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Fano Resonances from Quadrupole-dipole Split Mode Interference in Photonic Crystal Waveguide-single-cavity Structure

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Abstract. In this paper, a waveguide-single-cavity structure in a square-lattice photonic crystal is proposed to generate Fano resonances by the interference of two split modes in the structure with a rectangle defect column in the cavity. Through analyzing the band map of the modes in the bandgap region, Fano resonances with different line shape are found by tuning the parameters of the defect column. The results show that the bright and dark modes for Fano resonances are controllable by the parameters of the defect cavity simultaneously. The Q factor of Fano modes increases with the dark mode going farer from the bright mode and an ultra-high value 10^6 of Q is obtained. These Fano modes can be applied in many optical devices, such as ultra-narrow filters, switch, and sensors.

Introduction

Photonic crystals (PhCs) are periodic structures that are useful in controlling electromagnetic (EM) waves. PhCs contain regularly periodic dielectric constant in different direction, so that the motion of photons will be affected, waves with some wavelengths are forbidden in all directions and are called photonic bandgap (PBG). Distinct defective and localized properties in PhCs bring peculiar optical applications, such as omni-direction mirrors [1], micro-cavity devices [2], PhC waveguides (PCWs) [3], and PhC filters [4]. Furthermore, high Q-factor PhC cavities have the ability to concentrate electromagnetic fields in extremely small spatial regions, which attracted much attention and have been widely used in diverse area of research [5].

As is known, a Fano resonance arises from the interference of two difference modes. For their mode properties of asymmetric and ultra-sharp line shape, Fano resonances have been applied in many optical fields, such as optical switches [6], lasing [7, 8], and biosensors [9-12]. Fano resonances in high Q photonic crystal cavities always have extremely high Q factors [13]. The advantage of photonic crystal cavities with small mode volume and high Q factor has attracted tremendous interests for Fano device applications [14-16]. In 2D PhC cavity systems, Fano resonances as we known have been produced by the interference of two modes originated from different cavities. Few works illustrate Fano modes originated from the interference of two modes in one cavity.

In this paper, a simple defect PhC cavity embedded in a PCW is proposed to generate Fano resonances. Fano resonances are formed by the intersection of two split bands in one cavity, which are totally different with the case based on modes from different cavities. The results show that the bright and dark modes of the Fano resonances can be tuned by the parameters of the defect cavity simultaneously. Furthermore, these Fano resonances also have unique high Q-factor.

Schematic and Idea

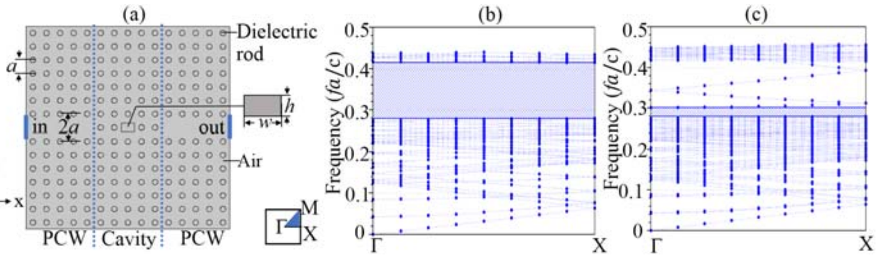

Figure. 1. (a) Schematic of the waveguide-single-cavity structure. (b) Band map of perfect PhC. (c) Band map of PCW.

A schematic of a point-defect-PhC cavity directly coupled with two PCWs as input and output ports is shown in Fig. 1(a). The cavity is formed by replacing the cylinder with a rectangular column in the center of the array. The structure has horizontal symmetry about the central vertical axis of the structure. The model is surrounded by perfect matched layer (PML) to absorb electromagnetic waves scattering to the free space. The constant of the square lattice PhC is a and the dielectric pillars with permittivity εr = 12.15 are arranged in air background. The width of the PCWs is 2a. The width (w) and height (h) of the rectangular defect pillar are the most important parameters for manipulating Fano line shape. Two ports are marked as blue color to guide the wave into and out the PCWs. A TE mode with electric field in z direction propagates from the port 'in' to the port 'out'. In simulation, we take the PCW and the cavity as supercells, respectively. Band maps based on the supercells were calculated before calculating the transmission properties and Fano resonance properties. The band maps are obtained by the plane-wave expansion method. The band maps of the perfect PhC and the PCW are shown in Fig. 1(b) and Fig. 1(c), respectively. We can see that this structure has a large PBG for TE mode between the frequencies 0.2788 and 0.4144 in units of fa/c (c is the light speed in vacuum), and the PCW has four waveguide modes in the frequency range of 0.3012–0.4144 in the PBG.

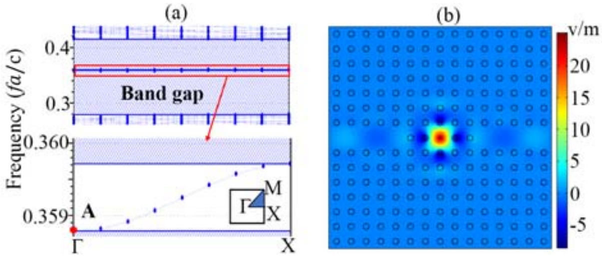

Figure. 2. (a) Band map with parameters of $h = 0.1a$, $w = 0.1a$ and the enlarged image of the band A, (b) the field distribution of a mode in band A in the PCW-cavity system at the red point when $fa/c = 0.358$ and $k = 0$.

The band map of the cavity based on the cavity supercell containing a rectangular defect column is illustrated in Fig. 2(a) with h = 0.1a and w = 0.1a. The band map shows a trapped band 'A' (or tunneling mode) in the PBG marked by a red rectangular box, enlarged in the lower part of Fig. 2(a). The tunneling mode is in the range of the PCW guiding mode, so it can propagate in the whole structure. The field distribution in the PCW-cavity system of this band is demonstrated in Fig. 2(b). Band 'A' in the band gap is produced by the localized mode that can tunnel through the cavity and propagate to the output port (resonance tunneling). Band 'A' can be called as cavity band as it is generated from the cavity resonance. There is only one cavity band in the band gap as the rectangular defect pillar or rod is small. Therefore, for a directly coupled system, more than one cavity is indispensable for using two modes to generate Fano resonances. In the following, we will vary the width 'w' and height 'h' to split this cavity mode into more than one modes for acquiring Fano resonances in a single cavity.

Intersection of Split Cavity Modes and Fano Resonances

Figure 3(a) shows the band map of the structure for h = 0.63a, w = 0.941a. Three bands appear as the height and width of the rectangular column in Fig. 3(a) increases. Two passbands are trapped in the PBG (diagonal-line-filled area), indicated with red rectangular frame. The enlarged image obviously illustrates the two bands very close to each other. They will intersect with each other by tuning the parameter w or h. The field Ez distribution for 'B' and 'C' are shown in Figs. 3(b) and 3(c),

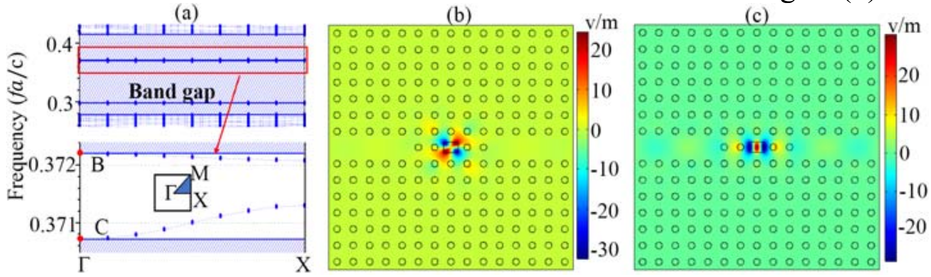

Figure. 3. (a) Band map for the parameters of $h = 0.63a$, $w = 0.941a$ (upper part) and the enlarged image of the cavity bands B and C (lower part). (b) The E_z distribution of band B at the red point in the PCW-cavity system for $fa/c = 0.3712$ and $k = 0$. (c) The E_z distribution of band C at the red point in the PCW-cavity system for $fa/c = 0.3697$ and $k = 0$.

respectively. It shows that 'B' and 'C' are quadrupole mode and dipole mode, respectively. The field distribution of the quadrupole is mainly constrained around the four corners of the cavity, and more dielectric pillars along the diagonal directions provides more restriction for band 'B', while more rods along *x* on the two sides of the cavity provides more restriction for band 'C'. As the two modes intersect, they can interfere to produce Fano resonances, and the quadrupole mode 'B' acts as dark mode with sharp spectrum shape, while the dipole mode 'C' acts as bright mode with relative broad spectrum shape. Physically this is understandable because in the diagonal directions more pillars exist, so there is stronger Bragg reflection along the diagonal directions than that by the pillars at the two sides of the cavity in the *x* direction, so that mode 'B' has narrower spectrum shape than that of mode 'C'. Moreover, the two bands can be controlled simultaneously by tuning the parameter '*w*' or '*h*'.

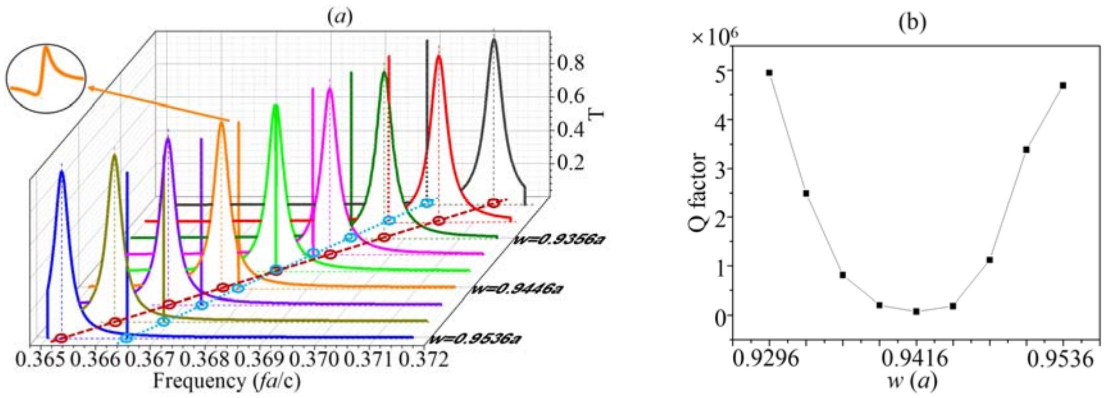

Figure. 4. (a) The transmission spectra for fixed h of 0.63a while w varies from 0.9296a to 0.9536a, the blue circles and the red circles represent the spectra position of Fano dips due to the dark mode and the Lorentz peaks due to the bright mode, respectively. (b) The Q factor of the Fano modes in (a).

Figure 4(a) shows the transmission spectra for fixed h of 0.63a while w varies from 0.9296a to 0.9536a. The different color curves represent different width of the rectangular pillar in the cavity. The blue and the red dashed lines represent dip and peak frequencies of the dark mode B and the bright mode C, respectively. The broad band of the bright mode C and ultra-sharp band of dark mode B are Lorentz and Fano line shape, respectively. Figure 4(a) shows that both the bright mode C and dark mode B have a significant linear blue shift with the decrease of w, while the bright mode C shifts faster than the dark mode B. Physically, this can be understandable because the field concentrates mainly in the rectangular pillar in the cavity for mode C, while the field concentrates at the four corners of the cavity, so that the effective refractive index for the cavity due to the rectangular pillar for mode C is much larger than that for mode B. As a result, mode C will have larger blue shift as w decreases. A symmetric line shape appears when the two modes coincide with each other at w = 0.9416a (the green curve). In Fig. 4(b) shows the influence of w on the Q factors of Fano resonances. When w = 0.9296a, an ultra-high Q factor of 5×106 is obtained with the dark quadrupole mode being relatively far away from the bright dipole mode. When w = 0.9416a, the Q factor takes minimum and the dark mode coincides with the bright mode. These Fano modes can be used in optical switches, ultra-narrow filters and sensors.

Conclusion

In summary, Fano resonances induced by two modes in a directly-coupled waveguide-single-cavity structure in a square lattice photonic crystal have been realized and numerically investigated. The origin of the Fano modes is the interference between the two cavity modes due to mode split by the rectangular pillar in the cavity. The Fano modes have ultra-high Q values, and the Fano resonance frequency can be controlled by the width of the rectangular pillar. The results can be used in multiple areas such as high-Q-factor filters, sensors, switches.

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