized in two-dimensional photonic crystals when the triangular lattice of air holes are replaced by a rectangular lattice. Compared with the two-dimensional PC slab, the coupling region of directional coupler in woodpile structure can be three dimension space. Since, off-plane adjustment can be also considered.

In this paper, an off-plane directional coupler in woodpile structure is designed, simulated and analyzed. Our structure includes two x-type waveguides (WGs) as displayed in Fig. 1. The performance of the device is simulated using the finite-difference time-domain method. The commercial software we bought is developed by East FDTD, Dongjun Technology, Shanghai, China. The results show that the coupling length can be adjusted effectively by controlling the distance of the two rods and the width of rods. Moreover, an ultra-shorten coupling length less than 2a is also observed.

The rest of the paper is organized as following. In Section 2, an off-plane directional coupler are designed, simulated and analyzed. In Section 3, we analyze the effect of the two rods shifting on the coupling length. In Section 4, an ultra-shorten coupling is obtained by decreasing the width of rods. Finally, we summarize the paper in Section 5.

2. An off-plane directional coupler

A woodpile-structure is designed. It includes a certain number of rods with square section as 0.32$a \times$ 0.32a. The dielectric constant for background media and dielectric rods are 1.0 and 9.0, corresponding to the dielectric constant of air and Alumina (Al_2O_3), respectively. And the lattice constant is a. The complete bandgap is in the frequency range of 0.377-0.461[c/a]. Our structure includes 24 layers along the stacking direction. Off-plane directional coupler is designed as shown in Fig. 1. A directional coupler in woodpile structure is displayed in Fig. 1(a). In order to display clearly, we also

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* Corresponding authors.
E-mail addresses: liurj@aphy.iphy.ac.cn, fengzf@mail.buct.edu.cn (Z. Feng).

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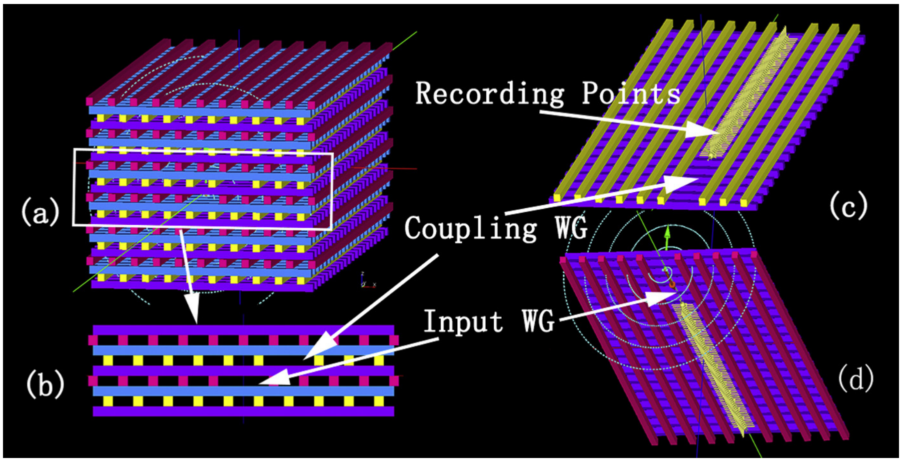

Fig. 1. (a) Schematic diagram of an off-plane directional coupler in woodpile structure. The dielectric constants for background media and dielectric rods are 1.0 and 9.0. The parameters for rods are $0.32a \times 0.32a$. (b) XOY plane structure. (c) Coupling waveguide included of recording points. (d) Input waveguide included of the light source.

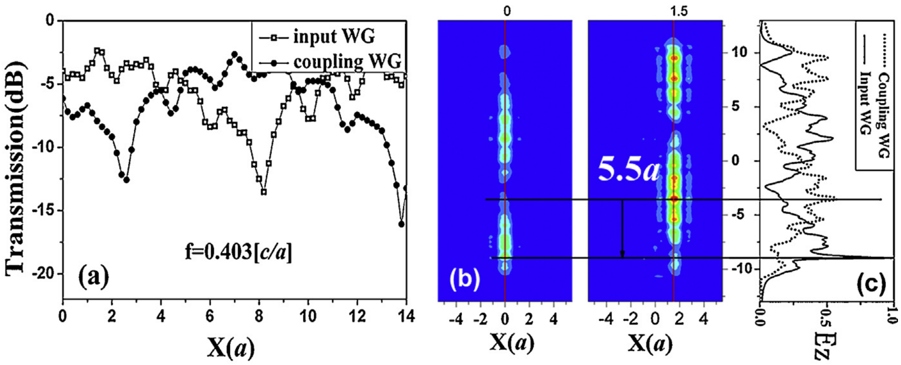

Fig. 2. (a) The relationship between the transmission intensity with the distance at the frequency of 0.403[c/a]. (b) The field distributions at the frequency of 0.403[c/a] for input and coupling WGs. (c) calculated Ez field pattern at the frequency of 0.403[c/a] for input WG (solid line) and coupling WG (dot line).

show the XOY plane structure included of nine layers (b), coupling waveguide included of all recording points (c) and input waveguide included of the light source (d). It is clear that the device is formed by two parallel x-type WGs. And both WGs are located at different stacking layers. Input WG is located at the 13th from the top of the sample, while coupling WG is located at 11thlayer. The horizontal and vertical distances between input and coupling WGs are $1.5a$ and $0.64a$, respectively.

In general, the coupling length can be given by analyzing the dispersion relation. In our simulation, the coupling length is determined accurately by transmission spectra and field distribution. Namely, many recording spots are introduced in input and coupling WGs as shown in Fig. 1(c) and (d). In our simulation, the interval between adjacent recording points is $0.2a$. The light source, which is located in input waveguide layer and propagates along y positive direction, is placed at the distance $1.5a$ from the before surface of the sample. And the electric field is always kept parallel to the stacking direction. In order to avoid the influence of the light source, the first recording point begins at the distance $5.5a$ from the before surface of the sample. By analyzing the transmission spectra for different recording spots, the relationship between transmission intensity and the distance at a specific frequency can be given. The field distributions are also simulated and analyzed by finite-difference time-domain (FDTD) method based on the Yee algorithm [23,24]. According to analysis for transmission spectra and E_z field patterns, the coupling length can be confirmed accurately.

Firstly, the transmission property is considered when the rods are not shifted. The transmission spectra for all recording spots are simulated and analyzed. The relationship between transmission intensity with the propagation distance at the frequency 0.403[c/a] can be given as displayed in Fig. 2(a). The hollow square-line is input WG, while the dot-line is coupling WG. From Fig. 2(a), we can observe that the wave propagates alternately between two WGs. It is known that the coupling length for the certain frequency is equal to the distance between adjacent peak and deep. According to the result, the coupling length at the frequency 0.403[c/a] is about $5a \sim 6a$. In order to determine accurately the coupling length, the field distribution is also simulated. The E_z recording planes are arranged in 11th and 13th layers, respectively. The result is shown in Fig. 2 (b). Both input and coupling WGs are displayed simultaneously. It is clear that the specific frequency wave is really propagated between input and coupling WG. By analyzing the relationship of propagation intensity with distance as shown in

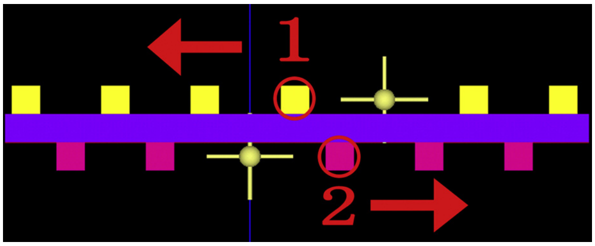

Fig. 3. Schematic diagram of the optimization design. The rods marked 1 and 2 will shift along the arrow direction.