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Polarization sensitive near-complete reflection from photonic crystal slab in centered rectangular lattice

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In this study, reflective properties have been systematically calculated for two-dimensional photonic crystal slabs in centered rectangular lattices with elliptical patterns for transverse electric polarization along perpendicular *x*- and *y*-directions. The slab structures can be geometrically optimized for a near-complete reflection over a broad wavelength range. The reflection from the photonic crystal slabs is polarization selective, allowing a complete reflection for one polarization and complete transmission for the other polarization, which could be useful for a laser cavity mirror without using Brewster windows. The dependence of the reflection on the slab thickness and the structural parameters demonstrates the effect of guided-mode resonances on the reflection.
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I. INTRODUCTION

Two-dimensional (2D) photonic crystal (PhC) slabs have become a promising class of dielectric structures for micro- and nano-photonics due to their ability to control light at wavelength scales, and they offer opportunities for vertically stacked high density photonic/electronic integrations such as terahertz lasers,[1] semiconductor lasers,[2,3] high-quality resonance cavities,[4,5] and ultra-compact optical filters.[6–9] A broad-band near 100% reflection for normally incident light can be obtained with a single dielectric layer of a PhC slab, which is far more compact than traditional multi-layer film structures. The strong reflection from the 2D PhC slabs relies on the guided resonance (also called Fano resonance, in analogy to atomic physics) phenomena in the slabs, in which in-plane guided resonances are strongly coupled to out-of- plane radiation modes due to phase matching provided by the periodic lattice structure.[6–9]

If the reflection from the PhC slab can be designed to reflect one polarization completely while allowing 100% transmission for the other polarization, the PhC slab can be used as a polarization splitter with a complete contrast.[3,6] Control of the polarization mode in this way is expected to give rise to lasers with desirable features such as perfect single-mode emission over a large area, without the use of Brewster windows.[3,6] For terahertz wavelengths, there are challenges to making optical elements such as filters, reflectors, anti-reflection coatings, etc. due to the long wavelength.[1] The PhC slab mirror can provide a solution for these challenges. Traditionally, well-studied 2D PhC slabs consist of holes etched in dielectrics with square, hexagonal, or honeycomb lattices. Polarization selectivity of the reflection has been achieved by changing the circular unit cell pattern to elliptical in a square lattice.[3,10] There are also other methods of manipulating the electromagnetic wave polarization—for example, using metamaterials.[11]

In this paper, we study the normal-incidence reflection from PhC slabs in a centered rectangular lattice in order to increase the polarization sensitivity. The simulations show polarization sensitive, broad, near-complete reflection bands from the PhC slab. The broad reflection bands are shown to be related to guided-mode resonance.

II. SIMULATION MODEL

The symmetry of the 2D centered rectangular lattices is lower than that of 2D hexagonal lattices, which can be considered the special case of a centered rectangular lattice.[12] If the ratio of lattice constants in a centered rectangular lattice in the *y* and *x* directions of a Cartesian coordinate system equals $\sqrt{3}$, the lattice becomes hexagonal. Figure 1(a) shows a 2D PhC slab with an elliptical pattern in a centered rectangular lattice. The lattice constants in the *x* and *y* directions are labeled as *a* and *b*, and the axis sizes of the elliptical pattern are labeled as *dx* and *dy*, respectively. The thickness of the slab is *th*. The simulation of normal-incidence reflection from the PhC slab was performed for different lattice structures with *b*/*a* ratios between 1.4 and 2.5 using MIT's MEEP simulation software package.[13] For a structure with a certain *b*/*a* ratio, the normal-incidence reflection is simulated for various elliptical pattern parameters *dx* and *dy*. The initial values for *dx* and *dy* are of optimized structures in which the maximum overlap occurs for in-plane *TE* and *TM* photonic bandgaps for a 2D PhC slab with a thickness of 0.32*a*. The reflection was analyzed for electrically polarized light along the *x* and *y* directions.

MEEP control programs were written to model the geometry with a computational cell of *ab*, as shown in Fig. 1(b). The materials were distinguished by their different dielectric

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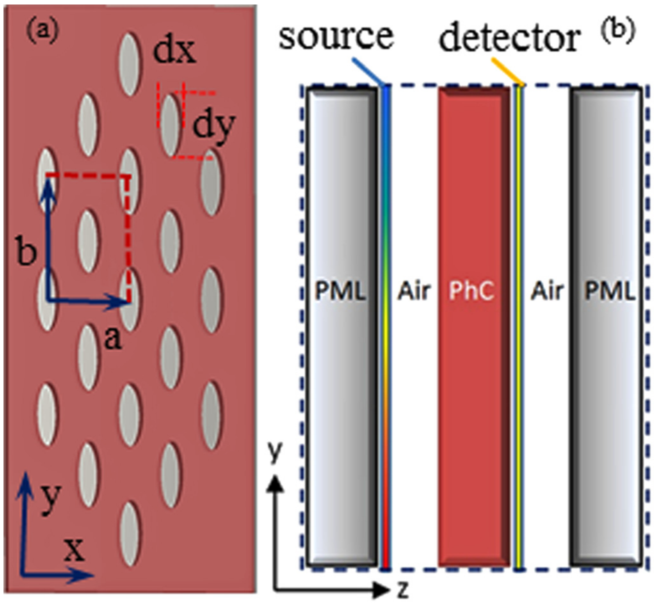

FIG. 1. (Color online) (a) Scheme of a photonic crystal slab with elliptical air-holes in a silicon background with geometric parameters. (b) Computational domain.

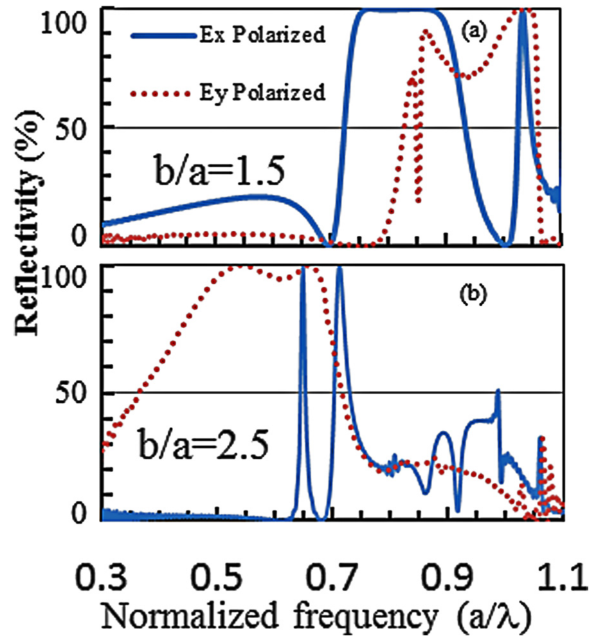

FIG. 2. (Color online) Polarization dependence of the reflection spectra from 2D photonic crystal slabs with different lattice constants of (a) $b/a = 1.5$ and (b) $b/a = 2.5$.

constants. A dielectric constant of 11.9 (a typical dielectric constant for silicon) was used for the high index material, and holes were introduced into the slab by choosing a dielectric constant of 1, representing air. The boundary conditions consisted of periodic boundary conditions in the x and y directions and perfectly matched layers in the z-direction. The structures were excited by a two-dimensional temporal Gaussian pulse source with a range of normalized frequencies (in units of a/λ) between 0.3 and 1.2 propagating along the z-direction. On the opposite end of the slab, a source detector was positioned. Two simulations were performed, one with and one without the PhC slab, in order to normalize the outputs as a percentage of the source input. The normal-incidence transmission was determined by dividing the flux obtained through the PhC slab by that obtained without the slab. The reflection was taken as one minus the normalized transmission percentage and may include losses.

III. RESULTS AND DISCUSSION

Figure 2 shows the reflection from PhC slabs with $b/a = 1.5$ and 2.5. The lattice with $b/a = 2.5$ is stretched from the hexagonal lattice, whereas the one with $b/a = 1.5$ is compressed from the hexagonal lattice. A region of high reflection appears for the compressed elliptical pattern ($dx = 0.91a$, $dy = 0.84a$) in the lattice with $b/a = 1.5$ and for the stretched elliptical pattern ($dx = 1.1a$, $dy = 1.41a$) in the lattice with $b/a = 2.5$. For $b/a = 1.5$, a broad region of reflectivity over 99% appears for E polarization along the x direction in a normalized frequency range between 0.75 and 0.88. The broad band reflection is due to both the guided-mode resonance (Fano resonance) and the constructive overlapping of guided-mode resonances.[6–9,14,15] The reflectivity drops to almost zero on either side of the broad spectrum around 0.69 and 1.01. Above 1.01, there is an asymmetrical high reflection peak due to a guided-mode resonance at a resonance frequency of 1.03. For the E polarization along the y direction, several guide-mode-resonance related peaks appear in Fig. 2(a). A transmission over 98% appears at the normalized frequency range between 0.73 and 0.77, overlapping with a partial section of the high reflection range for E polarization along the x direction. Such polarization selectivity is desired for the PhC slab to be used as a cavity mirror without a Brewster window.[3,6,10]

For the lattice with $b/a = 2.5$ in Fig. 2(b), both broad and narrow peaks appear due to the guided-mode resonance. In agreement with the lattice of $b/a = 1.5$, the high reflection region is also polarization-sensitive, and a complete reflection for one polarization and complete transmission for the other polarization appear at a certain frequency range. In contrast with the $b/a = 1.5$ lattice, the broad reflection appears for E polarization along the y direction here. Considering the elliptical pattern in the lattice, both broad reflections occur in the direction with a relatively large axis size of the elliptical air hole. This indicates that there is strong coupling between the incident wave and the leaky waveguide mode of the PhC slab along the major axis direction of the elliptical hole.

Figure 3 shows the normal-incidence reflectivity as a function of the slab thickness th for a lattice with $b/a = 1.5$ ($dx = 0.91$, $dy = 0.84$) for polarization along the x direction. Because the elliptical pattern was optimized for a high reflection for $b/a = 1.5$ and $th = 0.32a$, the reflection band becomes narrower in frequency and weaker with increasing or decreasing thickness. As shown in Fig. 3(a), when the thickness is increased from $0.32a$ to $0.35a$ and $0.40a$, the onset of near-complete reflection is shifted toward a lower frequency range (longer wavelength). This can be understood from the guide-mode resonance. With increasing

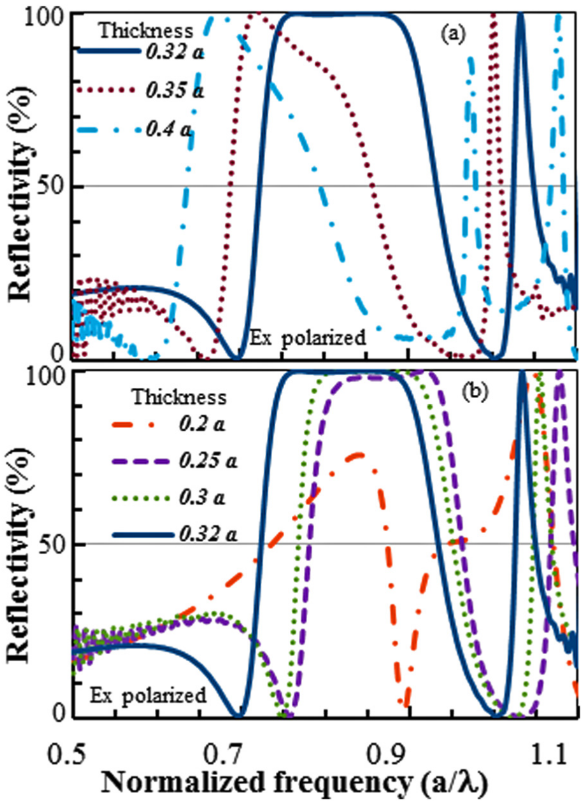

FIG. 3. (Color online) Thickness dependence of the reflection spectra from photonic crystal slabs in lattice with $b/a = 1.5$ and electric polarization in the x direction with (a) increasing slab thickness and (b) decreasing slab thickness.

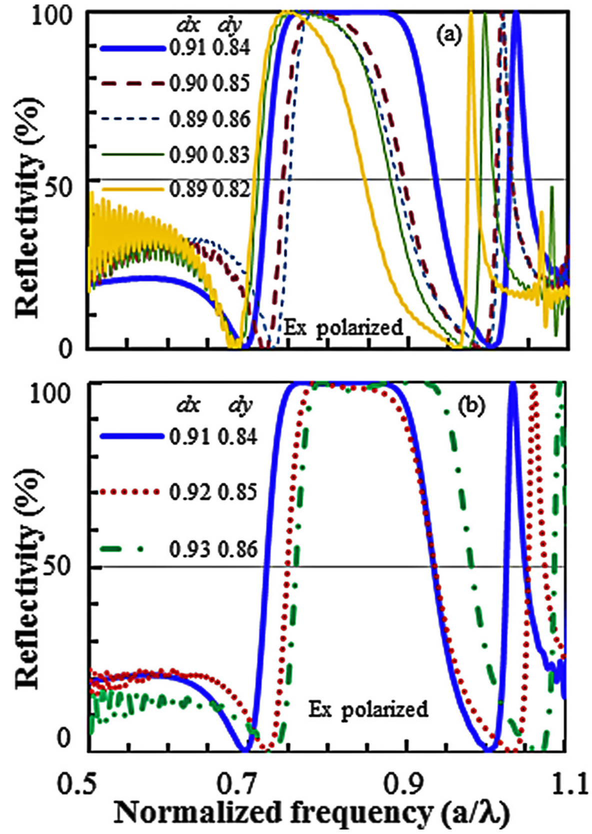

FIG. 4. (Color online) Structural variation dependence of reflection spectra from photonic crystal slabs in lattice with $b/a = 1.5$ for electric polarization in the x direction when the major axis size of the air hole becomes (a) smaller and (b) bigger.

thickness, the effective refractive index of the PhC slab increases, and thus the wavelength of the leaky waveguide mode increases. With the same in-plane elliptical pattern parameters and increasing thickness, the wave with a shorter wavelength has a weaker mode confinement than the one with a longer wavelength. Thus the shape of the high reflection band becomes less symmetric with a higher reflection at longer wavelengths.[14]

When the thickness decreases from $0.32a$ to $0.30a$ and $0.25a$, as shown in Fig. 3(b), the location of the near-complete reflection band is shifted toward a higher frequency range (shorter wavelength) due to the fact that the effective refractive index of the PhC slab decreases. When the thickness drops to $0.20a$, the broad reflection band becomes narrower, and the asymmetric Fano-resonance is clearly seen.

Figure 4 shows the normal-incidence reflectivity of the PhC slab changing with a parameter variation of the elliptical pattern in the lattice of $b/a = 1.5$ for polarization along the x direction. As shown in Fig. 4(a), the reflection band becomes narrower and the reflectivity becomes smaller when the major axis size of the air hole becomes smaller. The onset of near-complete reflection is shifted toward a higher frequency range (shorter wavelength) with increasing air-hole size (dashed lines) due to the fact that the effective refractive index of the PhC slab decreases. On the other side, the onset of near-complete reflection (solid lines) is shifted toward a lower frequency range (longer wavelength) with decreasing air-hole size. Figure 4(b) shows the normal-incident reflectivity of the PhC slab changing with the increasing major axis size of the air hole for polarization along the x direction. At $dx = 0.93a$ and $dy = 0.86a$, the reflection band is still broad, but the reflectivity drops in the central part of the band. The location of the broad reflection is shifted toward a higher frequency with increasing major axis size due to decreasing effective refractive index. The fact that these interesting phenomena in Figs. 3 and 4 can be explained by the effective refractive index related to a leaky waveguide-mode further indicates that the strong broad reflection is due to guided-mode resonance.

IV. SUMMARY

In summary, the normal-incidence reflection has been studied for PhC slabs with elliptical air holes in a silicon background in lattices with centered rectangular symmetry. Near-complete reflections over a broad wavelength range have been simulated. The reduced symmetry in the lattice and the pattern has increased the polarization sensitivity, allowing a complete reflection for one polarization and complete transmission for the other polarization, which could be useful for a laser cavity mirror without using Brewster windows. The dependence of the high reflectivity on the slab thickness and elliptical air-hole structural parameter has been studied and explained by guided-mode resonance theory.

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