A Flexible Design of Waveguide Intersections with Low Cross-talk in Hexagonal Photonic Crystal Structures

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Abstract—A new design for constructing adjustable waveguide intersections in rode-type photonic crystal of hexagonal lattice is proposed. The design utilizes the strong dependence of the defect coupling on the cavities field pattern and their alignments. By changing the radii of the coupled cavities, an adjustable low cross-talk intersection is obtained.

I. INTRODUCTION

In recent years, photonic crystal (PC) researches promise compact optical integrated circuits due to potential ability of PCs to control of light propagation with the existence of photonic band gap (PBG) [1]. Waveguide intersections with low cross-talk and high bandwidth are a key element in implementation of integrated photonic circuits. In 1998 Johnson et al. proposed criteria to eliminate cross-talk for a waveguide intersection based on a two-dimensional (2D) square lattice PC by using a single defect with doubly degenerate modes [2]. Lan and Ishikawa presented another mechanism based on strong dependence of the defect coupling on the field pattern in the defects and the alignment of the defects (i.e., the coupling angle) [3]. They asserted that their design leads to a 10nm wide gain at the central wavelength of 1310nm with cross-talk as low as -10 to -45 dB, while in Ref. [2] the width of the transmission band with comparable cross-talk is only 7.8nm. In the above mentioned design, the value of the central wavelength of the low cross-talk transmission band depends to the radii of the air-holes in PC structure, so setting of the central wavelength of the transmission band is a challenge. Liu et al. proposed another waveguide intersection for light waves based on PC coupled resonator optical waveguide (CROW) [4]. In this paper we propose a flexible design for the construction of PC waveguide intersections of hexagonal lattice with low cross-talk. By changing the radii of the coupled cavities, an adjustable low cross-talk intersection, in the PBG regions of the PC structure, can be obtained.

II. FUNDAMENTAL APPROACH TO FLEXIBLE INTERSECTION DESIGN IN PCs OF HEXAGONAL LATTICE

As has been presented by Ref. [3], by combining of the coupled cavity waveguides (CCWs) with the conventional line defect waveguides a new waveguide can be constructed, which is referred to hybrid waveguides. In a CCW the defect coupling depends strongly on the field patterns in the defects as well as the coupling angles. Hence based on the field patterns in the intersections, prediction of the cross-talk is possible. For example for the isotropic field patterns, the coupling strength is independent of the defect alignment, so with this defect mode the cross-talk is large. In the case of the dipole field patterns, due to considerable overlapping of the field distributions, finite cross-talk will be obtained. Generally, the field patterns which have minimum overlapping of field distributions are desired. In Ref. [3] the value of the central wavelength of the low cross-talk transmission band depends to the radii of the air-holes in PC structure, so adjusting of the central wavelength of the transmission band is a challenge. In this paper we introduce a flexible design of low cross-talk intersections based on varying the radii of the coupled cavities which placed in the intersections. By this manner the central wavelength of the low cross-talk transmission band can be shifted in a wide-range domain. Fig. 1 shows the structure of the proposed intersection, which composed of interaction of two hybrid PC waveguides of hexagonal lattice. Generally, there are two types of PC lattice structures, air-hole-type and rode-type. Despite of easier fabrication of PC waveguide based on air-hole-type structures than rode-type, there are limitations on frequency bandwidth of the single mode region and the group velocity [5]. Moreover in PC waveguides based on rode-type structure the large bandwidth and the large group velocity can be achieved, and recently such waveguides have been used for fabrication of photonic devices [6].

III. SIMULATION AND RESULT

Without losing generality, here we consider a 2D hexagonal array of infinitely long dielectric rods (pillars) in air. The rods have refractive index \( n_{rod} = 3.4 \) and radius \( r = 0.29a \), where \( a \) is the rode-to-rod pitch. These parameters lead to a PBG for the TM mode (i.e., with incident electric field parallel to the rods) from \( a/\lambda_0 = 0.6542 \) to \( 0.7643 \) (third TM PBG), here \( \lambda_0 \) is the free-space wavelength. To determine the PBG regions of the PC structure, the MIT Photonic-Bands package is used.

To assess the performance of the proposed device, the finite-difference time-domain (FDTD) method is used for simulation.

Appendix [ 1 ]
All the FDTD simulations below are for TM polarization. The excitations are electromagnetic pulses with Gaussian envelope, which are lunched to the input port from the left. The field amplitudes are monitored at suitable positions around the intersection in horizontal and perpendicular waveguides. In FDTD calculations we set the grid size parameter to 0.04. Fig. 2 (a) and (b) shows the transmission properties of the intersection, where the radii of the coupled cavities are set to \( r_g = 0.62a \) and \( r_p = 0.64a \), respectively (we choose the lattice constant to be \( 1 \mu m \) in FDTD calculations). Fig. 3 (a) and (b) shows the transmission and the cross-talk of the intersection when the radii of the coupled cavities are set to \( r_g = 0.62a \) and \( r_p = 0.64a \), respectively. From Fig. 2 (a) and (b) can be seen that there exists around \( 6 \mu m \) regimes in which the transmission is about 0.45. Also Fig. 3 (a) and (b) depicts that there is cross-talk as low as \(-6 \) to \(-44 \) dB. Fig. 4 (a) and (b), shows the defect mode field distributions in one of the hybrid PC waveguide for wavelengths of 1.326 \( \mu m \) and 1.344 \( \mu m \), respectively.

Based on FDTD simulations can be seen that, varying the radii of the coupled cavities from 0.62a to 0.66a, leads to similar transmission properties, while the central wavelength of the transmission band varying from 1.32 to 1.37 \( \mu m \). Table 1 shows variations of central bandwidth, \( \lambda_{\text{cav}} \), of the transmission band for different radii of the coupled cavities. As can be seen, by increasing the defect radii the central wavelength of the transmission band also increases as expected from the electromagnetic variational theorem [1]. Consequently, we present an approach to construction of flexible PC waveguide intersections in which the central wavelength of the transmission bands is adjustable. It must be noted that, the transmittance of the intersection is only 0.45 which is originated from the coupling efficiency between the line defect waveguide and the incident field [7].

IV. CONCLUSION

In summary, by using of strong dependency of coupling strength on the field pattern in the defects and the coupling angles, we construct a low cross-talk waveguide intersection which consists of two crossing hybrid waveguide in the rode-type PC of hexagonal lattice. By varying the radii of the coupled cavities of the intersection an adjustable transmission band, in 50nm wavelength domain is obtained.

[2] Appendix
Figure 3. The transmission and cross talk in dB when the radii of the coupled cavities chosen to (a) \( r_2 = 0.62a \) and (b) \( r_2 = 0.64a \).

Table 1. Values of Central Wavelength of Transmission Band with Low Cross-Talk for Various Radii of Coupled Cavities

<table>
<thead>
<tr>
<th>( r_2 )</th>
<th>0.62( a )</th>
<th>0.63( a )</th>
<th>0.64( a )</th>
<th>0.65( a )</th>
<th>0.66( a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_{\text{cen}} )</td>
<td>1.326</td>
<td>1.339</td>
<td>1.344</td>
<td>1.365</td>
<td>1.377</td>
</tr>
</tbody>
</table>

References


Figure 4. The field distributions of the defect mode in one of the hybrid PC waveguide of the proposed intersection when wavelength is equal to (a) 1.326\( \mu \)m and (b) 1.344\( \mu \)m.