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Frequency tuned air-slot mode-gap cavities in two dimensional photonic crystals

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ABSTRACT

We present frequency tuned air-slot mode-gap nanocavities in two dimensional photonic crystals by introducing elliptical air holes in the cavity region. Shape alteration from the regular circle to ellipse offers a great structural freedom to tune the optical properties of the nanocavities. By changing the ellipticity and orientation angle of the ellipse, the resonant frequency of nanocavities can be continuously tuned almost covering the entire mode gap region. It is also found that the resonant frequency is very sensitive to the shape alteration and the fine tuning of the cavity resonant frequencies can be performed. The results show that our designs can be used to construct flexible PC devices with broadband and controllable frequency tuning.

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1. Introduction

Recently, various optical cavities have been developed and fabricated for the strong photon confinement and matter-field interaction. The typical cavities involve Fabry–Perot cavities [1], microspheres [2], whispering-gallery-mode resonators [3] and photonic crystal nanocavities [4–7]. In particular, two dimensional (2D) silicon photonic crystal (PC) nanocavities can have high quality factor (Q) and small mode volumes (V) approaching one cubic wavelength. They are currently attracting much interest for the realization of single photon emitters, highly sensitive sensors and strong coupling regime for quantum communication. In view of above applications, first of all, a narrow active region which can be air or filled with other nonlinear material is required for achieving strong coupling between the light and matter, meaning the photonic crystal nanocavity with high Q/V; in addition, resonant frequency tunability in a wider bandwidth is desirable for more freedoms and flexibilities in implementing dense photonic integration. Actually it is important not only to increase the Q factor but also to extend the operating wavelength ranges. Air-slot PC nanocavities [8–11] with wide frequency tunability offer a good choice for the above applications. So far, many different approaches have been developed to tune the resonant frequency of PC nanocavities. Methods based on free carrier injection [12], micro-electromechanical system [13] and gas condensation [14] can provide limited frequency tuning ranges, typically less than 10 or 20 nm. In contrast, structural changes to the PC cavities allow wider tuning ranges, although the changes are irreversible. Furthermore, composite structures can realize active and inactive tuning of cavity's frequency in wide ranges by importing structural changes into linear or nonlinear materials.

It is well known that structure is the kernel of nanocavity designing [15]. The shape of a nanocavity is also the key element for engineering its optical properties in addition to the size factor. In this letter, we present a tunable air-slot mode-gap nanocavity in 2D silicon photonic crystals by changing the shape of the nanocavity. When the shape of the air holes changes from circle to ellipse, the ellipticity and the orientation angle can have a great influence on the localized cavity modes. Through changing the ellipticity and the orientation angle of air holes in the cavity region, the resonant frequency can be continuously tuned in a wide range. The shape changing offers a new method to engineer the optical properties of PC devices. Our theoretical result indicates that our designs can be used to construct flexible PC devices with broadband and controllable frequency tuning. Although the presented designs are idealized 2D structures, it is feasible to implement such designs in 2D silicon PC slab.

This paper is organized as follows. We first present the design of our air-slot mode gap nanocavity and analyze its dispersion properties, from which we can find appropriate operation frequency for the nanocavity. In order to continuously tune the cavity resonant frequency in a wide range, we introduce elliptical-shaped holes in the cavity region instead of the regular circular air holes. Several

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kinds of nanocavities, including the "butterfly" nanocavity, are proposed and their optical properties are investigated by finite-difference time-domain simulations. We find that the shape alteration can have a great influence on the optical properties of the nanocavities. Finally, we briefly summarize this paper.

2. Nanocavity design and dispersion properties

The 2D PC is made of a triangular lattice of air holes immersed in silicon. The length of the PC's lattice constant is *a*, and the refractive of index of the background material is 3.45. We construct an air-slot PC nanocavity confined with mode gap. Fig. 1 shows the schematic diagram of the designed air-slot PC nanocavity. First, a major channel (W1 waveguide) is created by removing a single line of air holes along the Γ–K direction and it is a single mode waveguide. Then a 0.186*a*-width air-slot in the *y* direction is introduced into the center of W1 waveguide. An air-slot mode-gap cavity is formed by local modulation of the diameters of the two rows of air holes adjacent to the slot waveguide axis. The air holes in the red, blue and green boxes, which are shown in Fig. 1, are considered as cavity region, tapered regions and mirror regions, respectively. The air holes in the two green boxes are considered as the mirror regions, and their radius is 0.27*a*, the same as the air holes in the background PC. Correspondingly, the air holes in the red box serve as the cavity region, whose radius is 0.32*a*. The tapered regions in the two blue boxes are introduced between the mirror regions and cavity region to localize light more gently, whose radii of three air holes linearly decrease outwards from 0.32*a* to 0.27*a*. The detailed radii of air holes in the tapered region are 0.3075*a*, 0.295*a* and 0.2825*a* outwards respectively. Note that the radii of air holes in the cavity region and mirror regions are chosen as 0.32*a* and 0.27*a*, respectively, mainly for the reason that the suitable ratio of the air-hole radius *r* to the lattice constant *a* will result in a larger band gap and working bandwidth, which provide more freedoms and flexibilities in implementing integrated circuits [19–22].

To better understand the modes of air-slot PC nanocavity, we investigate the modes and dispersion of slotted PC waveguide for the background region and cavity region, respectively. The well-established 2D plane-wave expansion method is used to calculate the band structures for slotted W1 waveguide. In our simulations, 40 pixels per lattice constant *a* together with periodic boundary condition are used and good accuracy can be guaranteed. As shown in Fig. 2, the PC exhibits a 2D TE-polarized band gap ranging from 0.2037 to 0.2553a/λ. Two guided slotted waveguide modes appear

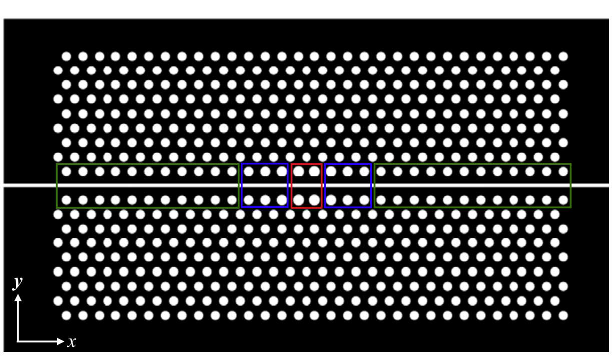

Fig. 1. The schematic diagram of an air-slot nanocavity confined with mode gap created in a 2D triangular-lattice photonic crystal. The air holes in the red box are considered as cavity region, where the radius is 0.32*a*, where *a* is the lattice constant. The air holes in the blue boxes are linearly decreasing in radius outwards from 0.32*a* to 0.27*a*, which make up the tapered regions. The radius of the air holes in the two green boxes is 0.27*a*, the same as the air holes in the background. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

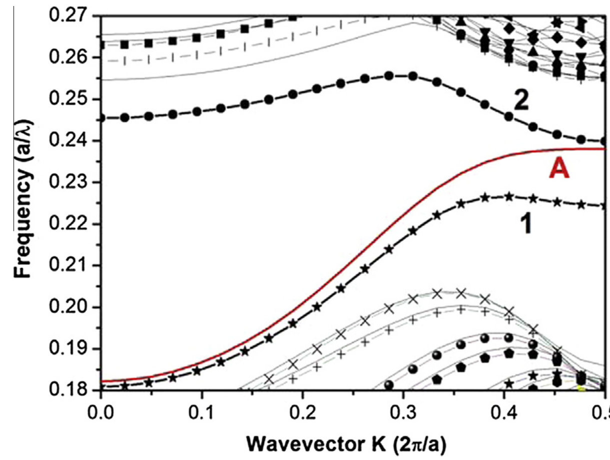

Fig. 2. The band diagrams for the 0.186*a*-width air-slot PC waveguide simulated by 2D plane-wave expansion method. The black star and circle dot lines correspond to the guided modes (mode 1 and 2) for the background air-slot waveguide with the radius of air holes being 0.27*a*, while the red line corresponds to the guided mode of the cavity-region air-slot waveguide with the radius of air holes as 0.32*a*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

within the whole TE band gap, which are designated as mode 1 and 2 by the black lines with star and circle points, respectively. Mode 1 and 2 can be classified to the fundamental even mode and higher-order odd mode, respectively, according to the symmetry of the E_y field component with respect to the mirror reflection plane passing through the waveguide central axis. As a result, a mode-gap region ranging from 0.2266 to 0.2403a/λ is formed between mode 1 and 2 for generating a high Q nanocavity when selecting suitable operation frequency. The corresponding geometric parameters of the designed PC structure are as follows: the air hole radius *r* is 0.27*a*, the width of air-slot in the y direction is 0.186*a*, and the refractive index of the background silicon is 3.45.

It is known that the waveguide modes can be tuned when changing the radius of the first row of air holes neighboring to the central axis of W1 PC waveguide [16]. Similarly, through changing the radius of the two rows of air holes adjacent to the slot waveguide axis to 0.32*a*, the slotted waveguide modes can be tuned to a higher frequency. As a result, the fundamental even mode 1 (now designated as mode *A*) still lies within the photonic band gap as shown by the red line in Fig. 2, while the odd mode 2 lifts to the higher frequency and be outside of the PC band gap. It is easy to find that the part operating frequency of even mode *A* locates within the mode gap region by comparing the band diagram of cavity region and background region. Therefore, above frequency region can be the suitable operation frequency for the air-slot nanocavity. In addition, the nanocavity has a rather large working bandwidth which supports a single mode from 0.2266 to 0.2403a/λ when the air slot width is selected as 0.186*a*.

3. Optical properties of the tunable air-slot nanocavities

Two dimensional finite-difference time-domain (2D FDTD) simulations [17,18] were carried out to analyze the transmission spectra of the designed air-slot mode-gap nanocavity shown in Fig. 1. In the simulations, 40 pixels per lattice constant *a* together with Berenger's perfectly matched layer (PML) boundary condition are used, which is enough for ensuring the good accuracy. The normalized resonant frequency of the nanocavity is 0.23519a/λ which corresponds to the fundamental even mode *A* in the mode gap region as shown in Fig. 2. In the above simulations, there are 3 air holes in each tapered region. Then we simulate different tapered regions

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