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# Off-plane directional coupler in woodpile structure

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ABSTRACT

Directional couplers are essential building blocks for large scale optical integration equipments. Using finite difference time domain method, off-plane directional coupler formed by two straight waveguides in woodpile structure are designed, analyzed, and simulated. First, the coupler length for different frequency is given through analyzing transmission spectrum and field distribution. The results show that the light wave can be coupled from input waveguide to output waveguide. At the same time, off-plane power splitters and wavelength division multiplexers based on directional coupler are designed, simulated and analyzed. They also show good energy transfer property.



## 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 photonic crystals [1,2]. Photonic crystals (PCs), which are often fabricated periodic dielectric materials, have attracted a great deal of attention because of the existence of photonic bandgap (PBG) in which certain electromagnetic waves are forbidden to propagate in a particular frequency range [3,4]. When cavities or waveguides are introduced in such periodic structure, the defect mode will be produced in the PBG. It is possible to realize various active and passive optical devices in PCs which include cavity or waveguide. Over the past few years, various optoelectronic devices based on two dimensional (2D) PCs [5–16], such as power splitters [10–12], wavelength division multiplexers (WDM) [13,14] and channel drop filters [15,16], have been already reported theoretically and experimentally. In these devices, directional couplers [5–9] that the light wave can be coupled completely from one waveguide to another waveguide are very important.

Directional couplers, which are formed by two parallel waveguides (WGs) placed in close proximity, are essential components for optical network. There have many theoretical and experimental reports about directional couplers in 2D PCs [5–9], which are relatively easy to realize at optical wavelengths. Compared with two-dimensional PCs, three-dimensional PCs have an advantage of a complete bandgap within which light wave cannot propagate along any direction. It is expected to serve as a good platform for ultra-compact novel optical devices. In the past few years, woodpile structure has been investigated theoretically and experimentally [17–24]. Recently, in-plane optical devices in woodpile structure have been reported [18,20,21]. For example, Liu et al. [18] has designed a planar waveguide coupler, which is composed of two parallel straight type II Y waveguides.

In our paper, an off-plane directional coupler in woodpile structure is first considered. Our design involves two *x*-type WGs (input and output), which are located in different layers of a crystal platform. The performance of the device is simulated and analyzed by the finite-difference time-domain (FDTD) method. According to the transmission spectrum and field distribution, coupler length for different frequency can be given accurately. Based on this structure, off-plane power splitter and WDM are designed.

The paper is organized as follows: In Section 2, we briefly describe an off-plane directional coupler including two parallel waveguides in woodpile structure. In Section 3, we determine the coupler length by transmission spectrum and field distribution. We have also studied the off-plane power splitter based on directional coupler in Section 4. In Section 5, an off-plane WDM is considered. Finally, we summarized this paper in Section 6.

## 2. The structure of the off-plane directional coupler

A woodpile structure working in microwave wavelength is considered. It includes a certain number of rods with square section as

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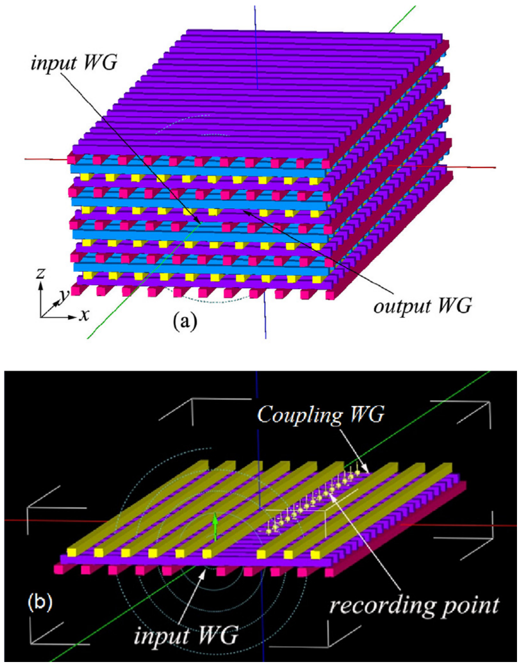


**Fig. 1.** (a) 3D schematic configuration of woodpile structure. (b) 3D schematic diagram an off-plane directional coupler including many recording spots.

3.2 mm × 3.2 mm. The dielectric constants for background media and dielectric rods are 1.0 and 9.0, corresponding to dielectric constant of air and Alumina ($Al_2O_3$), respectively. The center-to-center distance a between the rods is 10 mm and the filling ratio is 0.32. The light wave propagates along the *y* positive direction.

It is known that directional couplers are a key component for optical network. Many optical devices are designed based on directional couplers. To make full use of 3D PCs superiority, off-plane directional coupler must be considered. Since, we design an off-plane directional coupler as shown in Fig. 1 As described in Ref. [19], the waveguides in woodpile structure can be generally classified three types: *x*-type, *y*-type and *z*-type. In our design, *x*-type waveguide, which includes two pass bands, is selected. From Fig. 1(b), it is clear that the structure is composed of two *x*-type parallel waveguides (input and coupling or output) by moving one single rod. The input waveguide is located in the 9th layer, while the output waveguide is located in the 11th layer. The horizontal distance between two waveguides is 1.5a, while, the vertical distance is 6.4 mm.

The transmission propeties and field distributions are simulated and analyzed by finite difference time domain (FDTD) method based on the Yee algorithm [23,24]. A perfectly matched layer absorbing boundary condition, which is set at 8, is designed at the edges of the simulational zone. In all simulations, we only consider TM polarization. For the light source, we choose a Gaussian source.

## 3. Determining the coupler length

In general, the coupler length can be given by the dispersion relation. In our simulation, the coupler length is determined accurately by transmission spectrum and field distribution. Namely, we design many recording spots in input and coupling waveguide as shown in Fig. 1(b). The light source, which is located in input WG and propagates along *y* positive direction, is placed at the distance 1.5a from the left surface of the sample. In order to eliminate the influence of the incident light, the first recording point begins at the distance 5.5a from the left surface of the sample. The interval between the adjacent recording points is 2 mm.

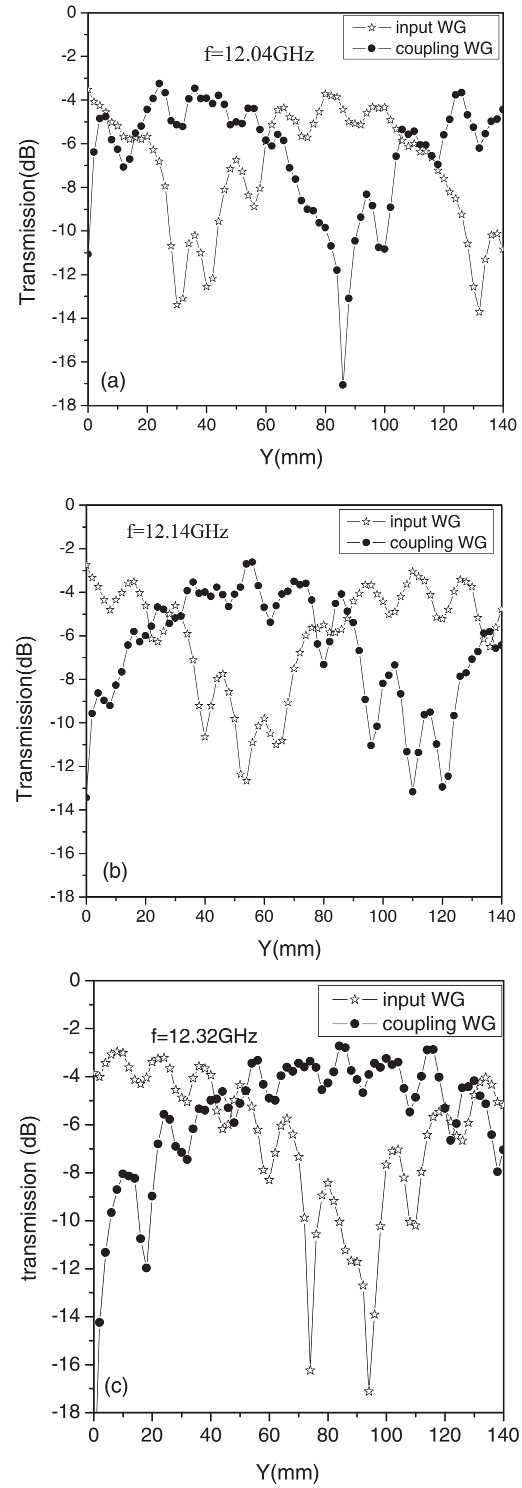


**Fig. 2.** The relationship between transmission intensity with the distance at the frequency of (a) 12.04 GHz, (b) 12.14 GHz and (c) 12.32 GHz, respectively.

The transmission spectra for every recording spots are given and analyzed by FDTD method. According to the transmission spectra, the relationship between transmission intensity with the distance for a specific frequency in input WG and coupling WG can be given as shown in Fig. 2 The frequency is 12.04 GHz, 12.14 GHz and 12.32 GHz in (a)–(c), respectively. From Fig. 2(a), we can see that the curve is similar to the sine variation. It is known that the coupling length is equal to the distance between adjacent peaks and deep. So, we can draw a conclusion that the coupling length at the