The research on magnetic tunable characteristics of photonic crystal defect localized modes with a defect layer of nanoparticle

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In this study, based on magnetic tunable characteristics of nanoparticle magnetic fluid, we design the photonic crystals' defect-localized modes with a defect layer of nanoparticle magnetic fluids. The transmission spectrum of one-dimensional photonic crystals with a defect layer of nanoparticle magnetic fluid is calculated numerically using the transfer matrix method. The results indicate that the wavelength of defect localized modes moves to short wave with the increasing of magnetic field intensity. The maximum variation is 7 nm. When the thickness deviation of defect layer is in the range of 5 nm, the variation of the wavelength is 6 nm. The bandwidth of the defect localized modes is 0.2 nm and its quality factor is of the order of 10^3. Therefore, the variation of the wavelength of defect-localized modes, which is caused by the thickness deviation of a defect layer, could be compensated by changing the magnetic field. In this study, the defect-localized modes with a certain wavelength are realized.

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The research about optical and magneto-optical properties of magnetic fluid is a significant direction in magnetic fluid study[1]. The photonic crystal filled with magnetic fluid is known as tunable photonic crystal. Due to its contactless magnetic control adjustable advantage, tunable photonic crystal is a potential material in the fabrication of magnetic control tunable photonic devices. It has attracted much attention and become a new research hotspot in the field of tunable photonic crystals[2–5]. The study involves the preparation, characteristics of tunable photonic crystal, and applications in photonic devices, etc.[6–9]. Notably, colloid ferrofluid was used as the basic material to design one-dimensional (1D) photonic crystal and magnetic control 1D photonic crystals[2,5]. Photonic crystal fiber filled with Fe_3O_4 nanoparticles, which was temperature adjustable, was also reported[3]. Using magnetic fluid, hollow-core photonic crystal fiber Fabry–Perot sensor was developed for a magnetic field measurement[4,10].

In this article, based on magnetic field control characteristics of nanoparticle magnetic fluid, photonic crystal defect-localized modes were constructed. There was a defect layer filled with nanoparticle magnetic fluid in the photonic crystals. The transmission spectrum of photonic crystal with a defect layer-filled nanoparticle magnetic fluid was calculated numerically using the transmission matrix method[5]. The magnetic field tunable characteristic for the wavelength of defect localized modes was studied. The wavelength variation of defect localized modes with the thickness deviation of nanoparticle magnetic liquid was presented. The defect-localized modes with a certain wavelength was realized.

The refractive index of nanoparticle magnetic fluid can be regulated by an external magnetic field, and thus, the magnetic tunable characteristics of photonic crystals could be implemented. The system structure is shown in Fig. 1. Eight couples dielectric layers of TiO_2 (a layer) and SiO_2 (b layer) are coated between two flat glass G in turns. The intermediate space layers are filled with magnetic fluid (mf layer).

The a and b represent high and low refractive index of medium layer on both sides of the nanoparticle magnetic fluid defect layer, and n_a, n_{mf}, and n_b represent the refractive index of TiO_2, magnetic fluid, and SiO_2, respectively, and d_a and d_b represent the corresponding thickness of TiO_2 and SiO_2. The given light wave is vertically incident on the surface of 1D photonic crystals with a defect layer filled nanoparticle magnetic fluid (as shown in Fig. 1). The light is injected at $z < 0$ area. The flat glass G is in the area of $z < 0$ and $z > z_N$.

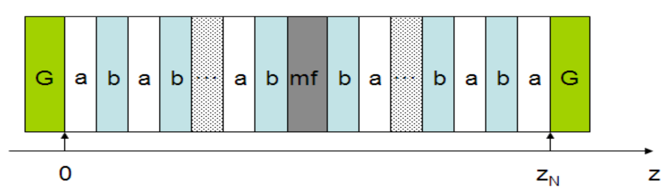

Fig. 1. The system structure of photonic crystals with a defect layer-filled with nanoparticle magnetic fluid.

The reflective coefficient of light waves by a transfer matrix method[11] is as per the following:

$$r=\frac{n_0\left(M_{11}+n_{N+1}M_{12}\right)-\left(M_{21}+n_{N+1}M_{22}\right)}{n_0\left(M_{11}+n_{N+1}M_{12}\right)+\left(M_{21}+n_{N+1}M_{22}\right)}. \tag{1}$$

The transmission coefficient is

$$t=\frac{2n_0}{n_0\left(M_{11}+n_{N+1}M_{12}\right)+\left(M_{21}+n_{N+1}M_{22}\right)}. \tag{2}$$

The reflectivity of light waves is $R=\left|\mathrm{r}\right|^2$, and the transmissivity is $T=\left|\mathrm{t}\right|^2$, where M_{ij} is the matrix element of transmission matrix M, which passes through N layers of the whole photonic crystals, and M is equivalent to the product of monolayer transmission matrix; the transmission matrix of dielectric at the j layer is

$$\mathrm{m_j}=\begin{pmatrix}\cos\varphi_\mathrm{j} & -\dfrac{1}{\mathrm{n_j}}\sin\varphi_\mathrm{j}\\ \mathrm{n_j}\sin\varphi_\mathrm{j} & \cos\varphi_\mathrm{j}\end{pmatrix}. \tag{3}$$

In $\varphi_j=\pm\dfrac{\omega}{c}n_jd_j$, "+" and "–" correspond to the positive refractive media and the negative refractive media, respectively. n_j and d_j correspond to the refractive index and the thickness of dielectric at the j layer, respectively. n_0 and n_{N+1} are the refractive indexes of flat glass G. Formula (2) shows that the transmissivity of photonic crystals with a defect layer-filled magnetic fluid is relative to the wavelength of incident light. Both primitive materials of photonic crystals and material parameters of the defect layers of magnetic fluid, such as refractive index and thickness, have an influence on transmission coefficient.

TiO_2 and SiO_2 are selected as primitive materials of photonic crystals. The refractive index n_a and n_b are 2.35 and 1.46, respectively. The optical thickness could be obtained by the following equation: n_ad_a = n_bd_b = $\lambda_0/4$, where λ_0 is central wavelength, which is 1550 nm. The refractive index n_{mf} of magnetic fluid is closely related to the distribution of magnetic particles in a magnetic fluid. Main factors that affect the distribution of magnetic particles in the magnetic fluid are the magnetic dipole–dipole interaction between particles, Brownian motion of particle, external magnetic field, and light-trapping[12,13]. In our experiment, the wavelength of the light source was 1550 nm; the concentration of water-based Fe_3O_4 magnetic fluid was 1.2 g/ml; the room temperature was 20°C; the refractive index of magnetic fluid (n_{mf}) was reduced from n_{mfh} = 1.4471 to n_{mfl} = 1.4246 with the increasing magnetic strength range from 0 Oe to 1661 Oe[14]. Water-based Fe_3O_4 was chosen as the defect layer of photonic crystals.

Only magnetic field H and incident light wavelength λ, which works on the defect layer of magnetic fluid, can be changed for the preparation of photonic crystals with a defect layer filled with nanoparticle magnetic fluid. To accomplish magnetic tunable on the defect-localized modes of photonic crystals, we can modulate the refractive index n_{mf} of the defect layer of magnetic fluid by changing magnetic field H. This leads to change of the wavelength of defect-localized modes.

In our work, the following parameters are taken: n_a = 2.35, n_b = 1.46, n_{mfl} = 1.424, n_{mfh} = 1.447, $\overline{n_{mf}}$ = 1.43, n_ad_a = n_bd_b = $\lambda_0/4$ and $\overline{n_{mf}d_{mf}}$ = $\lambda_0/2$. λ_0 is the central wavelength. The transmission spectra at different magnetic field strengths (different refractive index n_{mf} of magnetic fluid) are calculated numerically using Matlab programming. As shown in Fig. 2, the defect modes wavelength will move towards short-wave with the increasing of additional magnetic field or the decreasing of refractive index of magnetic fluid. When the refractive index of magnetic fluid reduces from 1.447 to 1.425, the defect modes wavelength shift from 1555 nm to 1548 nm and the maximum variation is 7 nm.

Due to the limit of the technology conditions, there is a deviation of the thickness in the defect layer. The transmission spectra of photonic crystals are simulated numerically when the thickness deviation of defect layer is in the range of 5 nm. It means that the thickness of defect layer is in between 537 nm and 547 nm.

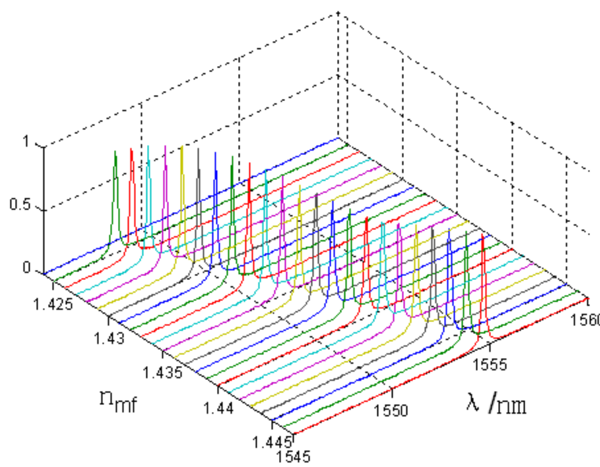

Fig. 2. The transmission spectra of photonic crystals at different refractive index n_{mf} of magnetic fluid.

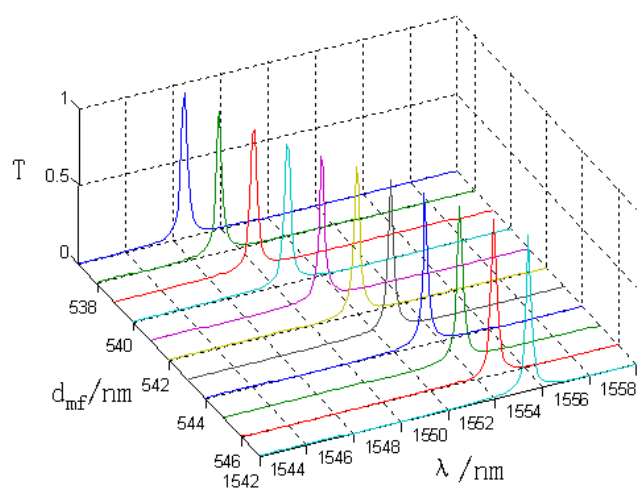

Fig. 3. The transmission spectra of photonic crystals as the change to thickness of the defect layer of magnetic fluid.

As shown in Fig. 3, the wavelengths of defect localized modes shift from 1547 nm to 1553 nm with a variation of 6 nm.

According to the definition of quality factor[15], it can be obtained as per the following equation: $Q = \frac{\lambda_c}{BW}$, where λ_c is the central wavelength of defect modes, $BW = |\lambda_1 - \lambda_2|$, which is the bandwidth of defect modes; λ_1 and λ_2 are wavelengths corresponding to 1/e of transmissivity of central wavelength of the defect modes. From Figs. 2 and 3, we can obtain that the bandwidth of the defect-localized modes is 0.2 nm and it has a higher quality factor in the order of 10^3.

When nanoparticle magnetic fluid is introduced into 1D photonic crystals as a defect, its tunable function can be realized by changing the magnetic field worked on the magnetic fluid. When the external magnetic field strength is increased, the wavelength of the defect-localized modes in photonic crystals moves towards shorter wavelength with a maximum variation of 7 nm. Moreover, due to the limit of the technology conditions, the thickness of the defect layer will be in fluctuation. The variation of defect-localized modes' wavelength is 6 nm when the thickness deviation of the defect layer is in the range of 5 nm. The reason for defect modes wavelength shift is that the position of the defect modes depends on the refractive index and thickness of periodic dielectric. Defect modes wavelength must meet the condition of standing wave $\delta = k\lambda = n_{eff}\Delta d$, where δ is optical path difference, k is an integer, λ is the wavelength of incident light, n_{eff} is refractive index, and Δd is geometric path difference. With the increasing of n_{eff}, k and Δd are in constant values, the wavelength shifts towards the longer wavelength, and with the increasing of Δd, k and n_{eff} are in constant values, the wavelength shifts towards the longer wavelength. The bandwidth of the defect modes is 0.2 nm, and the quality factor is in order of 10^3. Therefore, the change of the wavelength, which is caused by the thickness deviation of a defect layer, can be compensated with the changing of the magnetic field. The defect localized modes with a certain wavelength are realized. Photonic crystals with the defect layer-filled nanoparticle magnetic fluid are designed for the magnetic tunable control filter, which is of high quality. It is worth mentioning that the refractive index of magnetic fluid can be adjusted by changing the concentrations of magnetic fluid [16,17].

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