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Photonic crystal higher order three-port channel drop filter

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ABSTRACT

We present a photonic crystal (PC) three-port channel drop filter (CDF) with flat-top response and high quality factor value of 8836.7, and it can be used in the dense wavelength division multiplexing (DWDM) system. The CDF is engineered based on the three-port system with the wavelength-selective reflection feedback, where both micro-cavities are the synthesized coupled-resonators. In this case, the conditions to achieve complete power transfer are same to that of the corresponding three-port system while both micro-cavities are the single-mode resonators. As two micro-cavities are single point-defect resonators or synthesized coupled-resonators respectively, it is confirmed that these CDFs exhibit different response characteristics by the simulation results calculated by using two dimensional finite-difference time-domain (2D-FDTD) method, and these filters will find applications in future wavelength division multiplexing (WDM) optical communication systems.

1. Introduction

Photonic crystals (PCs) channel drop filters (CDFs) have been engineered and fabricated owing to their compact and integrated characteristics. Because they have the potential applications in photonic integrated circuits (PICs) and dense wavelength division multiplexing (DWDM) optical communication systems, the researches have been focused in the areas [1–22].

In order to make full use of the precious bandwidth resources in DWDM systems, the CDFs are required to have high-Q-factor characteristics. At the same time, these CDFs are also required to have the transmission characteristics with steep roll-off and flattened pass-band. By engineering appropriate point-defect structure in PCs, the former can be quite easily obtained [3]. Whereas, the second requirement cannot be met in most case, where the CDFs are usually designed by utilizing the single-defect modes in PCs, and they have Lorentzian line shapes [4–9]. Noda's research group has engineered and fabricated the CDF with a flat-top and sharp roll-off response, where the high-order line shape is realized by introducing an additional point-defect micro-cavity based on the original filter with a Lorentzian line shape [21]. To realize high-order filtering performance, a third-order Chebyshev filter has been designed by using coupled point-defect resonators embedded in a 2D PC waveguide [3]. A similar CDF with Chebyshev frequency responses has also been designed based on the equivalent circuit model by Dai et al. [22]. These designs of higher-order pass-band filter will benefit greatly to the engineering of the high-order CDFs.

In this letter, the CDF with higher-order response and high quality factor is presented based on our previous three-port CDF. In the primary three-port CDF, two individual single-mode micro-cavities is used to obtain high channel drop efficiency [8]. For the CDF with a Lorentzian line shape, almost complete power transfer between the bus waveguide and the channel drop waveguide can be realized by means of the constructive interaction between two single-mode micro-cavities modes, where they are the channel drop micro-cavity and the wavelength-selective reflection micro-cavity, respectively. In this case, two synthesized coupled micro-cavities are adopted as two resonant micro-cavities, respectively. For the designed three-port CDF, according to aforementioned theory analysis, the phase conditions need to be satisfied in order to achieve high channel drop efficiency. Subsequently, the phase term is met by changing the propagation constant of the part of bus waveguide, which is located between the resonant micro-cavities, and it is completed by increasing the radius of two rows of rods at the nearest border of the corresponding bus waveguide section. For the CDF using two synthesized coupled micro-cavities, the conditions to achieve 100% channel drop efficiency are same to that of the primary three-port CDF using two single-mode resonant micro-cavities. Such higher-order three-port CDF can realize a multi-channel multiplexer/demultiplexer structure easily, and it

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maybe becomes an essential device in future DWDM optical communication systems.

2. Section

Fig. 1(a) shows a three-port CDF with two micro-cavities based on 2D PCs. The PCs consist of a square lattice of high-index dielectric rods (ε = 11.56) in air, where their radius is 0.20a, and a is the lattice constant. The periodic structure possesses a band-gap only for the transverse electric (TE) mode in the frequency range of 0.287c/a < f < 0.42c/a. As shown in Fig. 1(a), the channel drop micro-cavity is obtained by reducing the radius of one rod (r = 0.028a), and two surrounding rods have a radius of 0.163a, which are located at the interface between the cavity and drop wave-guide or bus waveguide, respectively. The wavelength-selective reflection micro-cavity is gotten by setting a point-defect rod adjacent to the bus waveguide. As shown in Fig. 1(a), the point-defect with the smaller rod has a radius of 0.028a, and the surrounding rod has a radius of 0.157a to preserve the same resonant frequency of two cavities, which lies between the cavity and bus waveguide. All the

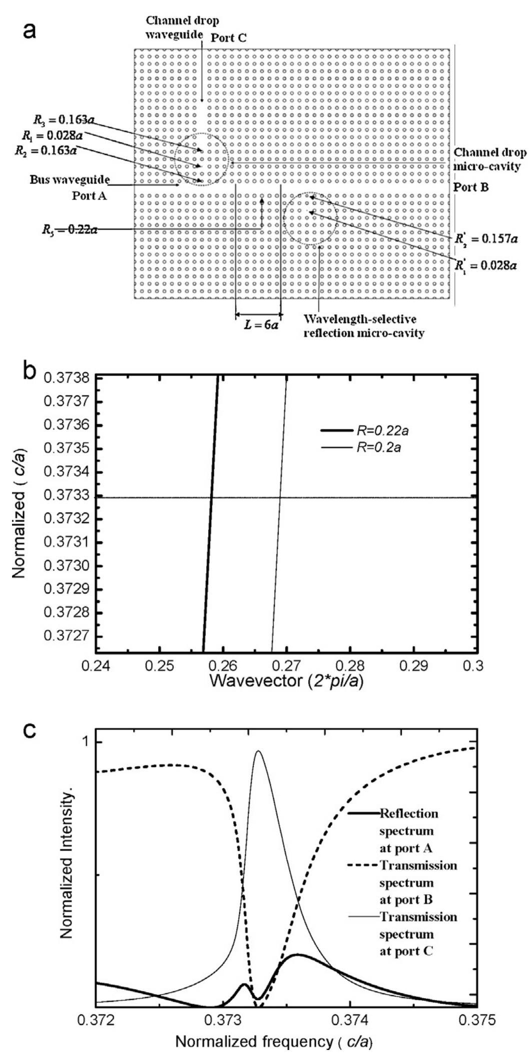

Fig. 1. (a) The structure of three-port CDF in 2D-PC of square lattice composed of dielectric rods in air. Two single-defect resonators are utilized as channel drop micro-cavity and reflection micro-cavity, respectively. In the bus waveguide section between two micro-cavities, the waveguide propagation constant is changed to meet the phase term, and the radius of border air holes in the waveguide section is R_5 = 0.22a. (b) Shift of PBG mode for different radii of border holes. (c) Transmission spectra for the designed CDF calculated using the 2D-FDTD method.

point-defect rods have the same dielectric constant as the background rods. By means of coupled mode theory (CMT) in time, the conditions to achieve complete power transfer via the system are [8],

$$\varphi = 2\beta(d-L) + 2\beta' L = 2(n+1)\pi, \quad (1)$$

except that the same resonant frequency of two micro-cavities and the certain ratio value of the quality factor for the channel drop micro-cavity need to be satisfied, where β is the propagation constant of the original bus waveguide at resonant frequency, β' is the propagation constant of the adjusted bus waveguide, d is the distance along the bus waveguide between two micro-cavities, L is the length of the changed bus waveguide, and n is an integer number.

In the above case, the resonant frequencies of two micro-cavities are calculated by using two dimensional finite-difference time-domain (2D-FDTD) method with perfectly matched layers (PMLs) absorbing boundary conditions. The simulation results show that they have equal normalized resonant frequency (f = 0.37329c/a), where c is the velocity of light in free space. Because the structure of the channel drop micro-cavity is similar with that of the corresponding micro-cavity in Ref. [8], the certain value of the quality factor ratio of the channel drop micro-cavity is also met.

The phase equation (1) is fulfilled by changing the dispersion curves of the bus waveguide section mode. In the above situation, we design that the distance d is equal to 14a. We raise the radius of the part dielectric rods R' = 0.22a, where they are adjacent to the bus waveguide core between the two cavities, and the length of the modified bus waveguide section L is 6a. Fig. 1(b) shows the change of dispersion curves of bus waveguide for two different radii of nearest neighbor dielectric rods, which are calculated by the plane wave expansion (PWE) method. As R' = 0.22a is satisfied, β' is 0.258(2π/a) for the modified bus waveguide at the resonant frequency 0.37329c/a, while β is 0.269(2π/a) for the original bus waveguide. With the radii of these border dielectric rods increased, on the contrary, the propagation constant of the waveguide diminishes. According to the expression (1), the phase φ is equal to 14.8π, which is approximately close to 15π. Then, it is clear that the term (1) is also satisfied in this example. Subsequently, the entire CDF is calculated by using the 2D-FDTD method. Fig. 1(c) shows that almost complete power transfer occurs at f = 0.37329a/λ. More than 95% channel drop efficiency is realized, and the CDF has a Lorentzian line shape with the low quality factor value of 1004.

To obtain higher quality factor and higher order filter response, synthesized coupled-resonator micro-cavity is utilized as channel drop micro-cavity or wavelength-selective reflection micro-cavity. The synthesized coupled-resonator micro-cavity is used to realize the third-order Chebyshev band-pass filter in Ref. [3], and the filter has a quality factor value of 8846.7, a flat bandwidth of 50 GHz, and ripples of 0.3 dB in the pass-band with a center frequency of 0.37329c/a. As shown in Fig. 2(a), the primary point-defect micro-cavity is replaced with the synthesized coupled-resonator micro-cavity, and it is chosen as a channel drop micro-cavity. In the synthesized micro-cavity, the radius of the smallest rods is R_1 = 0.08a, one rod with R_2 = 0.123a is placed in the parallel orientation on each side of the defect, and three rods with R_3 = 0.15a are put in the vertical direction on each side of the defect.

In Fig. 2(a), the wavelength-selective reflection micro-cavity is same to that in Fig. 1(a). In this case, the resonant frequencies of two micro-cavities are same, so other structural parameters are same to that in Fig. 1(a). The filter response has been calculated by 2D-FDTD method with PML absorbing boundary conditions. The transmission curves at port A, port B, and the back-reflection spectrum from port C are described as the thin solid, dashed, and thick solid lines, respectively. From Fig. 2(b), the transmission at port C is close to 100% at the resonant frequency. It is interesting to note that the reflection spectrum at port A is almost completely absent