Design of optical notch filters based on photonic crystal micro cavities

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ABSTRACT

One of the most efficient and easiest methods to introduce a micro scale optical notch filter is to create a single point defect next to a line defect (waveguide) in a photonic crystal (PC) structure. Changing the nature and the size of the local defect can simply change the properties of the resonant modes. Increasing the radius of the defective rod leads to resonance of higher order modes and some degenerate modes. We have employed the 2D finite-difference time-domain method in a square lattice dielectric-rod PC structure to compute the frequency, symmetry, field distribution, coupling efficiency, and quality factor of the resonant modes of a point defect next to a waveguide for various sizes of the defective rod. We have shown that the quality factor of higher order modes can be more than 7 times greater than those of the lower order modes. So we can improve the spectral selectivity and give near-ideal drop efficiency for the notch filter.

1 INTRODUCTION

Photonic crystals are materials that have a periodic variation in refractive index. 2D PCs have received a lot of attention because of their possible use in integrated optics, where they might be used to control and manipulate the flow of light in an optical chip. In such applications the devices mainly use the most important property of PCs, photonic band gap (PBG). Most proposals for devices that make use of two-dimensional crystals do not use the properties of the crystal directly but make use of a defect mode [1]. Two main defect types are point defects and line defects which correspond to photonic crystal cavities and waveguides [2].

Any resonator next to a waveguide can lead to a PC notch filter; but the easiest method is to create a single point defect next to a line defect which also leads to great compactness, high wavelength-selectivity and ideal drop efficiency. By adding a point defect to a PC structure, a micro cavity can be made to trap electromagnetic energy with wavelength inside the PBG [2]. By increasing the radius of the defect, higher order modes can be motivated which may have quality factors greater than those of lower order modes.

In this paper, various properties of resonant modes for different sizes of the point defect of a notch filter are investigated using 2D finite-difference time-domain method in a square lattice dielectric-rod PC structure.

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2 PC NOTCH FILTERS BASED ON WAVEGUIDE-CAVITY COUPLING

Consider a 2D photonic crystal structure which consists of an array of infinitely long dielectric rods located on a square lattice of length *a* in air. Each rod has a radius of 0.2*a*, and a refractive index of 3.4. The structure exhibits a large PBG for transverse magnetic (TM) modes between the normalized frequencies 0.29 and 0.42 (in unit of *c/a*, where *c* is the velocity of light in vacuum) [3]. For the remainder of this paper only the PC structure mentioned above and only TM modes are considered.

A point defect can be made by changing the refractive index of a rod, modifying its radius, or removing a rod altogether. The defect can also be made by changing the index or the radius of several rods [3]. In reference [3] a point defect (by changing the radius of a rod) is introduced in the perfect array of rods and localized modes and their frequencies are obtained for different radiuses of the defective rod. Fig. 1 shows the result acquired in ref. [3].

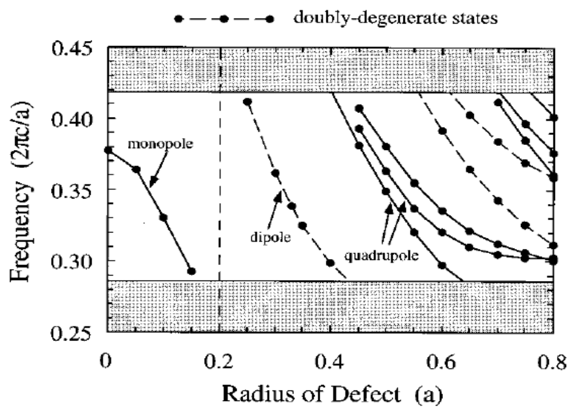
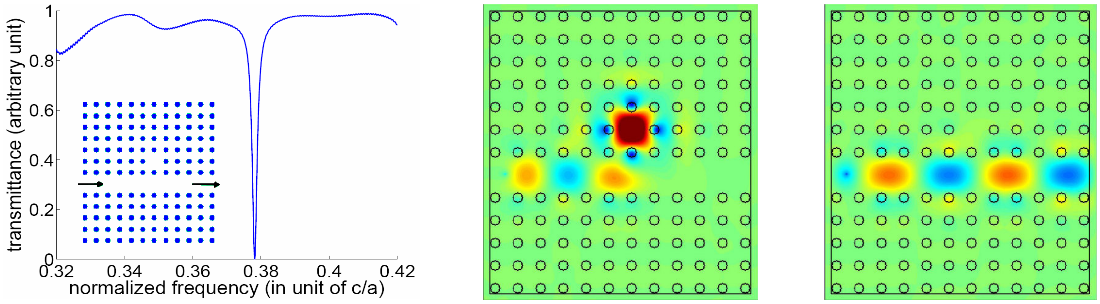


Fig. 1. Frequency of the defect states in an array of dielectric rods with radius 0.2a. The defect is introduced by changing the radius R of a single rod [3].

By putting a point defect next to a waveguide, it can be coupled to the waveguide at its resonance frequencies to trap some of the electromagnetic energy propagating in the waveguide. So the signal is dropped from the waveguide to the cavity at its resonance frequencies and is coupled back to the waveguide (reflection) [2]. It should be noted that Fig. 1 is no longer valid for a point defect which is put next to a waveguide. Resonance frequencies and even resonant modes are not exactly the same as what is shown in Fig. 1.

3 SIMULATION AND RESULTS

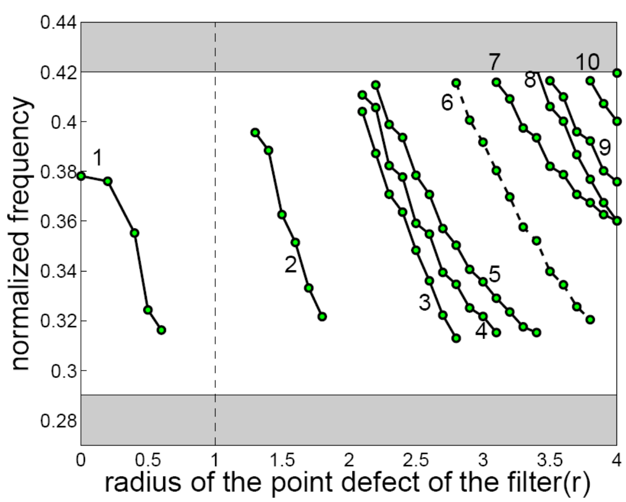
Fig. 2(a) shows the transmission spectrum of a PC notch filter composed of a cavity next to a waveguide. The cavity is created by removing a rod and the waveguide is created by removing a single line from the 2D PC. The inset is the schematic of the filter. This transmission spectrum and all other results throughout this paper are obtained using 2D finite-difference time-domain (FDTD) method [4]. Fig. 2(b) and 2(c) depict the electric field distribution of the filter at the resonance frequency and at a non resonance frequency. Since the field in the cavity doesn't have a node, it is called a monopole [3].



(a) (b) (c)

Fig. 2. A PC notch filter.(a) transmission spectrum, (b) electric field distribution at f=0.3781c/a, (c) electric field distribution at f=0.34c/a.

Now we investigate a filter whose point defect is created by changing the size of a rod. First, we gradually reduce the radius of a rod from the value of r=0.2a as the point defect. Initially, the perturbation is too small to couple any energy from the waveguide to the cavity. But when the radius reaches about 0.6r, a resonant mode appears in the vicinity of the defect. As the radius of the rod is further reduced, the filtered frequency sweeps upward across the gap. Fig. 3 shows the filtered frequency for several values of the radius. The filtered frequency can be tuned by adjusting the size of the rod [3].



1	Monopole	
2	Dipole	
3	Quadrapole(odd)	
4	Quadrapole(even)	
5	2nd order monopole	
6	Hexapole(degenerate)	
7	2nd order dipole	
8	Octapole(odd)	
9	Octapole(even)	
10	2nd order quadrapole(odd)	

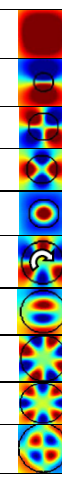
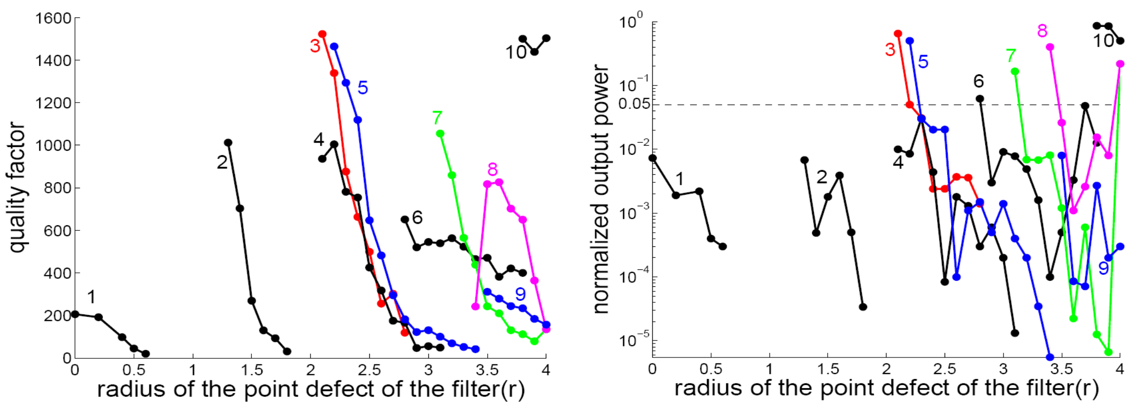


Fig. 3. Filtered frequencies and resonant modes of a PC notch filter for several values of the radius of the point defect.

Instead of reducing the radius of the point defect, now we gradually increase its size. When the radius reaches 1.3r, a dipole starts to resonate. Unlike what is shown in Fig. 1, it is not a doubly degenerate mode. Because of the presence of the waveguide next to the cavity, only the dipole which has an even symmetry (with respect to the line perpendicular to the waveguide) resonates. As the radius of the rod is further increased, the filtered frequency sweeps downward across the gap. As shown in Fig. 3, more resonant modes can be created in the cavity by increasing the radius further.

The coupling efficiency and the quality factor of different modes are different from each other. The drop efficiency of a notch filter is ideal if there is a strong coupling between the waveguide mode and the resonant cavity mode. A resonant mode with high quality factor can lead to a filter with a great spectral selectivity. Fig. 4 shows the quality factor and the output power of the notch filter (normalized to the input power) for different modes of different sizes of the point defect. It can be seen that some higher order modes have quality factors greater than 1400, whereas a monopole has a maximum quality factor of about 200. In order to design a high Q optical notch filter using diagram 4(a), two main issues should be noticed. First, the drop efficiency of the selected mode should be checked to be acceptable using diagram 4(b). The dashed line in Fig. 4(b) shows the 5% normalized output power which is the acceptable value for most applications. Second, the FSR (Free Spectral Range) should be checked using Fig. 3 to be more than the desired value for the considered application. FSR is defined as the spectral range between two successive minima in the transmission spectrum of the notch filter [5].



(a) (b)

Fig. 4. (a) Quality factor and (b) normalized output power of a notch filter for different modes of different sizes of the point defect.

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