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Wavelength routers with low crosstalk using photonic crystal point defect micro-cavities

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ABSTRACT

A broadband photonic crystal (PhC) waveguide crossing is proposed with low crosstalk. On the basis of the structure, two 1×2 PhC λ-routers are constructed by exploiting several PhC point-defect micro-cavities. By means of the interference coupling between the point-defect modes in micro-cavities, the incidence light with the resonant wavelength can be routed to the designed output port in the router. To achieve the high routing efficiency with narrow pass-band width, the micro-cavity structure is elaborately engineered to satisfy the condition of the quality factor ratio, which consists of these rods with the gradual radii. Their performances are demonstrated by the numerical results calculated by the finite difference time domain (FDTD) and the plane wave expansion (PWE) methods. Furthermore, the analysis of the $4 \times 4\lambda$ -router configuration, obtained by assembling these basic wavelength routing elements, is reported to highlight its performances with a theoretical maximum crosstalk between the ports equal to −27.23 dB.

1. Introduction

The chip multiprocessor (CMP) architectures are composed of small processing cores and their multiple replications, which can get good results by using multiple threads across the cores with parallel code execution [1]. In the architectures, the communications among different cores plays a critical role, which is usually implemented by the aid of photonic communication network. In order to allow on-chip photonic communication, various components must be integrated into the photonic networks-on-chip (NoC), such as multiplexers/de-multiplexers [2], filters [3–5], modulators [6–8] and switches [9–11]. Among all these components, the switch is one of the most essential components to realize the signal routing functions among *N* transmitters and *N* receivers, and it also can be assembled into higher order matrices as the basic building block. By choosing the suitable states of the different switches, the signal within the network can be routed from the given input port to the given output port [12].

Based on thermo-optic effects in silicon-based switches [13,14], the active switch controls the signal paths dynamically according to the variation of the refractive index induced by applied voltages. While in passive switch components, the signal routing is always operated by means of the wavelength resonance mechanism [15–25]. Specifically, the routing function is realized by the resonant wavelengths of the routing devices encountered along propagation path. Therefore, the wavelength of the input optical signal decides its routing path, and the routing links are selected by changing the wavelength of the input signal. Compared with the active switch, the passive approach does not have the ability to reconfigure the routing links. Nevertheless, the passive switch has obvious superiority over the active device in other fields. For example, the passive component has lower power consumption and shorter signal delay than the corresponding active component.

In the past two decades, photonic crystals have inspired great interest due to their potential in building ultra-compact devices for integrated photonic network [26–42]. Due to periodic modulation of refractive index, PhC is able to inhibit the propagation of the light at given wavelength ranges, which is called photonic band gap (PBG) effect. Based on the PBG effect, a lot of optical devices, such as multiplexers/de-multiplexers, filters, modulators and switches, etc. have been designed and fabricated in PhC structure. Recently, a passive PhC router configuration has been proposed by exploiting PhC ring resonators [15,16]. Based on such routing mechanism, a 1×2 router is firstly built, and it is made of a broadband crossing between two PC waveguides and a PCRR. By assembling eight such 1×2 routers, a 4×4 λ router configuration is designed by the authors. However, in future photonic

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communication network, $N \times N$ λ-router configuration ($N \gg 4$) needs to be constructed, and it can be obtained by assembling a large number of 1×2 routers. If single 1×2 router cannot theoretically offer a low crosstalk, $N \times N$ λ-router cannot offer a suitable crosstalk level in theory due to the crosstalk accumulation from the massive assembling of 1×2 routers. Although the proposed crossing has the bandwidth of 280 nm (crosstalk is less than −10 dB) in Ref. [15], only 32 nm bandwidth can be realized at the low crosstalk of less than −30 dB. For such crossing structure, in one hand, within the wide bandwidth, its crosstalk is so large that the accumulation crosstalk cannot be endured in these cascaded crossing structures; on the other hand, with low crosstalk, the operation bandwidth is so narrow that $N \times N$ λ-router configuration ($N \gg 4$) suffers from the limited wavelength resources.

In this paper, with low crosstalk and wide bandwidth, a novel crossing structure between two PhC waveguides has been proposed. It consists of four 90° annular dielectric grooves, and the crosstalk values are less than −30 dB within 60 nm bandwidth, except at the frequency position in which the light is completely reflected back to the incident port. On the basis of the crossing structure, by means of the coupling interference between the point-defect modes in micro-cavities, the light can be routed from the input port to the designed output port. Based on the reflection feedback from the crossing or the wavelength-selective reflection micro-cavity, two 1×2 routers are designed, respectively. Within narrow pass-band width, to achieve high routing efficiency, a PhC micro-cavity with a high quality factor is elaborately engineered to satisfy the condition of the quality factor ratio, which consists of these rods with the gradual radii. On the basis of these 1×2 routers, a 4×4 λ-router is engineered and its behavior with theoretical low crosstalk is demonstrated by the numerical results, calculated by two dimensional finite difference time domain (2-D FDTD) method.

2. 1 × 2 routers using PhC point defect micro-cavities

The entire structure is designed based on a background PhC, and it consists of silicon rods ($\varepsilon = 12.0409$) of radius $r = 0.175a$ in air ($\varepsilon = 1$) with a square lattice of constant $a = 540$ nm. The photonic band-gap is present within the normalized frequency range of $0.30178(c/a) < f < 0.44735(c/a)$ only for the transverse magnetic (TM) mode with the electric field being parallel to the rods, where, f is the normalized frequency, and c is the light velocity in free space. Fig. 1(a) shows the waveguide crossing structure in Ref. [15], which is engineered by optimizing the position of the dielectric rods near the crossing (the rods are shifted $0.25a$ from their original lattice position along the horizontal and vertical directions) [15]. As mentioned earlier, this structure provides a broadband operation with large crosstalk, and only 32 nm bandwidth is present with the low crosstalk value of −30 dB.

As shown in Fig. 1(b), based on such background PhC, the proposed PhC waveguide crossing is constructed by four 90° annular dielectric grooves. The central point among four 90° grooves is named by O, and arbitrary two grooves are symmetrical in the space, so only the groove in the top left corner is described for simplicity. The centers of four annular grooves are the central points of four silicon rods, respectively, denoted by A, B, C and D, respectively. The radius of each annular groove is equal to $R = 3a$ and the width of each annular groove W_g is the same as the diameter of the background PhC silicon rods, i.e., $W_g = 2r$. The midline of the groove, tangent to the line through the centers of the inner row of silicon rods, starts at the center of the silicon rod denoted by E and ends at the one denoted by F. Such a topological structure is expected to provide a wide bandwidth with a low crosstalk. The validity of the proposed crossing will be discussed below.

The results are further demonstrated by calculating its transmission behavior. These numerical results are obtained by using 2-D FDTD method. In Fig. 1(b), as a Gauss pulse is launched at the W input port, its transmission spectra are displayed in Fig. 1(c), which are calculated by normalizing the transmitted power at the other output ports (i.e., E, S and N) to the input port W. The crosstalk between the different ports is set in decibels as $CT_{m,n} = T_n - T_m$ (m and n are W, E, S and N), where the transmittances at the through and isolated ports are denoted by T_m and T_n in decibels, respectively. The operation bandwidth of the crossing is defined as the wavelength range where the crosstalk is given under a certain standard reference value. As shown in Fig. 1(c), at CT ≤ −30 dB, the operation bandwidth is about 60 nm (i.e., from λ = 1529 nm to λ = 1589 nm), except the wavelength position around λ = 1539 nm, where the light with the wavelength is reflected completely back to the W input port. At λ = 1539 nm, the mode in the dielectric grooves is resonantly excited, and it is similar with one PhC micro-cavity coupled with the PhC waveguide directly. If the light with the wavelength can be routed at the low crosstalk, the operation bandwidth of 60 nm can be obtained for our proposed crossing at CT ≤ −30 dB, which is almost twice than that of the crossing in Ref. [15].

For the background PhC in Fig. 1(a), when the radius of these background silicon rods is increased to $r = 0.2a$ and other parameters are the same as those of the crossing in Fig. 1(a), its transmission spectra are displayed in Fig. 1(d). At CT ≤ −30 dB, the bandwidth is equal to 61 nm (i.e., from λ = 1572 nm to λ = 1633 nm), except the wavelength position around λ = 1600.2 nm with which the light is reflected back to the input port. Compared with the results in Fig. 1(c), the operation bandwidth in Fig. 1(d) is still about 60 nm at CT ≤ −30 dB. Fig. 1(e) shows the steady electric field patterns of the router at λ = 1585.5 nm, and the results with low crosstalk are further confirmed.

For the crossing structure consisting of four grooves with the radius $R = 3a$ and width $W_g = 2r = 0.4a$, because the light wave can alleviate the abrupt change of magnitude and direction vector of the wave-vector as soon as it possibly [27], the proposed crossing structure has wide operation bandwidth and low crosstalk. In essence, for the proposed annular structure, the light with TM mode is guided by the total internal reflection (TIR) effect, while the PBG effect is present for the crossing structure in Ref. [15]. For two crossing structures, the fabrication tolerances are of critical importance. The transmission spectra of the crossing structures are shown in Fig. 2 as the radius R and the width W_g of the grooves are changed. Fig. 2(a) and (b) show the results as only the radius R of four grooves are adjusted slightly ($R = 2.98a$ and $R = 3.02a$, respectively) based on the structure in Fig. 1(b). It is clear that about 40 nm bandwidth are present with the low crosstalk value of −30 dB in two cases. When only the width of these grooves are changed ($W_g = 0.36a$, $W_g = 0.44a$), the corresponding transmission spectra are shown in Fig. 2(c) and (d), respectively. About 40 nm bandwidth still can be obtained. From Fig. 2(c), there is even approximately 90 nm bandwidth present at CT ≈ −20 dB. With the increase of the width W_g, the internal modes are also increased in the grooves, so the transmission zeros are increased in the Fig. 2(d). The transmission spectra are shown in Fig. 2(e) when the radius and width of the grooves are random variation. For two grooves with the central points A and D, they satisfy the radius $R = 3.02a$ and width $W = 0.36a$, while $R = 2.98a$ and $W = 0.44a$ in the residual two grooves. About 40 nm bandwidth is present at CT ≈ −20 dB, the results indicate that the sensitivity to the fabrication errors is not so high due to the guiding mechanism with TIR effect.

As displayed in Fig. 1(d), at λ = 1600.2 nm, if the light with the reflected wavelength can be used as the routing signal, the operation bandwidth maintains the value of about 60 nm at CT ≤ −30 dB. Hence, a novel λ = 1600.2 nm router is built based on the proposed