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Design of A Ring resonator based Directional Coupler using 2-D Chalcogenide Photonic Crystal

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ABSTRACT

A directional coupler based on ring resonator using 2-D chalcogenide photonic crystal of square lattice has been proposed. In this structure two parallel waveguides are coupled by a ring resonator. The transmission spectra for proposed structure is obtained and studied for possible applications in optical communication.

Key words: Design, Ring resonator, Directional Coupler, 2-D Chalcogenide Photonic Crystal

INTRODUCTION

Photonic crystals (PCs) have attracted a lot of interest due to their tremendous control over light. Photonic crystals are periodic arrangement of dielectric materials with alternating regions of high and low dielectric costants [1-3]. These materials exhibit a photonic band gap (PBG) where light possessing certain values of wave vector is not allowed to propagate in the material. Novel concepts have been proposed, and various new applications of PC have been predicted, *e.g.* optical cavity, waveguide, optical filters, beam splitters, channel demultiplexers, and optical switches primarily based on two-dimensional photonic crystal waveguide (PCW) [4, 5]. Slow light phenomenon used in PC waveguides can be used to increase light-matter interactions [6]. This is also useful in design of all-optical switch made using directional coupler [7]. When two waveguides are brought sufficiently close to each other so that their modal fields overlap, power can be transferred periodically between the two waveguides, such a structure is known as a directional coupler [8].

Chalcogenide glasses are infrared transmitting materials containing the chalcogen elements S, Se or Te, combined with one or more elements such as As, Si and Ge. Chalcogenides have generated a great deal of interest because of their attractive properties: glasses can be formed over a wide range of compositions; the refractive index is high, typically between 2.4 and 3, linear absorption losses are low over a wide wavelength range and a large $\chi(3)$ nonlinearity (much larger than Si) [9]. Thus, the chalcogenide glass PC platform appears to be a promising architecture for confining and guiding light [10].

By setting closely spaced two parallel 2-D PC waveguides, a directional waveguide coupler can be formed [11]. The main advantage of such approach relies on achieving strong coupling due to the separation between two waveguides. 2-D PC-based directional couplers have been previously proposed in a simple manner for implementing wavelength demultiplexers [12]. Furthermore, a three-port directional PC waveguide coupler with a coupling region of only 21 µm has been fabricated on a silicon-on-insulator wafer [13].

In the present work, the directional coupler is described consisting of a ring resonator near two air waveguides in two-dimensional (2-D) photonic crystal of square lattice.

NUMERICAL METHOD

Fig. 1 depicts the proposed directional coupler structure implemented on a square lattice consisting of a chalcogenide material of refractive index n = 2.405 and radius $r = 0.2a$ (a being the lattice constant) embedded in air. This structure has a photonic band gap (PBG) for TM modes ranging from 0.392316 to 0.466784 in normalized frequency units ($\omega a/2\pi c$). To create the waveguide directional coupler, two parallel waveguides are created by removing two entire rows of rods, which are separated by a ring resonator. The defect created between the waveguides introduces a localized mode in the PBG region. It is used to couple the light signal between two waveguides.

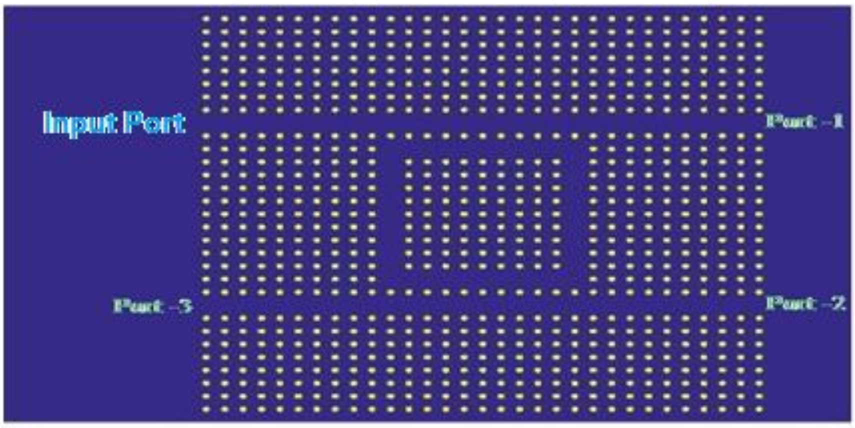


Fig. 1 The schematic diagram of 2-D chalcogenide photonic crystal as directional coupler

Waveguides in the 2D photonic crystal are studied using Finite-Difference Time- Domain (FDTD) method [13] with perfectly matched layer (PML). In the present work, we have used the FDTD method with a computational domain of 30x25 lattice constants (total 750 unit cells). The waveguides are along the direction of the longer side of the computational domain. Each unit cell contains 441 (21x21) discretization grid points for the FDTD time- stepping formulas. The computation domain is surrounded by PML. The total number of time steps is 10,000 with each time step $\Delta t = 0.99c/\sqrt{\Delta x^2 + \Delta y^2}$, where c is the speed of light and Δx and Δy are space intervals.

A pulse source is located at the input access waveguide. The source is the product of the Gaussian function and the exact solution (at the center frequency) of the guided mode in the access waveguide. Moreover, one can easily normalize the transmission spectra, by comparing the energy flow (Poynting vector) through the output port with that without PC waveguides in between.

The operational bandwidth of the waveguide coupler directly determines the bandwidth of the resonator. The amplitude of the waves in two parallel waveguides can be described by the following spatial coupled mode equations [14]:

$$\frac{dA_1}{dz} = -jk_1A_1 + \kappa_{12}A_2 \tag{1}$$

$$\frac{dA_2}{dz} = -jk_2A_2 + \kappa_{21}A_1 \tag{2}$$

Where A_i is the field amplitude and k_i is the wave vector in waveguide *i*, in the absence of the coupling. The coupling coefficients are related by energy conservation as $\kappa_{12} = -\kappa_{21}$ [14]. With the coupling coefficient expressed in the absolute value $\kappa \equiv |\kappa_1| = |\kappa_2|$, the propagation constants for the coupled system is given as

$$k_{1,2} = \frac{k_1 + k_2}{2} \pm \sqrt{\left(\frac{k_1 - k_2}{2}\right)^2 + \kappa^2} \tag{3}$$

and their spatial field distributions are a linear combination of the individual waveguide modes. Light entering intoeither one of the constituent waveguide simultaneously excites both eigenmodes. Because of their different propagation constants, the spatial beating between the two transfers power between the two waveguides in a back-and-forth manner [15]. Maximum power transfer is given by and reaches 70% when $|k_1 - k_2| \ll \kappa$. The interaction distance to achieve this maximal transfer is

$$T = \frac{\kappa^2}{\left(\frac{k_1 - k_2}{2}\right)^2 + \kappa^2} \tag{4}$$

$$L_c = \frac{\pi}{k_1 - k_2} = \frac{\pi}{2\sqrt{\left(\frac{k_1 - k_2}{2}\right)^2 + \kappa^2}} \tag{5}$$

The operation of an ideal circulator requires the waveguide coupler to satisfy the following two conditions over a broad range of frequencies: complete power transfer between the waveguides, and an identical interaction length. Consequently, for the constituent one-way waveguide and two-way waveguide, the ideal conditions include identical dispersion relation ($|k_1 - k_2| \ll \kappa$) and identical coupling constant κ over as broad frequency range as possible.

RESULTS AND DISCUSSION

When a source excites the one-way waveguide from input port, the waveguide coupler transfers power from the one waveguide to the second waveguide, as indicated by the field pattern in each waveguide fig 3. At the frequencies where the uncoupled dispersion relations intersect, maximum power transfer reaches 50% efficiency, consistent with the coupled mode theory [14]. Over the frequency range between 0.425×2*πc/a* and 0.46×2*πc/a*, the peak transfer efficiencies hover above 50%, because $|k_1 - k_2| \ll \kappa$ is satisfied. A small variation in the coupling coefficient κ is observed in this range, resulting in a variation in the interaction length. Even though for a circulator one must use a fixed-length coupler for the entire operational bandwidth, we accomplished transmission ripple over a 14% relative bandwidth at a center frequency of 0.428× 2*πc/a* with a waveguide coupler.

At the center frequency of 0.426× 2*πc*/*a*, significant transmission can be seen from Port 1 and Port 3. The transmission spectra between these ports over a range of frequencies near the center frequency are shown in Fig.2. The sum of the transmission to Port 1 and Port 3 remains close to 60%. The reflection indicates the performance of the circulator is mainly limited by the bandwidth of the waveguide coupler, rather than the discontinuities in the system.

The Normalized transmission spectra at different ports are plotted for 2D PC of square lattice from two waveguides for above geometry in Figure 2

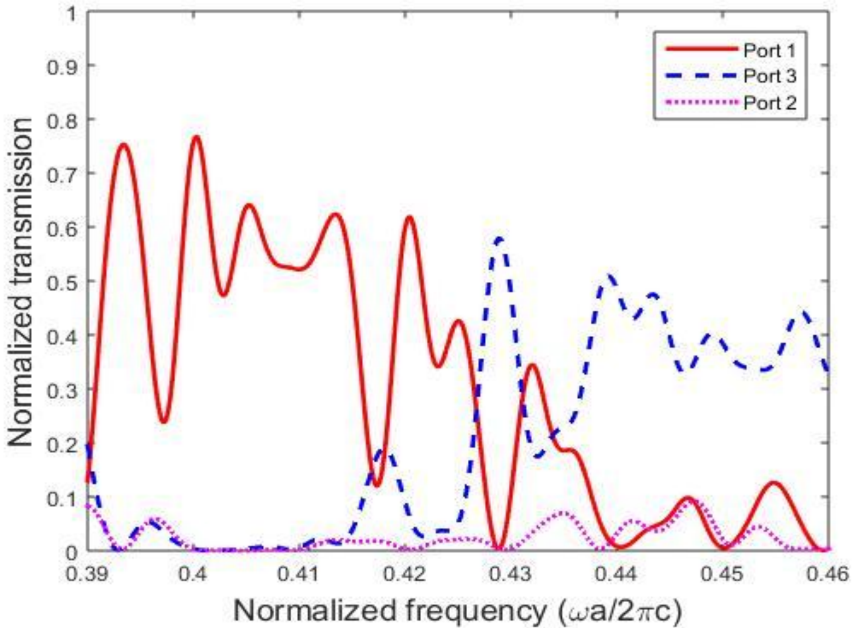


Fig. 2 Normalized transmission spectra for different port for 2D PC of square lattice from two waveguides

From Fig. 2 it can be observed that at port 1 we obtain about 60% transmission occurs between frequency range 0.39 to 0.425 in normalized scale. At port 1 at transmitted frequency values from 0.39 to 0.397 and 0.42 to 0.425 so that two narrow bands are open. This finds application as narrow band pass filter [16]. For frequency range 0.4 to 0.415 a wide band is open, so this can be used to form wide band pass filter. For frequencies 0.398, 0.418 and 0.428 the transmission is very low, so at these frequencies channel drop filter can be formed [17].

At port 3, about 50% transmission occurs between frequency range 0.425 to 0.46 in normalized scale. At port 1, in frequency range from 0.426 to 0.431 a narrow band with quality factor 85 is open. From frequency range 0.439 to 0.46 a wide band is open. At port 2 the transmission is very low.

At frequency 0.428, the transmission at port 1 is zero and at port 3 the transmission is significant. Therefore, when the frequency of the input signal is equal to the frequency of ring resonator, then the signal in the waveguide will be transmitted into the ring and we get the transmission from port 3, which is coupled to the ring.

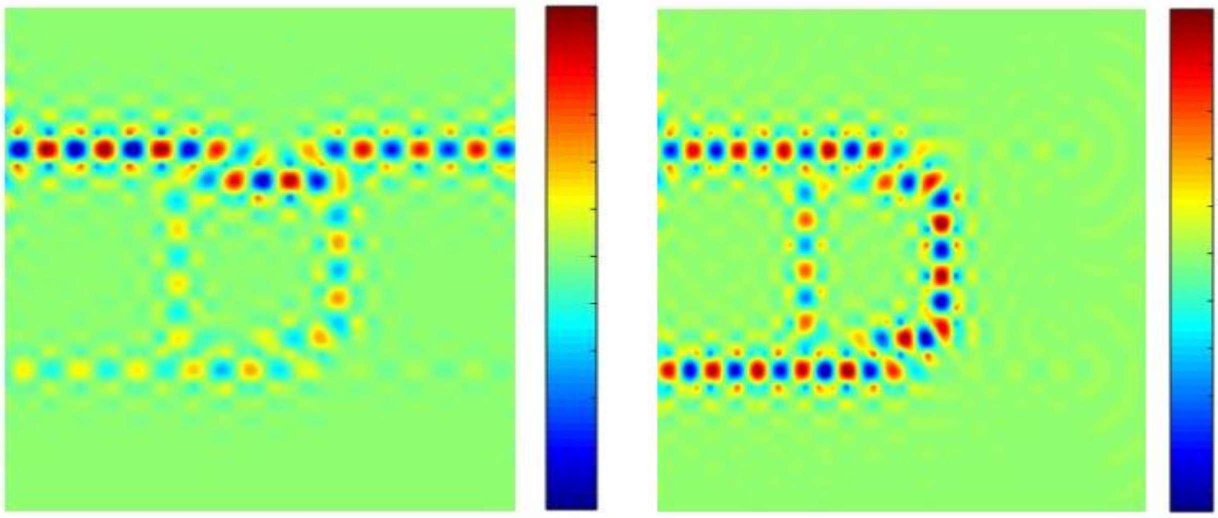
The coupling length between to waveguide is calculated using equation 5 in the normalized frequency range 0.425 to 0.46. In the normalized frequency region 0.426 to 0.431 the coupling is strong so we obtain a sharp peak and maximum transmission at port 3. But in region 0.439 to 0.46 the coupling is weak so the transmission curve is flat.

The variation in coupling length L_c with Δk values are displayed in table 1

Table -1 Variation in coupling length L_c with Δk

Δk(2π/a)	*0.005*	*0.021*	*0.035*
Coupling Length (L_c)	*100a*	*23.84a*	*14a*

The analysis shows that the coupling length L_c decreases with increasing Δk, which is similar result obtained by A. W. Lima et. al. [18]



(a) (b)

Fig. 3 The field distribution diagram for 2-D chalcogenide As_2S_3 photonic crystal as directional coupler for Normalized frequency (a) below 0.425 (b) above 0.425

The field pattern shown in figure 3 indicates that when normalized frequency is below to the value 0.425, we obtain the output at port 1. When the normalized frequency above to 0.425, the signal is transmitted through the ring and the output is obtained at port 3 by coupling the ring.

CONCLUSION

In the present work, a ring resonator based directional coupler is formed. The transmission and bandwidth of waveguide coupler was calculated using FDTD. It is found that the transmission for uncoupled mode is approximately 60%. In case of coupling the transmission is reduces to 50%. The coupling for directional coupler is found to strongly couple with the center frequency region. The field distribution was drawn and found to have the behavior similar to earlier researcher.

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