High efficiency filtering using two-dimensional photonic crystal coupled cavity structures

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Transmission spectra of coupled cavity structures (CCSs) in two-dimensional (2D) photonic crystals (PCs) are investigated using a coupled mode theory, and an optical filter based on CCS is proposed. The performance of the filter is investigated using finite-difference time-domain (FDTD) method, and the results show that within a very short coupling distance of about 3λ, where λ is the wavelength of signal in vacuum, the incident signals with different frequencies are separated into different channels with a contrast ratio of 20 dB. The advantages of this kind of filter are small size and easily tunable operation frequencies.

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Photonic crystals (PCs) have attracted much attention since they were put forward by Yablonovitch and John[1,2], and many potential applications of them are proposed in nonlinear optics[3] and all-optical communication systems[4]. Micro- and nano-photonic devices based on PC structure, such as optical waveguide[5,6], beam filter[7], power splitter[8], optical bistable switching[9], and low threshold laser[10] are all widely investigated.

Among these various PC structures, PC coupled cavity structures (CCSs) attract special interests[11−14]. A PC-CCS, developed by A. Yariv's research group[11], is formed by a series of high quality cavities. When the coupling between cavities is weak, tight binding method can be used to derive the dispersion relation of CCS[11,14], and a broad continuous eigen frequency band can be predicted. PC-CCSs with the continuous bands have been widely used in power splitter[14], arbitrary bend waveguide[14], broad band optical limiter[15], and frequency conversion[16]. When the coupling between cavities are strong, the continuous band would reduce to discrete eigen states, and the tight binding theory becomes invalid[17]. Up to now, the continuous band CCS has been widely investigated, while the discrete CCS is seldom discussed[17,18].

In this paper, we investigate the spectrum properties of discrete mode CCS in a two-dimensional (2D) PC. Based on the results, we propose a kind of CCS filter and numerically investigate it using finite-difference time-domain (FDTD) method[19]. Results show that the advantages of this kind of filter are very short coupling length, high contrast ratio and easily tunable operation frequency band.

Figure 1(a) shows a typical CCS in a 2D PC. The PC is formed by infinite long dielectric cylinders according to square lattice, while the cavities are formed by removing a series of cylinders along the (1,0) direction. The lattice constant is a, radius of rods r is $0.2a$, and the relative dielectric constant ε_a is 11.56, so the refractive index n_a is 3.4. The background medium is the air with relative dielectric constant $\varepsilon_b = 1.0$, namely, the refractive index n_b is 1.0. The number of cavity is N ($N = 3$ in this figure). In order to obtain transmission spectra with proper line widths shown as follows, we introduce another freedom to the structure, i.e., the refractive index of the two rods to the two ends are changed to n_d, as shown by the two open circles of Fig. 1(a).

Figure 1(b) shows the filter formed by two CCSs with

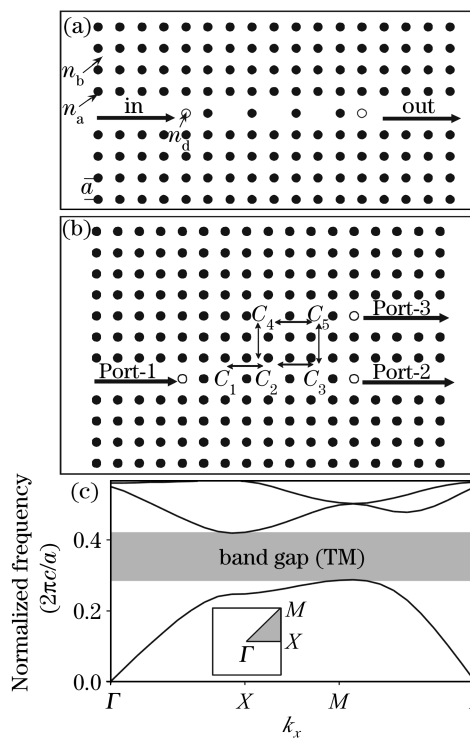

Fig. 1. (a) Schematic structure of a 2D CCS with $N = 3$ in square lattice PC embedded in air; (b) three-port filter formed by two CCSs. The small arrows between the cavities represent their coupling; (c) dispersion diagram of the PC structure for TM polarization mode. The band gap is about $(0.29 - 0.41)2\pi c/a$.

$N = 3$ and $N = 2$. Signals with different frequencies are sent into Port-1, then will be separated from Port-2 and Port-3 with a high contrast ratio. Figure 1(c) shows the band gap structure of the PC. A band gap for transverse mode (TM) mode (with electric vector parallel with the cylinders) opens in $(0.29 - 0.41)2\pi c/a$, and the filtering discussed in this paper is also limited to the TM polarization.

The coupled mode theory for discrete mode CCS in one-dimensional (1D) PC has been investigated in Ref. [17]. However, it should be developed further for the following two aspects. First, it is a 2D PC in our case while it is 1D in Ref. [17]. Second, the coupling between cavities C_n $(n = 1, 2, 3, 4, 5)$ is different, such as the coupling between C_2 and C_1, and that between C_2 and C_4, as shown in Fig. 1(b). In order to extend the coupled mode theory, we express the the eigen states of the CCS by the superpositions of that of each cavity,

$$\mathbf{E}(\omega, \mathbf{r}) = \sum_{n=1}^{5} A_n \mathbf{E}(\omega_0, \mathbf{r} - \mathbf{R}_n), \quad (1)$$

where $\mathbf{R}_n$ is the center coordination of the nth cavity, and $\mathbf{E}(\omega_0, \mathbf{r} - \mathbf{R}_n)$ is the eigen state of the nth $(n = 1, 2, \cdots, 5)$ cavity. ω_0 is the eigen frequency of a single cavity, and ω is that of the CCS. The coefficients A_n can be arbitrary numbers. $\mathbf{E}(\omega_0, \mathbf{r})$ satisfies the following normalized condition of $\int \varepsilon_0(\mathbf{r})\mathbf{E}(\omega_0, \mathbf{r}) \cdot \mathbf{E}(\omega, \mathbf{r})\mathrm{d}\mathbf{r} = 1$.

Considering the coupling between C_i and C_j (with $i, j \in \{1, 2, 3\}$ or $i, j \in \{4, 5\}$), and also those between C_i and C_k (with $i \in \{1, 2, 3\}$, and $k \in \{4, 5\}$), using a similar process proposed in Ref. [17], one also can obtain N eigenmodes for the N-cavity CCS filter of Fig. 1(b). The eigen frequency of the sth mode is

$$\omega_s = \omega_0 \sqrt{\frac{C^s - \beta'}{C^s - \alpha' + C^s \Delta\alpha}}, \quad (2)$$

$$\left(C^s = -\frac{1}{2\cos[s\pi/(N+1)]}, \quad s = 1, \cdots, N\right)$$

where $\Delta\alpha$ is the same as that in Ref. [17]. $\alpha' = (\alpha_1 + \alpha_2)/2$ and $\beta' = (\beta_1 + \beta_2)/2$, where $\alpha_1(\beta_1)$ and $\alpha_2(\beta_2)$ are the coefficients when the inter-cavity distance is $2a$, such as C_1 and C_2 in Fig. 1(b), and $3a$, such as C_2 and C_4 in Fig. 1(b), respectively.

We obtain the transmission spectra of $N = 2$ and $N = 3$ with different n_d using FDTD method, and the results are shown in Fig. 2. From Figs. 2(a) and (b), 3(2) peak values can be observed clearly for the 3-cavity (2-cavity) CCS. As shown in Figs. 2(a) and (b), when $n_\mathrm{d} = 1.0$ (dashed line), the confinement of the CCS is weak, which results in the linewidths of eigenmodes large. However, for a practical filter, a very small linewidth is always necessary, and this can be done by tuning the extra freedom of n_d. When we set $n_\mathrm{d} = 2.8$ (solid line), the linewidth of the eigenmode is decreased obviously, as shown by the solid line.

Figure 2(c) shows the transmission spectra from Port-2 (solid line) and Port-3 (dashed line) of the CCS filter. There are five transmission peaks for this 5-cavity structure, which agree with the coupled mode theory

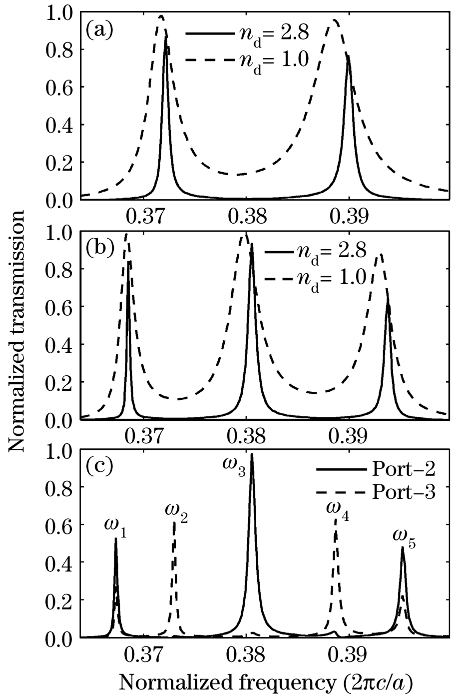

Fig. 2. (a) Spectrum changes with N and n_d. Solid lines are for $n_\mathrm{d} = 2.8$, and dashed lines are for $n_\mathrm{d} = 1.0$. $N = 2$; (b) the same as (a) but $N = 3$; (c) transmission spectra of the filter at Port-2 (solid line) and Port-3 (dashed line) with $n_\mathrm{d} = 2.8$.

presented above, and these frequencies can be divided into 3 groups obviously. The first group is $\omega_3 = 0.3802(2\pi c/a)$. The relative transmission of this frequency from Port-2 is $T_2(\omega_3) \approx 0.98$, while that from Port-3 is only $T_3(\omega_3) \approx 1.0 \times 10^{-2}$. The contrast ratio is about 20 dB. The second group includes $\omega_2 = 0.3728(2\pi c/a)$ and $\omega_4 = 0.3882(2\pi c/a)$. The transmission of this group from Port-3 are $T_3(\omega_2, \omega_4) \approx 0.65$, while those from Port-2 are $T_2(\omega_2, \omega_4) \approx 6.0 \times 10^{-3}$. The contrast ratio of this group is about 20.4 dB. The third group includes $\omega_1 = 0.3672(2\pi c/a)$ and $\omega_5 = 0.3946(2\pi c/a)$, which transmit from both Port-2 and Port-3 and cannot be used as a filter. For these two modes, the localizations in C_3 and C_5 are at the same order, which results from the coupling between C_1 and C_5.

In order to verify the results further, we obtain the field distributions at steady states for both the first and second groups using FDTD method, and the results are shown in Fig. 3. Figure 3(a) shows the field distribution of ω_2 (for ω_4, similar results can be obtained and are not shown here). The energy localized in C_5 is very large, while that in C_3 is very weak, therefore it can only transmit from Port-3. Figure 3(b) shows the field localization of ω_3. The localization intensity in C_3 is much larger than that in C_5, therefore it transmit from Port-2 mostly.

The above results and analysis show that for a two-color signal with frequencies of $\omega_2(\omega_4)$ and ω_3, after a coupling length of about $8a$ (about three times of wavelength of the signals in vacuum), the two signals can be separated to a ratio about 20 dB. Due to the easily

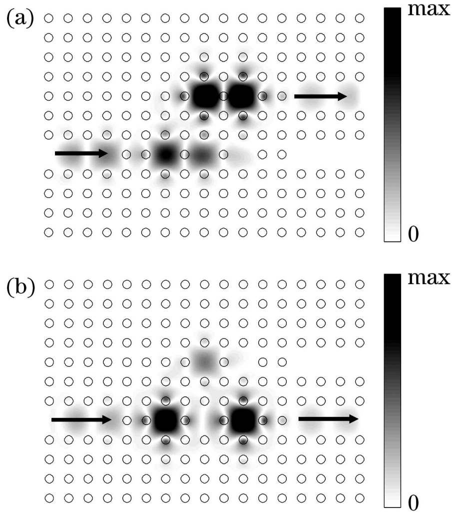

Fig. 3. (a) Distribution of electric field $|\mathbf{E}_z|$ inside the filter at steady state for $\omega_2 = 0.3728(2\pi c/a)$; (b) the same as (a) but for $\omega_3 = 0.3802(2\pi c/a)$.

tunable eigen frequencies of CCS, coupling strength and the eigen frequency of the single cavity, a proper structure for the required frequency band in practice can be easily found.

In summary, we have investigated the transmission spectrum of PC coupled cavity structure, and a coupled cavity filter is proposed. By tuning the confinement of the structure, we obtained the proper transmission linewidth. Using a coupling length of $8a$, the two operation frequencies are separated to a ratio about 20 dB. Due to the small volume, high efficiency, and easily tunable structure, this kind of filter may have potential applications in integrated optical circuits.

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References

1. E. Yablonovitch, Phys. Rev. Lett. **58,** 2059 (1987).
2. S. John, Phys. Rev. Lett. **58,** 2486 (1987).
3. V. Berger, Phys. Rev. Lett. **81,** 4136 (1998).
4. J. C. Knight, Nature **424,** 847 (2003).
5. A. Mekis, J. C. Chen, I. Kurland, S. Fan, P. R. Villeneuve, and J. D. Joannopoulos, Phys. Rev. Lett. **77,** 3787 (1996).
6. T. Yu, X. Jiang, Q. Liao, W. Qi, J. Yang, and M. Wang, Chin. Opt. Lett. **5,** 690 (2007).
7. S. Fan, P. R. Villeneuve, J. D. Joannopoulos, and H. A. Haus, Phys. Rev. Lett. **80,** 960 (1998).
8. M. Bayindir, B. Temelkuran, and E. Ozbay, Appl. Phys. Lett. **77,** 3902 (2000).
9. L. Chen, X. Deng, W. Ding, L. Cao, and S. Liu, Opt. Commun. **209,** 491 (2002).
10. M. Lončar, T. Yoshie, A. Scherer, P. Gogna, and Y. Qiu, Appl. Phys. Lett. **81,** 2680 (2002).
11. A. Yariv, Y. Xu, R. K. Lee, and A. Scherer, Opt. Lett. **24,** 711 (1999).
12. M. Bayindir, B. Temelkuran, and E. Ozbay, Phys. Rev. Lett. **84,** 2140 (2000).
13. S. Mookherjea and A. Yariv, Phys. Rev. E **65,** 026607 (2002).
14. E. Ozbay, M. Bayindir, I. Bulu, and E. Cubukcu, IEEE J. Quantum Electron. **38,** 837 (2002).
15. W.-Q. Ding, L.-X. Chen, and S.-T. Liu, Chin. Phys. Lett. **21,** 1539 (2004).
16. W. Li, L. Chen, D. Tang, W. Ding, and S. Liu, Opt. Eng. **46,** 064602 (2007).
17. W. Ding, L. Chen, D. Tang, W. Li, and S. Liu, Opt. Commun. **265,** 500 (2006).
18. W. Ding, L. Chen, and S. Liu, Chin. J. Quant. Electron. (in Chinese) **21,** 702 (2004).
19. A. Taflove and S. C. Hagness, *Computational Electrodynamics: the Finite-Difference Time-Domain Method* (2nd edn.) (Artech House Inc., Norwood, MA, 1995).