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The Quality Factor in 2D Anisotropic Photonic Crystal Cavity

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This work focuses on the study of the influence of geometrical parameters on the quality factor of a cavity H1, realized with one missing hole in the center. For obtaining the H1 characteristics and the band structure of the photonic crystal, the finite difference time domain (FDTD) method, which is based on solving Maxwell's equations in a spatially and temporally discretized domain, and plane wave expansion (PWE) method, which is a resolution method of Maxwell equations in the frequency domain, were used respectively. In this method, one simulates a space of theoretically infinite extent with a finite computational cell. The quality factor increases until a maximum value equal 1.23×10^6 for a filling factor $r/a = 0.44$, and then decreases to a value of 3.39×10^5 for a filling factor $r/a = 0.47$.

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1. Introduction

The idea of photonic crystals (PhCs) was created by Yablonovitch and John in 1987 [1–2]. PhCs are new materials, optical properties of which help to manipulate light across the wave length, along two or three space directions. From a theoretical perspective, the study and development of the properties of photonic bandgap materials is based on the strong similarity between the Schrödinger and Maxwell equations. They were shown to be analogous to an integrated optical semiconductor. Many of the most interesting applications of photonic crystals are associated with imperfections or defects in a periodic structure. This is primarily because defects often support localized optical states with completely different properties, compared to the extended states within the bands. Two possible defect types are the point defect and the line defect, which correspond to a photonic crystal cavity [3–4] and photonic crystal waveguides [3]. Photonic crystal cavity with high Q can be effectively used for point defect lasers [5], optical filters [6–7], and cavity quantum electrodynamics (QED) [8–9]. The design of photonic crystal cavity with prescribed frequency response is highly needed for several applications [10–11]. The cavity considered in this work is realized by the photonic crystal of two-dimensional air holes with a triangular lattice structure, with one missing hole in the center. This structure is realized using the anisotropic tellurium material. The choice of tellurium is motivated by the high refractive index. This will allow us to explore the possibility of opening a full band gap for remarkably different situations.

2. Numerical method

The PWE method is illustrated in several papers. Here, we summarize the theory very briefly. Maxwell's equations in a transparent, time-invariant, source free and non-permeable ($\mu = \mu_0$) space can be rewritten as Helmholtz's equation [12–13]:

$$\nabla \times \left[\frac{1}{\varepsilon(\boldsymbol{r})}\nabla \times \boldsymbol{H}(\boldsymbol{r})\right] = \left(\frac{\omega}{c}\right)^2 \boldsymbol{H}(\boldsymbol{r}), \quad (1)$$

where $\nabla \times \boldsymbol{H}(\boldsymbol{r}) = 0$. The dielectric tensor $\varepsilon(\boldsymbol{r}) = \varepsilon(\boldsymbol{r}+\boldsymbol{R})$ is periodic with respect to the lattice vectors $\boldsymbol{R}$ generated by primitive translation and it may be expanded in a Fourier series on $\boldsymbol{G}$, the reciprocal lattice vector as [13]

$$\varepsilon(\boldsymbol{r}) = \sum_{\boldsymbol{G}} \varepsilon(\boldsymbol{G}) \exp(i\boldsymbol{G}\boldsymbol{r}). \quad (2)$$

The uniaxial material has two different principal refractive indices, known as the ordinary refractive index n_0 and the extraordinary refractive index n_e. For such anisotropic materials, the dielectric tensor $\varepsilon(\boldsymbol{r})$ is a second rank tensor [8]. In the principal coordinates, the diagonal elements of $\varepsilon(\boldsymbol{r})$ are related to the principal refractive indices as

$$\varepsilon_{xx} = n_e^2, \varepsilon_{yy} = \varepsilon_{zz} = n_0^2, \quad (3)$$

while the other dyadic elements are all zero.

$$\begin{bmatrix} n_e^2 & 0 & 0 \\ 0 & n_0^2 & 0 \\ 0 & 0 & n_0^2 \end{bmatrix} \quad (4)$$

3. The photonic crystal design

In this paper, all of the proposed PCB are designed using 2D triangular lattice photonic crystal of air holes. The number of circular rods considered for both X and Z directions are 11. The lattice constant is 300 nm, which is a distance between the two neighboring rods, denoted as a. The radius of the rod is $0.4 \times a$ (0.12 μm). This structure is realized using anisotropic tellurium material, which is a kind of positive uniaxial crystal with principal refractive indices $n_e = 6.2$ and $n_0 = 4.8$ ($\varepsilon_{xx} = n_e$, $\varepsilon_{yy} = \varepsilon_{zz} = n_0$), Fig. 1.

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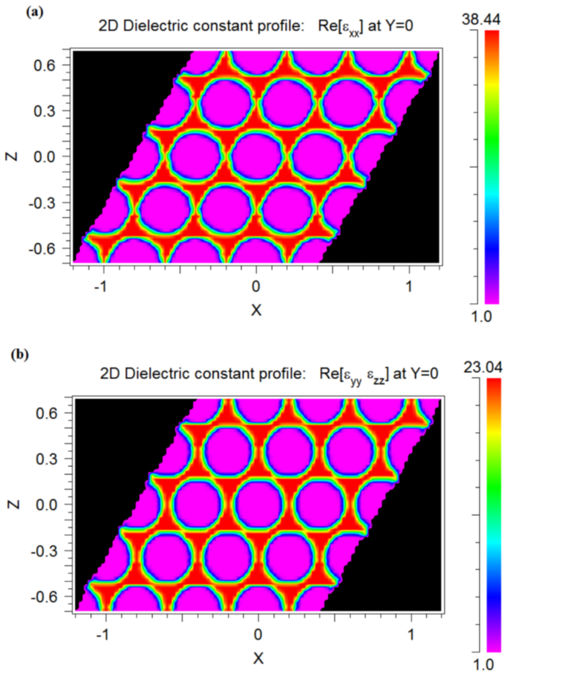

Fig. 1. The Dielectric constant: (a) ordinary dielectric constant ε_{xx}, (b) extraordinary dielectric constant $\varepsilon_{yy} = \varepsilon_{zz}$.

The gap map shown in Fig. 2 represents the variation, position and the width of TE/TM photonic band gap (PBG), which is obtained by varying the defect size or the radius of the rod. The figure gives us the layout of the card strips of our basic structure (CP2D triangular). For low filling factors in air, there is no gap. It should reach $r/a = 0.18$ to opening the band gap. For both TE and TM polarizations, a wide band gap appears for $r/a = 0.45$.

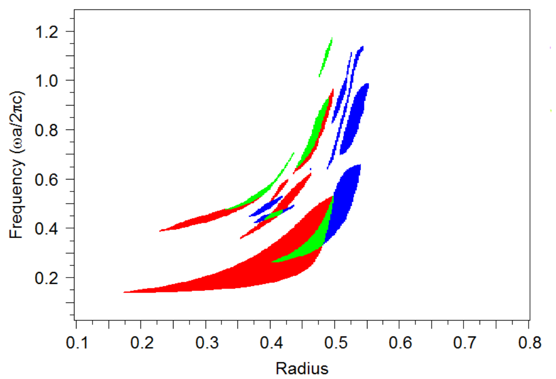

Fig. 2. Sight of top of the photonic crystal with a triangular lattice of air holes.

So, for the two polarizations, the increase of the filling factor, results in a significant widening of the band gap and a shift towards lower wavelengths.

In Fig. 3a and 3b, we show the dispersion diagram of normalized frequency versus the wave vector, for the transverse electric (TE) modes of the 2D photonic crystal of air holes. It has been calculated along the Γ-K-M-Γ edge of the Brillouin zone by employing a 2D plane wave expansion (PWE) method and finite difference time domain (FDTD). The TE PBGs exist in the structures which are indicated by the red region. TE polarization is considered for this simulation. The normalized frequency of first reduced TE PBG is observed from 0.26913 a/λ to 0.14158 a/λ, whose corresponding wavelength ranges from 1140 nm to 2070 nm. Second PBG is from 0.37372 a/λ to 0.33418 a/λ, whose corresponding wavelength ranges from 836 nm to 926 nm, and third PBG is observed from 0.46684 a/λ to 0.44133 a/λ, whose corresponding wavelength ranges from 688 nm to 712 nm.

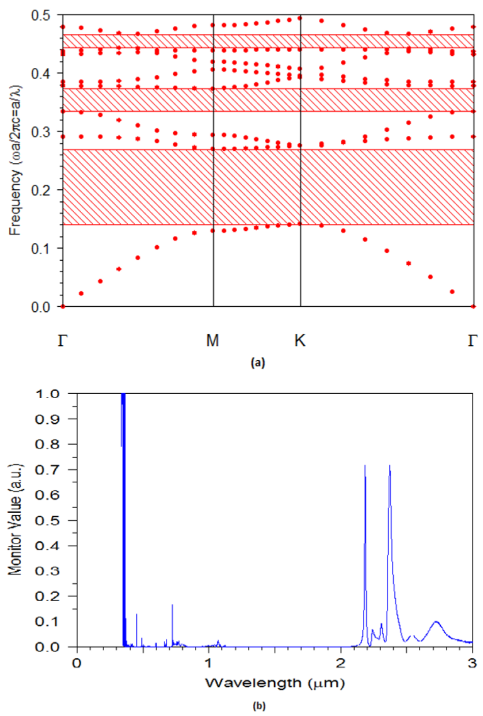

Fig. 3. Band diagram of a two-dimensional photonic crystal made of anisotropic material (Te) in a triangular configuration to a filling factor of $r/a = 0.4$: (a) using the plane waves method, (b) using the FDTD method.

4. The microcavity design

In the structure of our 2D PC cavity, there is one missing hole in the center. The computational method used is based on a 2D finite difference time domain (FDTD) method algorithm. Perfectly matched layers (PML) conditions have been considered in the calculations to ensure no back reflection in the limit of the analyzed region [14].

Figure 4 shows the transmission of the H1 cavity in a triangular lattice for the frequency range associated with the photonic band gap (PBG). The resonant mode of the H1 cavity occurs at a wavelength $\lambda_0 = 1.391\ \mu$m which was prohibited before removing the hole. The Q factor is defined as $\lambda_0/\Delta\lambda$, where $\Delta\lambda$ is the width at half peak height (FWHM) and λ_0 is the wavelength of resonance. In this case, the Q-Finder automated tool calculates the Q factor using the finite difference time combined with fast harmonic analysis (FHA). The simulated quality factor is $Q = 3.26 \times 10^5$.This quality factor reflects the ability of the cavity to trap light and represents a measure of loss. At resonance, the photon undergoes multiple reflections between the two mirrors defining the cavity and comes out of it after a certain time. This time can be considered as the life of the photon in the cavity. To see the influence of the filling factor of the H1 cavity, we consider the basic structure where the radius of the holes is $r = 0.36a$, keeping the lattice parameter a fixed. Figure 5 shows that the quality factors are more enhanced with the increase of the filling factor, until a maximum value of 1.23×10^6 is reached, for a filling factor of $r/a = 0.44$. In the same time the wavelength of resonance gradually shifts towards shorter wavelengths, which results from the decrease in the cavity length with the increasing filling factor.

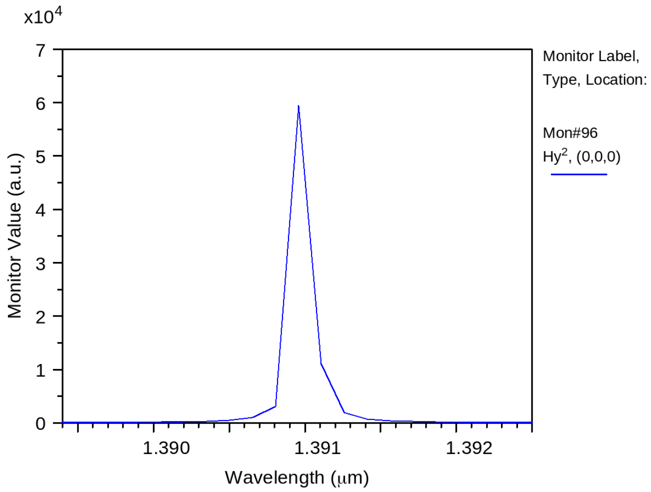

Fig. 4. Transmission of the H1 cavity in a triangular lattice.

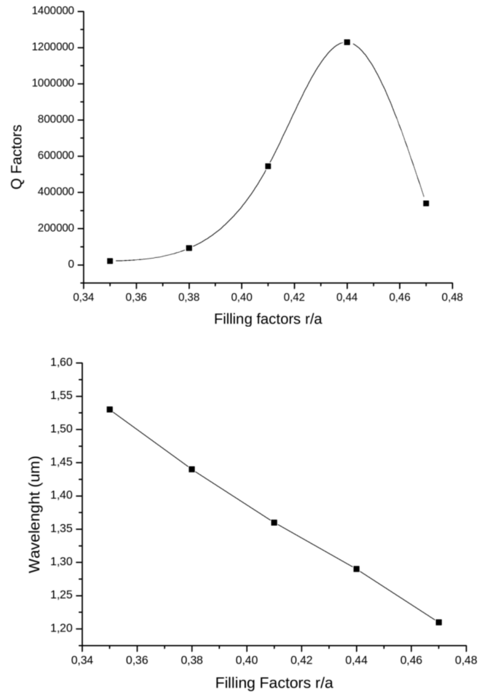

Fig. 5. Change in quality factor and wavelength as a function of filling factor of the H1 cavity.

5. Conclusion

In conclusion, this work is based on the study of photonic crystal cavity made of anisotropic materials (tellurium in our case) for the purpose of measurement and improvement of the quality factor. The tuning of the geometric parameters is employed to enhance the quality factor. The effect of variation of the filling factor, in the range of 0.35–0.47, on the quality factor of the H1 cavity was studied. The increased filling factor induces an increase in quality factor and reaches a maximum value of 1.23×10^6 for a filling factor of $r/a = 0.44$. We also demonstrate that the wavelength of resonance of the cavity is gradually shifted towards lower wavelengths, this is mainly due to the increasing of a filling factor r/a.

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