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RESEARCH ARTICLE

Transmission characteristics of linearly polarized light in reflection-type one-dimensional magnetophotonic crystals

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Abstract The propagation properties of linearly polarized light in reflection-type one-dimensional magnetophotonic crystals are studied by using the 4×4 transmission matrix method. The structure models of reflection-type one-dimensional magnetophotonic crystals are designed, the magnetic field direction control characteristics of reflection spectrum and Kerr rotation angle are discussed, and the effect of applied magnetic field direction and strength on reflection spectrum and Kerr rotation angle are analyzed. The results show that the non-diagonal elements in the dielectric constant of magneto optical materials change when the angle φ between applied magnetic field and optical path changes, the reflectivity and Kerr rotation angle decrease when the angle φ increases; when the applied magnetic field strength changes, the reflectivity and Kerr rotation angle increase when the applied magnetic field strength increases; by adjusting the angle φ and strength of the applied magnetic field, the rotation angle of Kerr can be adjusted to 45°, and a more flat reflection spectrum can be obtained by designing the appropriate structure.

Keywords magnetophotonic crystal, 4×4 transfer matrix method, magneto-optical effect, Kerr rotation angle

1 Introduction

Magneto optical material is an anisotropic material, its non-diagonal elements in dielectric constant is affected by external magnetic field [1,2]. The one-dimensional magnetophotonic crystals can be obtained by periodically arranging the magneto optical materials and dielectric materials [3,4], the enhanced magneto optic effect is obtained [5] and can be applied to the new magneto-optical isolator [6,7]. Reflection-type one-dimensional magnetophotonic crystals are composed of periodic one-dimensional magnetophotonic crystals and reflective layer materials [8,9], due to magneto-optic effect, high reflectivity and large Kerr rotation angle are produced; by adjusting the structure and setting several defect layers in reflection-type one-dimensional magnetophotonic crystals [10,11], a flat reflection spectrum can be obtained. In addition, by introducing an asymmetric dielectric layer on both sides of the magneto-optic dielectric layer, higher reflectivity and larger Kerr rotation angle also can be achieved.

In this paper, the physical models of reflection-type one-dimensional magnetophotonic crystals are designed. The reflectivity and Kerr rotation angle of linearly polarized light are calculated by use of the 4×4 transfer matrix method [12,13]. By changing the angle φ between the applied magnetic field and the optical axis, the effects of the angle φ on the reflectivity and Kerr rotation angle are discussed.

2 Methodology and theoretical model

When magneto optical material is affected by the external magnetic field, this is shown in Fig. 1.

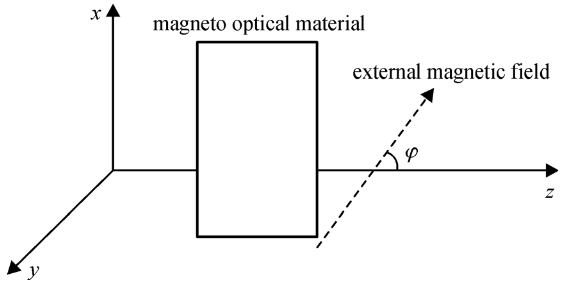

Fig. 1 Magneto optical material in an external magnetic field

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The external magnetic field affects the optical properties of magneto optical materials, and the dielectric tensor of magneto optical materials under applied magnetic field is as follows [14]:

$$\boldsymbol{\varepsilon}_{\mathrm{M}}=\begin{pmatrix} \varepsilon_1 & \mathrm{i}\varepsilon_{xy} & -\mathrm{i}\varepsilon_{xz} \\ -\mathrm{i}\varepsilon_{xy} & \varepsilon_1 & 0 \\ \mathrm{i}\varepsilon_{xz} & 0 & \varepsilon_3 \end{pmatrix}. \tag{1}$$

In which $\varepsilon_{xy}=\varepsilon_2\cos\varphi$ and $\varepsilon_{xz}=\varepsilon_2\sin\varphi$, the ε_2 is affected by the external magnetic field strength, and φ is the angle between the applied magnetic field and the optical axis. The non-diagonal elements in dielectric constant ε_{M} of magneto optical materials can be adjusted by changing the angle φ or the intensity of applied magnetic field.

In the thesis, the physical models of reflection-type one-dimensional magnetophotonic crystals are designed respectively, their structures are S1 $=(\mathrm{L/H})^4/\mathrm{M}/(\mathrm{L/H})^2/\mathrm{M}/(\mathrm{H/L})^2/\mathrm{M}/(\mathrm{L/H})^4$ and S2 $=(\mathrm{L/H})^3/\mathrm{MM}/(\mathrm{H/L})^5/\mathrm{MM}/(\mathrm{L/H})^5/\mathrm{MM}/(\mathrm{H/L})^3/\mathrm{Al}$, where H layer is the high refractive index dielectric material Si, L layer is the low refractive index dielectric material $\mathrm{SiO_2}$, M layer is the magneto optical material Ce:YIG, and the reflective layer material is Al. When the center wavelength of the polarized light is $\lambda_0=$ 1550 nm, the dielectric layers Si and $\mathrm{SiO_2}$ layers have refraction indices $n_{\mathrm{Si}}=3.48$ and $n_{\mathrm{SiO_2}}=1.495$ [15], and the thickness of the dielectric layers is set to $\lambda_0/(4n)$; the magnetic Ce:YIG layer has dielectric tensor elements $\varepsilon_1=\varepsilon_3=4.884$, $\varepsilon_2=0.009$ [16], the refraction indices of Ce:YIG is $n_{\mathrm{M}}^2=\varepsilon_1$, and the thickness of the magnetic layers is set to $\lambda_0/(4n_{\mathrm{M}})$. The incident medium is air, and the complex refractive index of the reflecting layer Al is $1.44+16\mathrm{i}$ [17].

When the external magnetic field is applied, the magneto optical material exhibits anisotropy. The non-diagonal elements in dielectric constant of the material are controlled by the angle of the applied magnetic field; the optical properties can be calculated by using the 4×4 transmission matrix method.

3 Numerical calculation

Reflective magneto-optic isolators require high reflectivity and 45° Kerr rotation angle. When the angle φ between the external magnetic field and the optical axis varies, the non-diagonal elements in dielectric constant of magneto-optical materials will change, and the reflectivity and Kerr rotation angle will also change. Firstly, when the structure is S1 and $\varepsilon_2=0.009$, linearly polarized light propagates in reflection-type one-dimensional magnetophotonic crystals. The variation of reflectivity with the wavelength λ and the angle φ of the normal incident light is numerically simulated and the results are shown in Fig. 2. With the increase of the angle φ, the reflectivity is reduced, but the change is very small. In Fig. 3, it is numerically simulated when the normal incident wavelength is 1550 nm; the reflectivity changes with the angle φ. According to Fig. 3, when the angle φ increases from 0° to 90°, the reflectivity is reduced from 0.99929 to 0.99905 and the reflectivity is basically unchanged.

Then, when linearly polarized light propagates in reflection-type one-dimensional magnetophotonic crystals, the variation of Kerr rotation angle with the wavelength λ and the angle φ of the normal incident light is numerically simulated. The results are shown in Fig. 4. With the increase of the angle φ, the Kerr rotation angle reduces. In Fig. 5, it is numerically simulated when the normal incident wavelength is 1550 nm. The Kerr rotation angle changes with the angle φ. According to Fig. 5, when the angle φ increases from 0° to 90°, the Kerr rotation angle reduces from 60.6° to 0. The Kerr rotation angle is adjusted to 45° when the angle φ is 44.86°, which meets the requirements of reflective magneto-optical isolator.

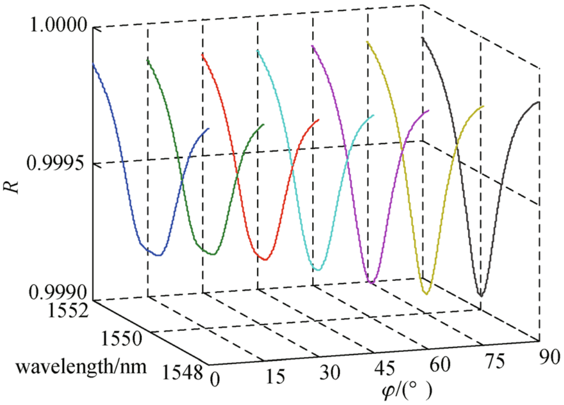

Fig. 2 Variation of reflectivity with the wavelength λ and the angle φ for the structure S1

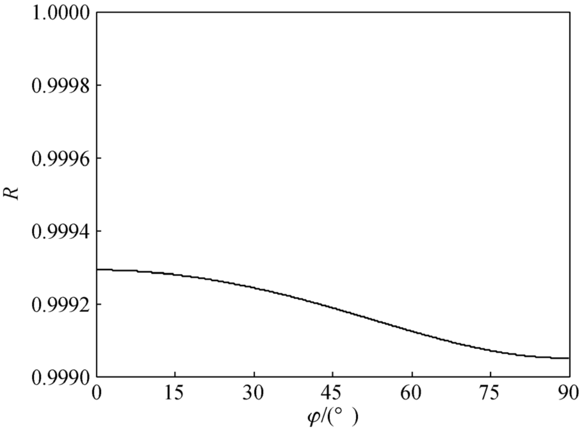

Fig. 3 Reflectivity varies with angle φ for the structure S1 when $\lambda=1550$ nm

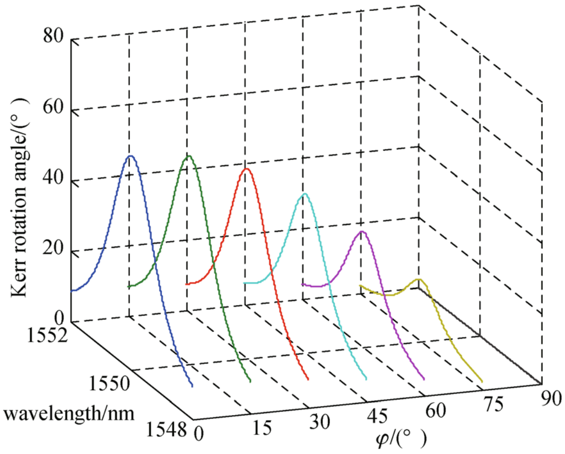

Fig. 4 Variation of Kerr rotation angle with the wavelength λ and the angle φ for the structure S1

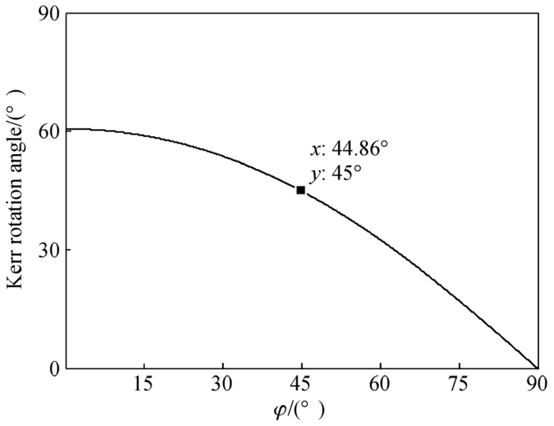

Fig. 5 Variation of Kerr rotation angle with angle φ for the structure S1 when $\lambda = 1550$ nm

The ε_2 is affected by the external magnetic field strength, changing the intensity of the applied magnetic field, the ε_2 in the magneto optical material changes from 0 to 0.009. When the structure is S1 and $\varphi = 0°$, linearly polarized light propagates in reflection-type one-dimensional magnetophotonic crystals. The variation of reflectivity with the wavelength λ and the ε_2 of the normal incident light is numerically simulated, and the results are shown in Fig. 6. With the increase of the ε_2, the reflectivity increases with small change. In Fig. 7, it is numerically simulated when the normal incident wavelength is 1550 nm, the reflectivity changes with the ε_2. According to Fig. 7, when the ε_2 increases from 0 to 0.009, the reflectivity increases from 0.99905 to 0.99929 and the reflectivity is basically unchanged.

Then, when linearly polarized light propagates in reflection-type one-dimensional magnetophotonic crystals, the variation of Kerr rotation angle with the wavelength λ and the ε_2 of the normal incident light is numerically simulated, and the results are shown in Fig. 8. With the increase of the ε_2, the Kerr rotation angle is increased. In

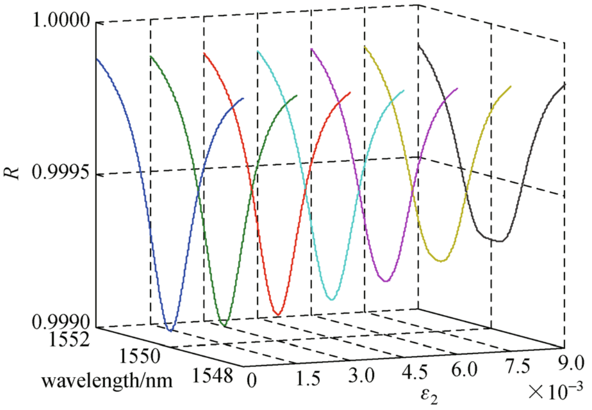

Fig. 6 Variation of reflectivity with the wavelength λ and the ε_2 for the structure S1

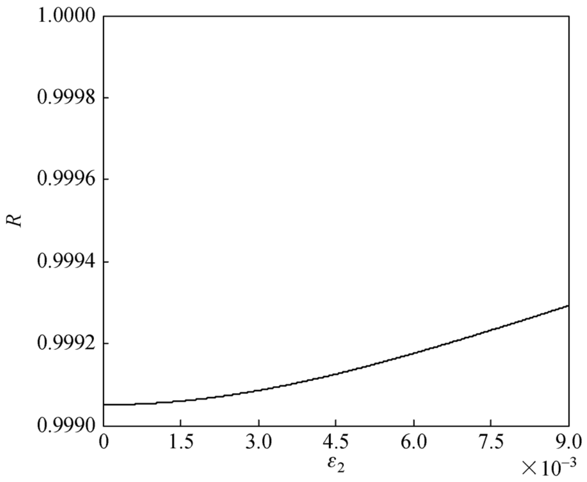

Fig. 7 Reflectivity varies with ε_2 for the structure S1 when $\lambda = 1550$ nm

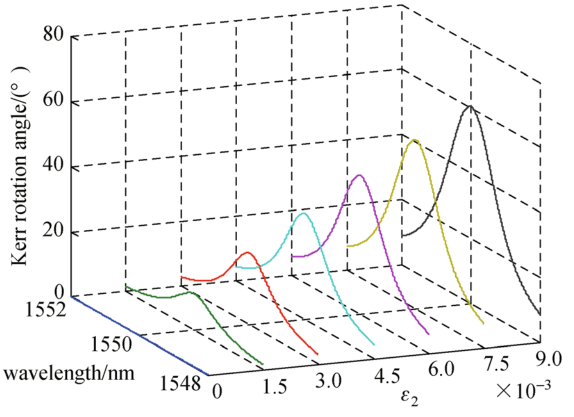

Fig. 8 Variation of Kerr rotation angle with the wavelength λ and the ε_2 for the structure S1

Fig. 9, it is numerically simulated when the normal incident wavelength is 1550 nm, the Kerr rotation angle changes with the angle φ. According to Fig. 9, when the ε_2 increases from 0 to 0.009, the Kerr rotation angle increases from 0 to 60.6°. The Kerr rotation angle is adjusted to 45° when the ε_2 is 0.006379, which meets the requirements of reflective magneto-optical isolator.

In addition to reflection-type one-dimensional magnetophotonic crystals with the structure of S1, reflection-type one-dimensional magnetophotonic crystals can be obtained by adding reflective layer materials at the transmission end. The structure is S2. When the structure is S2 and $\varepsilon_2 = 0.009$, linearly polarized light propagates in reflection-type one-dimensional magnetophotonic crystals. The variation of reflectivity with the wavelength λ and the angle φ of the normal incident light is numerically simulated, and the results are shown in Fig. 10. With the increase of the angle φ, the reflectivity is reduced, but the change is very small. In Fig. 11, it is numerically simulated when the normal incident wavelength is 1550 nm, the reflectivity changes with the angle φ. According to Fig. 11, when the angle φ increases from 0° to 90°, the reflectivity reduces from 0.97979 to 0.97801, the reflectivity is basically unchanged and the reflection spectrum is flat.

Then, when linearly polarized light propagates in reflection-type one-dimensional magnetophotonic crystals, the variation of Kerr rotation angle with the wavelength λ and the angle φ of the normal incident light is numerically simulated. The results are shown in Fig. 12. With the increase of the angle φ, the Kerr rotation angle reduces. In Fig. 13, it is numerically simulated when the normal incident wavelength is 1550 nm, the Kerr rotation angle changes with the angle φ. According to Fig. 13, when the angle φ increases from 0° to 90°, the Kerr rotation angle

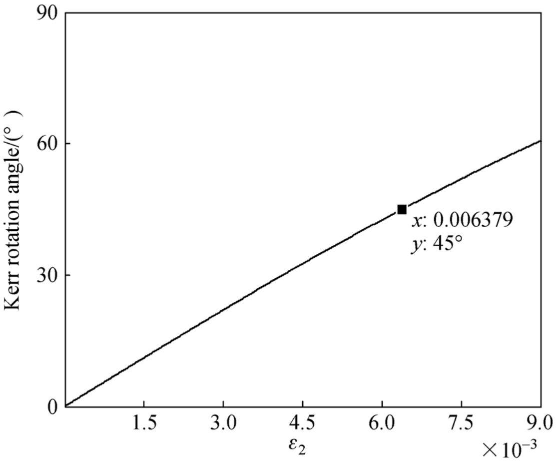

Fig. 9 Variation of Kerr rotation angle with ε_2 for the structure S1 when $\lambda = 1550$ nm

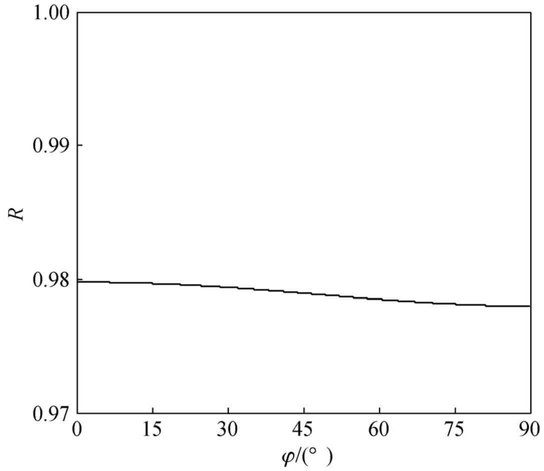

Fig. 11 Reflectivity varies with angle φ for the structure S2 when

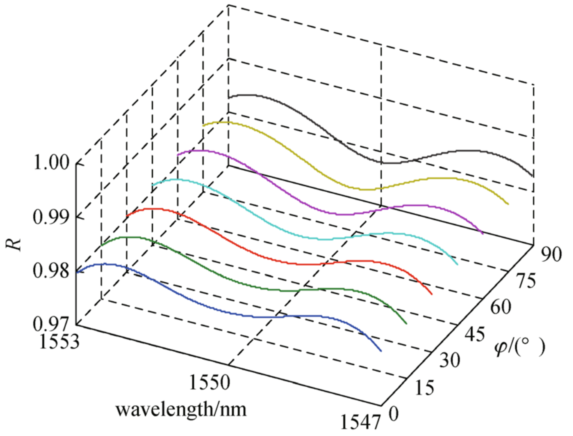

Fig. 10 Variation of reflectivity with the wavelength λ and the angle φ for the structure S2

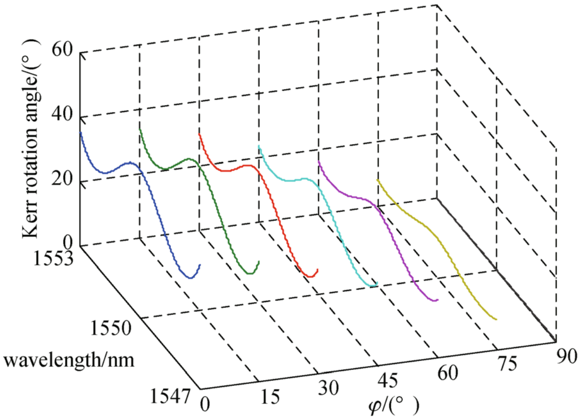

Fig. 12 Variation of Kerr rotation angle with the wavelength λ and the angle φ for the structure S2

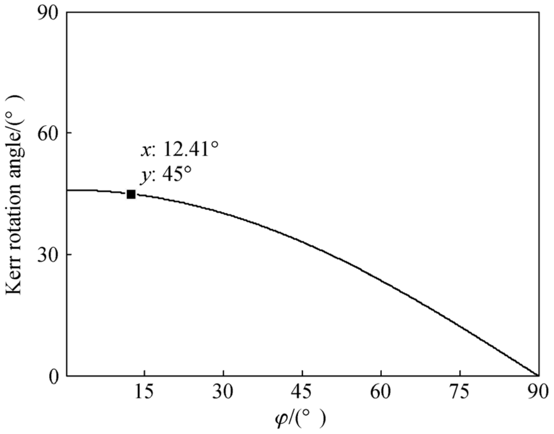

Fig. 13 Variation of Kerr rotation angle with angle φ for the structure S2 when $\lambda = 1550$ nm

reduces from 46.0° to 0. The Kerr rotation angle is adjusted to 45° when the angle φ is 12.41°, which meets the requirements of reflective magneto-optical isolator.

When the structure is S2 and $\varphi = 0°$, linearly polarized light propagates in reflection-type one-dimensional magnetophotonic crystals. The variation of reflectivity with the wavelength λ and the ε_2 of the normal incident light is numerically simulated, and the results are shown in Fig. 14. With the increase of the ε_2, the reflectivity increases, and the change is very small. In Fig. 15, it is numerically simulated when the normal incident wavelength is 1550 nm, the reflectivity changes with the ε_2. According to Fig. 15, when the ε_2 increases from 0 to 0.009, the reflectivity increases from 0.97801 to 0.97979, the reflectivity is basically unchanged and the reflection spectrum is flat.

Then, when linearly polarized light propagates in reflection-type one-dimensional magnetophotonic crystals, the variation of Kerr rotation angle with the wavelength λ and the ε_2 of the normal incident light is numerically simulated, and the results are shown in Fig. 16. With the increase of the ε_2, the Kerr rotation angle is increased. In Fig. 17, it is numerically simulated when the normal incident wavelength is 1550 nm, the Kerr rotation angle changes with the angle φ. According to Fig. 17, when the ε_2 increases from 0 to 0.009, the Kerr rotation angle increases from 0 to 46.0°. The Kerr rotation angle is adjusted to 45° when the ε_2 is 0.00879, which meets the requirements of reflective magneto-optical isolator.

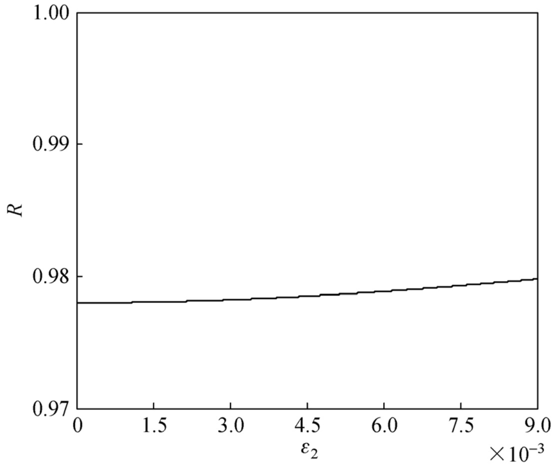

Fig. 15 Reflectivity varies with ε_2 for the structure S2 when $\lambda = 1550$ nm

4 Conclusion

In conclusion, two different designs of reflective one-dimensional magnetophotonic crystals are proposed. The physical models of reflective one-dimensional magnetophotonic crystals are formed by the asymmetric structure or adding Al as the reflection layer at its transmission end.

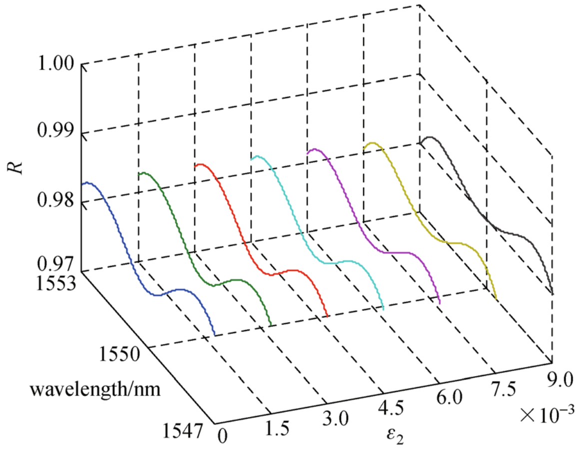

Fig. 14 Variation of reflectivity with the wavelength λ and the ε_2 for the structure S2

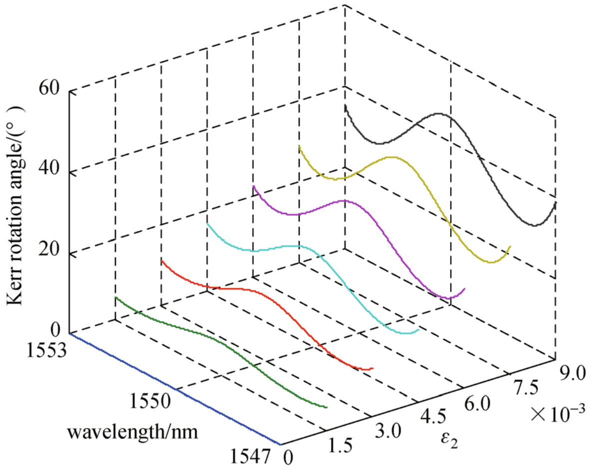

Fig. 16 Variation of Kerr rotation angle with the wavelength λ and the ε_2 for the structure S2

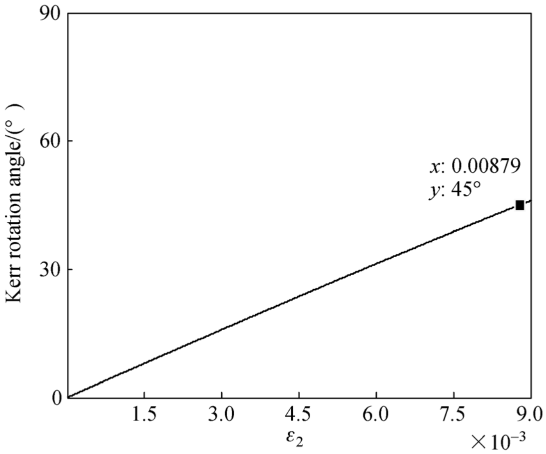

Fig. 17 Variation of Kerr rotation angle with ε_2 for the structure S2 when $\lambda = 1550$ nm

By changing the angle φ or the intensity of applied magnetic field, the non-diagonal elements in dielectric constant of magneto optical materials can be changed; the reflectivity and Kerr rotation angle can be adjusted to obtain a larger reflectivity and a suitable Kerr rotation angle. The model can be applied to fabricate reflective magneto-optical isolator.

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References

1. Vasiliev M, Alameh K E, Belotelov V I, Kotov V A, Zvezdin A K. Magnetic photonic crystals: 1-D optimization and applications for the integrated optics devices. Journal of Lightwave Technology, 2006, 24(5): 2156–2162
2. Wang H, Wang G, Han Y, Chen F. Polarization gaps in one-dimensional magnetic photonic crystal. Optics Communications, 2014, 310: 199–203
3. Ghanaatshoar M, Zamani M. Magneto-optical magnetic field sensors based on compact magnetophotonic crystals. Journal of Superconductivity and Novel Magnetism, 2015, 28(4): 1365–1370
4. Li J, Tang T, Zhang Y, Luo L, Sun P. Magneto-plasmonic sensor with one dimensional photonic crystal for methane detection. Optik (Stuttgart), 2018, 155: 74–80
5. Inoue M, Fujii T. A theoretical analysis of magneto-optical Faraday effect of YIG films with random multilayer structures. Journal of Applied Physics, 1997, 81(8): 5659–5661
6. Sharifian M, Ghadiri H, Zamani M, Ghanaatshoar M. Influence of thickness error on the operation of adjustable magneto-optical isolators. Applied Optics, 2012, 51(20): 4873–4878
7. Liu J, Wang S, Deng S, Wang Y, Zhang J. Polarization research of YIG based two-dimensional magneto photonic crystals. Optics Communications, 2017, 402: 319–325
8. Kato H, Inoue M. Reflection-mode operation of one-dimensional magnetophotonic crystals for use in film-based magneto-optical isolator devices. Journal of Applied Physics, 2002, 91(10): 7017–7019
9. Ghanaatshoar M, Zamani M, Alisafaee H. Compact 1-D magneto-photonic crystals with simultaneous large magnetooptical Kerr rotation and high reflectance. Optics Communications, 2011, 284 (14): 3635–3638
10. Zamani M, Eftekhari S, Ghanaatshoar M. Broadband flat-top spectra of transmittance and faraday rotation in 1D magnetophotonic crystals containing double-negative materials. Journal of Superconductivity and Novel Magnetism, 2015, 28(8): 2613–2619
11. Zamani M. All superconducting photonic crystals with wide-band flat-top responses in visible region. Journal of Superconductivity and Novel Magnetism, 2015, 28(12): 3513–3518
12. Berreman D W. Optics in stratified and anisotropic media: 4×4-matrix formulation. Journal of the Optical Society of America, 1972, 62(4): 502–510
13. Chen C J, Lien A, Nathan M I. 4 × 4 and 2 × 2 matrix formulations for the optics in stratified and biaxial media. Journal of the Optical Society of America A, Optics, Image Science, and Vision, 1997, 14 (11): 3125–3134
14. Fei H, Wu J, Yang Y, Liu X, Chen Z. Magneto-optical isolators with flat-top responses based on one-dimensional magneto-photonic crystals. Photonics and Nanostructures, 2015, 17: 15–21
15. Zamani M, Ghanaatshoar M. Design and error analysis of adjustable reflection-type magneto-optical photonic crystals for optical isolator application. Journal of Magnetism and Magnetic Materials, 2014, 358–359: 76–81
16. Abdi-Ghaleh R, Namdar A. Circular polarization bandpass filters based on one-dimensional magnetophotonic crystals. Journal of Modern Optics, 2013, 60(19): 1619–1626
17. Zamani M, Ghanaatshoar M. High performance reflection-type 1D magnetophotonic crystals with flat-top responses. Photonics and Nanostructures, 2013, 11(3): 234–240

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