Microcavity properties of 2D photonic crystal made by silica matrix doped with magnetic nanoparticles

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Abstract. In this present paper, quality factor of two-dimensional magneto-photonic crystals microcavity fabricated by SiO2/ZrO2 or SiO2/TiO2 matrix doped with magnetic nanoparticles, in which the refractive index varied in the range of 1.51 to 1.58, has been investigated. Finite difference time domain method (3D FDTD) with perfectly matched layers (PML) was used to calculate the transmission spectrum. We demonstrate that the Q factor for the designed cavity increases as the refractive index increases, and found that the Q factor decreases as the volume fraction VF% increases. The obtained results are useful for better designs of magneto photonic crystal devices.

1. Introduction

Recently, optical properties of sol gel process have been intensively studied [1–4], because of their importance in the manufacturing of optical devices such as optical isolator and circulator. A sol–gel process, a promising method to prepare metal oxide films at low temperature, is an attractive alternative to the other deposition techniques [5–6]. This technique can be used through simple procedures in the atmosphere and an atmospheric pressure, and it realizes the nanometer level control of thickness of each layer similar to dry processes. In addition, it has some advantages for the preparation of PCs with magneto-optical function, i.e., strong interlayer coupling, relatively low environmental burden and low capital cost. However, there have been scarce reports on preparation of PCs applicable to the magneto-optics using the sol–gel method [7].

Magneto-photonic crystals (MPCs) are a special kind of photonic crystals (PCs), constructed of magnetic materials. The first report arrived at the end of the 1990s, and at the beginning of the new millennium activity in this area is growing rapidly. The research on two-dimensional (2D) MPCs has been undertaken recently, together with expansion of the capability for a new class of devices more suitable for integration. This includes planar nonreciprocal devices specific to 2D MPCs, such as optical isolators based on line-defect waveguides [8] and circulators based on micro cavities [9], which have been demonstrated theoretically. The study of optical cavities based on magneto-photonic crystal slabs has attracted much attention [10–11]. There are many possible device applications of compact and efficient (MPCs) cavities, such as magneto-optical resonators, circulators, etc. In this case, the design of magneto-photonic crystal cavity with high quality factor and prescribed frequency response is highly needed for these applications. In this paper, we theoretically investigated the quality factor of magneto-photonic crystal microcavities, made by SiO2/ZrO2 or SiO2/TiO2 matrix doped with magnetic nanoparticles with low refractive index.
material which varied in the range of 1.51 to 1.58 at λ = 1.55 μm [12], using the finite difference time domain 3D (FDTD) method assisted by group theory in the time domain [13]. The magneto-photonic crystal microcavities (H1) are obtained by removing one hole missed of the 2D magneto-photonic crystal structure. We simulate a cavity that the MPC structure to ensure high transmission efficiency. In the first part of this work, we have investigated the effects of the contrast on the Q factor. In the second part, we have varied the concentration of magnetic nanoparticles VF% of the structure: magneto-photonic cavity realized by sol–gel process, and we study the influence of volume fraction VF % on the position of resonance wavelength and Q value.

2. Theoretical model

The model is a MPCS composed of 2D triangular lattice magneto-photonic crystal of air holes as shown in Figure 1. However, the triangular lattice is very suitable to study photonic band gap properties. Triangular lattice allows the opening of 2D photonic band gap, presents a good compromise namely for high felling factors and its lowly sensitive to the incidence angle compared to the square lattice [14-15]. In this paper, the lattice constant is 0.75 μm, which is a distance between the two neighbored holes, given as ‘a’. The radius of the hole is 0.27 μm. This structure is realized by SiO2/TiO2 or SiO2/ZrO2 material with low index of refraction which varied in the range of 1.51 to 1.58 at λ = 1.55μm [16]. The composite matrix is created using a doping procedure where the magnetic nanoparticles are introduced in the liquid preparation of a sol-gel process. SiO2/TiO2 or SiO2/ZrO2 slab have been doped with Maghemite nano particles whose average diameter is about 10 nm [17-18]. The magneto-optical permittivity tensor $\tilde{\varepsilon}$ of slab is written in coordinate system as:

$$\tilde{\varepsilon} = \begin{bmatrix} \varepsilon & \varepsilon_{xy} & 0 \\ -\varepsilon_{xy} & \varepsilon & 0 \\ 0 & 0 & \varepsilon \end{bmatrix}$$

(1)

Where $\varepsilon$ represents the diagonal elements of dielectric tensor $\varepsilon_{xx}$, $\varepsilon_{yy}$ and $\varepsilon_{zz}$. In our case, these elements are equal and they are given as follows:

$$\varepsilon = \varepsilon_{xx} = \varepsilon_{yy} = \varepsilon_{zz} = \varepsilon' + \varepsilon''$$

(2)

However, the complex refractive index of magneto optical matrix is given by: $N = n + ik$, where $n$ is the real part of complex refractive index for diagonal elements tensor and $k$ is the imaginary part of complex refractive index. The complex dielectric permittivity of diagonal elements is given by:

$$\varepsilon = (n + ik)^2$$

(3)

The real and the imaginary parts of dielectric tensor are given by:

$$\begin{cases} \varepsilon' = n^2 - k^2 \\ \varepsilon'' = 2nk \end{cases}$$

(4)

where $k$ is called the coefficient of extinction and it is given by:

$$k = \frac{\alpha \lambda}{4\pi}$$

(5)
Figure 1. Structure of 2D photonic crystal made with SiO2/TiO2 or SiO2/ZrO2 doped with magnetic nanoparticles.

Where $\lambda$ is the free space wavelength and $\alpha$ (1/cm) represents losses inside the matrix, it is linked to intrinsic absorption of magneto-optical matrix. However, the application of a magnetic field on material with a direction parallel to the light beam (Oz) produces an off-diagonal elements where the magnitude depends on the kind of material (on the faraday rotation $\theta_F$ and ellipticity $\eta_F$) [19].

$$\varepsilon_{xy} = -\varepsilon_{yx} = \varepsilon_{xy}' + \varepsilon_{xy}''$$

The real and the imaginary parts of $\varepsilon_{xy}$ are strongly depending on the Faraday rotation $\theta_F$ that is proportional to the concentration of magnetic nanoparticles VF%. These elements are given by:

Figure 2. The dielectric constant: diagonal dielectric constant $\varepsilon = \varepsilon_{xx} = \varepsilon_{yy} = \varepsilon_{zz} = 1.51^2$, and off-diagonal dielectric constant $\varepsilon_{xy} = -\varepsilon_{yx} = 0.016^2$. 
\[ \begin{align*}
\varepsilon'_{xy} &= \frac{\lambda}{\pi} (n\theta_F - k\eta_F) \\
\varepsilon''_{xy} &= \frac{\lambda}{\pi} (n\theta_F + k\eta_F)
\end{align*} \] (7)

In the limit of small off-diagonal components: \(|\varepsilon_{xy}| \ll |\varepsilon|\) and small absorption, an approximate expression for the imaginary part of \(\varepsilon''_{xy}\) is obtained [19–20]:

\[ \varepsilon''_{xy} = \frac{\theta_F \lambda \sqrt{\varepsilon}}{\pi} \] (8)

Figure 3, shows the band diagrams of non-magnetic structure of 2D photonic crystal for TE (blue) and TM (red) modes of the polarization. The matrix have a permittivity \(\varepsilon = 1.56^2\) and the magnitude of the off-diagonal elements are \(\varepsilon_{xy} = 0\), corresponding to the SiO2/TiO2 or SiO2/ZrO2 at optical communication wavelength \(\lambda = 1.55 \text{ µm}\) [21–22]. A dispersion diagram showing normalized frequency versus the wave vector for transverse electric (TE) and transverse magnetic (TM) modes of the 2D photonic crystal is given in Figure 2. It has been calculated along the \(\Gamma\)-X-M-\(\Gamma\) edge for the Brillouin zone by employing a 2D plane wave expansion (PWE) method. The gap map show two frequency band gaps for the TM polarized modes but no gap for TE modes with this refractive index contrast and relatively small \(r/a\). In the TM band diagram the fundamental band gap is centered near a wavelength of 1.5506. It extends between to wavelength range 1.5052-1.5961 \(\mu m\) for the waves with TE polarization for the refractive index \(n=1.56\).

![TE/TM Band Structure](image-url)

**Figure 3.** Dispersions curves and band-gaps for TM and TE polarizations for the 2D lattice without defects.
3. The microcavity design

This section presents the influence of refractive index contrast, was changed in order to predict the highest quality factor $Q$ to improve the transmission efficiency. The numerical tools used for our simulations are based on the two-dimensional finite difference time-domain method (FDTD) (RSoft Design Group, FullWAVE) [23]. The structure of our 2D PC cavity is shown in Figure 4, with one missing hole in the center, where the number of circular holes considered for both ‘X’ and ‘Z’ directions are 11. This cavity allows for very high quality factors while maintaining a size of the order of optical wavelength.

![Figure 4](image)

**Figure 4.** Sight of top of the H1 cavity made by removed one hole.

We begin our consideration by calculation the transmission spectra for a variety of refractive index ($n$) in the range 1.52 to 1.58. Figure 5. shows the spectral response of the microcavity formed by removing one hole obtained with the FDTD method of the impulse response for different values of refractive index $n = 1.52$ to 1.58. The spectrum calculated by TM polarization can be observed one cavity mode for different values of refractive index. We will call the mode of mode resonance wavelength. In order to show the location of resonance wavelength and quality factor, Fullwave software is used to simulate the transmission spectrum for different values of refractive index $n = 1.52$, to 1.58.

Figure 5 reports the simulations. The results show that more refractive index increase the resonance wavelength shifts towards the right $\lambda_0 = 1.5225$ to 1.5465 $\mu$m, and quality factor $Q= (\lambda_0/\Delta\lambda)$ varied from $Q = 57$ to 116. Figure 6. Presents the variations of resonance wavelength and quality factor as a function of refractive index. We begin our calculation of transmission spectra by increasing the refractive index. We show the dependence of quality factor and resonance wavelength as a function of the symmetric than the refractive index increases. After scanning of refractive index $n$ carefully, we find the highest $Q$ value $Q = 116$ with resonant frequency 1.5465 $\mu$m, which can be achieved at $n = 1.58$. 

![Figure 6](image)
4. Effect of the volume fraction

The refractive index of the structure was fixed at \( n = 1.58 \) and at series of simulations for different values of volume fraction \( VF\% \), from \( VF = 1\% \) (\( n_{xy} = 0.016 \)) to \( 20\% \) (\( n_{xy} = 0.073 \)). We begin our calculation of transmission spectra in Figure 7 by increasing the volume fraction. In addition, in Figure 8, we show the dependence of quality factor and resonance wavelength as a function of increased the volume fraction. The quality factor decreases as the volume fraction increased. After scanning of VF% carefully, we find the final Q value \( Q = 21 \) with resonant frequency 1.5506 µm, that can be achieved at \( VF = 20\% \) (see Figure 7 and Figure 8).

Figure 5. (a) Frequency response of the H1 microcavity formed by removing one hole triangular lattice as a function of refractive index, (b) the intensity field distribution for the microcavity at resonant wavelength 1.5465 µm (n=1.58).

Figure 6. Change in quality factor and Wavelength as a function of refractive index of the H1 cavity.
Figure 7. Frequency response of the H1 microcavity as a function of volume fraction (VF %).

The computational method used is based on a 3D finite difference time domain (3DFDTD) method algorithm. Perfectly, matched layer (PML) conditions have been considered in the calculations to ensure no back reflection in the limit of the analyzed region. This crystal is light by a Gaussian wave under normal incidence with a transverse electric (TM) polarized. The time step is chosen to 0.01. Note that it might be necessary to reduce the time step below the stability limit when simulating metals since the courant condition can change in this case.

To explore the effect of volume fraction due to off-diagonal elements, we have calculated the quality factor of MPC cavity for different values of volume fraction (VF %). We show in Figure 8, variations of quality factor and resonance wavelength as a function of the increased volume fraction of the MPC structure. From figure 4, we notice that the volume fraction due to off-diagonal elements have a great effect on the position of resonance wavelength and Q factor. The quality factor Q decreases from 68 for 1% to 21 for 20%. It is clear that as the VF% increases, the quality factor Q decreases, this leads to a weakened in transmission spectra.

Figure 6. Change in quality factor and Wavelength as a function of volume fraction of the MPCH1 cavity.
5. Conclusion
In summary, a novel magneto-photonic crystal platform cavity has been studied in this paper. The microcavity made by SiO2 / ZrO2 or SiO2 / TiO2 matrix doped with magnetic nanoparticles, characterized by low refractive index material which varied in the range of 1.51 to 1.58. In addition, we have numerically study the effect of the volume fraction due to off-diagonal elements on the Q factor for the H1 cavity in a 2D magneto-photonic crystal.

The different results of simulation obtained by 3D FDTD method in Fullwave software demonstrate clearly that the volume fraction due to off-diagonal elements have a great effect on the position of resonance wavelength and Q value. Thus, we reveal that a maximum absolute quality factor is achieved for non-magnetic structure VF=0% (n=1.58), and VF=1% for magneto-photonic crystal made by sol–gel process.

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