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Magneto-photonic crystal microcavities based on magnetic nanoparticles embedded in Silica matrix

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ABSTRACT

Using the three-dimensional finite difference time domain method (3D FDTD) with perfectly matched layers (PML), optical and magneto-optical properties of two-dimensional magneto-photonic crystals micro-cavity is studied. This micro-cavity is fabricated by SiO_2/ZrO_2 or SiO_2/TiO_2 matrix doped with magnetic nanoparticles, in which the refractive index varied in the range of 1.51–1.58. We demonstrate that the Q factor for the designed cavity increases as the refractive index increases, and we find that the Q factor decreases as the volume fraction VF% due to off-diagonal elements increases. These magnetic microcavities may serve as a fundamental structure in a variety of ultra compact magneto photonic devices such as optical isolators, circulators and modulators in the future.

1. Introduction

During the past few years, there had been a great deal of interest in studies of the sol–gel process in magneto-photonic crystals due to their potential application [1–5]. The integration of magneto-optical devices, such as nonreciprocal circulators, is still a great challenge, due to difficulties to embed magneto-optical materials with classical integrated technologies. Yttrium Iron Garnet (YIG), widely used in bulk optical circulators, requires an annealing temperature as high as 700 °C to be magneto-active. This temperature is evidently not compatible with integrated optical technologies. Furthermore, the realization of YIG films requires the use of Gadolinium Gallium Garnet as substrate. This substrate is not commonly used to realize integrated functions. To overcome this problem, researchers have worked on two different approaches. The first one deals with the hybrid integration of YIG on planar light-wave circuits by insertion in grooves [6] or by direct bonding on classical substrate, silicon [7] or glass [8] for example. The second one is the development of novel magneto-optical materials compatible with classical technologies. In this way, many efforts have been made to obtain such materials compatible with semiconductor substrate [9,10], but few concern glass substrate. Contrarily to classical techniques, high temperature is not required to obtain a magnetic behavior. Furthermore, this elaboration method is easy to implement and provide magneto-optical slabs with a refractive index value (n=1.5) close to that of other integrated optical devices. The inherent low refractive index contrast between the film and the substrate in sol–gel organic–inorganic waveguides, combined with a thickness larger than that of classical magneto-optical waveguides, should allow an efficient fiber coupling, which is highly desirable for laser-waveguide coupling. More and more, the sol–gel process gives a solution to fabricate integrated optic devices. It is considered as a versatile, flexible and a low-cost technique useful for the realization of integrated photonic devices [11,12].

The advances of photonic crystals structures are not limited to semiconductor material [13], a strong interest is also devoted to other structures containing, polymer [14], liquid crystal [15] and magnetic materials [16]. However, Magnetophotonic crystals (MPCs) are capable of providing magneto-optical (MO) characteristics [17,18]. Photonic crystal defect structures have been proved to be useful and received considerable attention for many applications in integrated optics. When line defect or cavities are introduced, light localization can be realized [19-21]. The photonic crystal (PhC) waveguides incorporating with microcavities can be used to design some kinds of magneto-optical devices such as optical isolator and circulator.

X. Jin et al. [17]. Proposed, demonstrated and investigated a highly compact three-port and four-port circulators with ultra-low insertion loss based on the square lattice square rod. In this structure, along with such a defect, there exist resonant modes, but the quality factor for the

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corresponding resonance modes is generally low so that the operating bandwidth can be wide (the quality factor of the resonance mode is rather low although the refractive index is high n=3.6). Wang and Fan present an analysis of nonreciprocal magneto-optical resonators in two-dimensional photonic crystals. In addition, they discuss the use of such resonators in high performance and large bandwidth planar optical circulator structures that are extremely compact. The maximum quality factor in this structure Q=367 for the high refractive index n=2.5 [22,23].

In this paper, we present a new kind of artificial magneto optical materials to study and investigate the influence of the volume fraction (concentration of magnetic nanoparticles VF%) on the quality factor in 2D magneto-photonic crystal cavity. The magneto photonic crystal micro-cavities (H1) or (L3) are obtained respectively by one hole missed of the 2D magneto-photonic crystal structure, or a line of three holes missed. This structure is realized by SiO_2/ZrO_2 or SiO_2/TiO_2 matrix doped with magnetic nanoparticles, the matrix is characterized by low refractive index which is varied in the range of 1.51–1.58 at λ=1.55 µm. We simulate a MPC cavity structure to ensure high transmission efficiency, using the 3D FDTD method. In the first part of this work, we will investigate 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 and we study the influence of volume fraction VF % on the position of resonance wavelength and Q factor.

2. Materials and theoretical model

The model is a MPCS composed of 2D triangular lattice magneto-photonic crystal of air holes as shown in Fig. 1. In this paper, the lattice constant is 0.75 µm, which is a distance between the two neighbored holes, denoted as '*a*'. The radius of the hole is 0.27 µm denoted as '*r*'. The composite matrix is created using a doping procedure where the magnetic nanoparticles are introduced in the liquid preparation of a sol-gel process. SiO_2/TiO_2 or SiO_2/ZrO_2 slab have been doped with Maghemite nanoparticles whose average diameter is about 10 nm [24,25].

The photonic crystal made by silica matrix is inherently suffering from low refractive index (n around 1,51–1,58 at λ=1550 nm) which is not suitable for photonic application. However, the formation of magneto optical effect by doping the silica matrix with magnetic nanoparticuls to provide magneto optical effect induces modal birefringence due to the difference in effective indices for horizontally polarized modes (HE, i.e. quasi-TE) and vertically polarized modes (EH, i.e. quasi-TM). And this latter reduces the performance of photonic crystal structure.

The permittivity tensor in magneto-optical materials, with magnetization perpendicular to the direction of light propagation, can be given as [26].

$$\varepsilon = \begin{pmatrix} \varepsilon_{xx} & i\varepsilon_{xy} & 0 \\ -i\varepsilon_{yx} & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix}_{oxyz} \qquad (1)$$

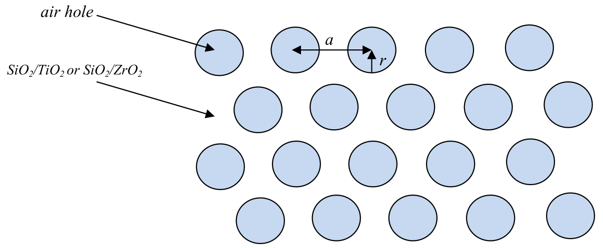

Fig. 1. Structure of 2D photonic crystal made with SiO_2/TiO_2 or SiO_2/ZrO_2 doped with magnetic nanoparticles.

each element of tensor εi=εi'+εi" has real and imaginary parts where i= xx or xy.

The diagonal part of the permittivity tensor ε_{xx},ε_{yy} andε_{zz} are equal and represent the permittivity of isotropic medium:

$$\varepsilon=\varepsilon_{xx}=\varepsilon_{yy}=\varepsilon_{zz}=\varepsilon'+i\varepsilon'' \qquad (2)$$

$$\varepsilon'_{xx} = n^2 - k^2, \quad \varepsilon''_{xx} = 2nk \qquad (3)$$

the *n* parameter is the real part of the complex refractive index, and *k* is the imaginary part given by:

$$k=\frac{\alpha.\ \lambda}{4\pi} \qquad (4)$$

λ is the free space wavelength and α (/cm) represents the losses and is linked to intrinsic absorption of magneto-optical matrix:

$$\alpha\,(cm^{-1})=23 \times \varnothing(\%) \qquad (5)$$

∅ (%) represents the concentration of magnetic nanoparticles

$$\theta_F\,(°/cm)=206 \times \varnothing(\%) \qquad (6)$$

The imaginary parts of ε_{xy} are strongly depending on the Faraday rotation θ_F that is proportional to the concentration of magnetic nanoparticles VF%. These elements are given by:

$$\varepsilon_{xy}=-\varepsilon_{yx}=\varepsilon'_{xy}+i\varepsilon''_{xy} \qquad (7)$$

$$\varepsilon_{xy}'=\lambda(n\theta_F-k\eta_F)/\pi \qquad (8)$$

and

$$\varepsilon_{xy}''=\lambda(n\theta_F+k\eta_F)/\pi \qquad (9)$$

In the case of $|\varepsilon'_{xy}| < < |\varepsilon\ |$ and small absorption, the imaginary part of ε''_{xy} can be approximated by [11]:

$$\varepsilon''_{xy}=Im\,(\varepsilon_{xy}) = \frac{\theta_F.\ \lambda\sqrt{\varepsilon}}{\pi} \qquad (10)$$

The refractive index of the host matrix can be varied in the range 1.51–1.58 at λ=1.55 µm. This flexibility of the refractive index will be helpful to suit the optical characteristics of the magneto-optical film with requirements of the desired application. [26].

3. Magneto-optical band gap calculation

The band-structure calculation was performed with the plane-wave expansion method (PWE) of the RSoft software. The band diagram of this structure has one forbidden band for TM-polarized modes but no forbidden band for TE modes with these specification parameters. The band gap in TM mode is suitable for our work which is in $1.4898 < \lambda < 1.5522$ µm wavelength that covers the wavelength range of optical telecommunications.[27,28].

For completeness, we also study the band gap in 2D magneto photonic structure and we simulate the influence of different volume fraction VF % introduced in the SiO_2/ZrO_2 matrix on the width of the photonic band gap. Fig. 2 presents the influence of volume fraction VF %for different values of refractive index contrast on the photonic band gap properties in order to predict the largest photonic band gap structures for telecommunications applications. The numerical tools used for our simulations are based on the two-dimensional plane wave expansion (PWE) method [29,30].

The results show that removing the anisotropy of these materials in this way, the PBG do not change but an upward shift in frequency. Also more refractive index increase the BGs shifts towards the right, and wavelength center λ_0=(λmin+λmax)/2 varied from λ_0=1.5210 for *n*=1.51 to 1.5628 for *n*=1.58.

The photonic band gap is strongly affected by refractive index (the diagonal elements of dielectric tensorε_{xx},ε_{yy} andε_{zz}) and the volume fraction (%) affect only the imaginary part of the off-diagonal