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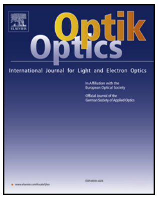

Original research article

Existence of high Faraday rotation and transmittance in magneto photonic crystals made by silica matrix doped with magnetic nanoparticles

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ABSTRACT

This paper focuses on studying the potential of CoFe2O4-doped magnetic nanoparticles SiO2 / ZrO2 matrix to produce high-performance one-dimensional magnetophotonic crystals (MPC) and to solve the problem of integrating magneto-optical devices. Given the importance of the magneto-optical Faraday effecton most non-reciprocal optical components, we studied the influence of different 1D structures on Faraday rotations.The potential of these structures offers a wide range of applications in the field of miniaturized and integrated non-reciprocal devicessuch as isolators.

1. Introduction

One-dimensional photonic crystals were introduced for the first time by Yablonovitch [1] and John [2],they are periodic dielectric materials and could be defined as Bragg's mirrors.They have the ability of controlling the propagation of electromagnetic waves across the materials [3,4]. The frequencies of the electromagnetic waves that travel across the photonic crystals are classified into permitted modes and photonic band gaps which, at particular wavelengths, are not crossed by the incident light [5–10].

The periodicity of the photonic crystals can be broken by introducing a different layer or by disordering the layers, the highly localized defect modes would then be created inside the photonic band gaps. This effect allows the corresponding electromagnetic wave with previously forbidden wavelength to propagate through the structure [9–13].

However, when the constituent materials of the photonic crystals have magneto-optical characteristics, or even only a defect layer is, the resulting structures are called magnetophotonic crystals (MPCs). One-dimensional MPCs arevery small in size and are able to provide unique optical and magneto-optical characteristics by exploiting the properties of photonic band gaps and defect modes.

Thus, these structures have attracted much attentions in the designing and manufacturingthe magneto-optical elements such as isolators and circulators [14–16]. Among the magneto-optical effects, the Faraday rotation, that is the rotation of the polarization plane of a linearly polarized light propagating through a magneto-optical support, finds important applications in telecommunications, where the integration of optical isolators based on this non-reciprocal effect of magneto-photonic materials remains to be done [17,18].

Yttrium iron garnet (YIG) and its derivedforms (Bi:YIG,Ce:YIG)are the most frequently usedmaterials to fabricate the non-

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reciprocaldevices, such as optical isolatorsand circulators.However, due to technical difficulties, it is always difficult to integrate these materials with conventional technologies, and integrated versions of non-reciprocal devices arenotavailable. This ismainlyduetoa high temperature (∼700∘C), necessary required for the crystallization ofYIG.In thiscontext, it is worthy to develop the other approaches to reach the integration of the nonreciprocal functions. The impossibility detaching (YIG) substrates such as III-V semiconductors, silica and silicon or other polymer materials, leads to develop other approaches to achieve integration of non-reciprocal functions.

The sol-gel technique is considered as a versatile, flexible and a low-cost technique useful for the realization of integrated photonic devices; it gives a solution to fabricate integrated magneto-optic devices [19,20].

Practically, the number of reflections that the electromagnetic wave undergoes inside the one-dimensional MPCs, periodic structures and micro-cavities, leads to the qualitative decrease of the group velocity of the wave. This increases the interaction time between the wave and the material. Thus, the exaltation of the value of the magneto-optical effects respectively at the edge and inside the photonic bandgap is possible [21].

Other authors have also theoretically modeled and experimentally demonstrated the exaltation of the value of Faraday rotation in one-dimensional MPCs in the form of micro-cavity structures [22,23].

In this paper we study the effect of position and number of defects on Faraday rotation effect of one-dimensionalmagnetophotonic crystalsmade by $SiO_2/ZrO2$ or SiO_2/TiO_2 doped with magnetic nanoparticles using sol-gel process in different configurations. We started by, varyingthe concentration of magnetic nanoparticles VF% of the structures, and introducing a defect at different locations. Then we followed by two defects and finish by three defects with variable locations. The result obtained gives the designs of magnetophotonic crystal devices.

2. 1D MPCs structure and design

The 1D MPCs structure is very favored for studying the properties of photonic bandgaps and Faraday rotation effect. It gives a large opening bandgap and it is a good compromise, especially for high slaughter factors and the incidence angle [24]. The 1D MPCs which are studied and analysed in present work, consists of a multilayer structure in periodic lattice SiO_2/ZrO_2 or SiO_2/TiO_2 with air gaps, of perioda = 645 nm. The structure is characterized by a background index of 1.57 and an air-to-air refractive index = 1. The thickness of the layers of material is $d_1 = 258$ nm and the gap width is $d_2 = 387$ nm with ($a = d1 + d_2$). Fig. 1 illustrates the 1D MPCs structure used for the study.

Thisstructureof magneto-photonic crystals iscalled"periodicstructure"(Fig. 1).It alternates high refractive index magneto-optical layers(SiO_2/ZrO_2orSiO_2/TiO_2)with layers of a low refractive index material(air).

In the representation Fig. 2 (a) we have demonstrated the presence of photonic bandgap in 1D photonic crystals compound of SiO_2/ZrO_2 or SiO_2/TiO_2 made by sol-gel process [24,25].

In the representation of the transmission spectrum (Fig. 2(a)), we distinguished the existence a photonic bandgap in the NIR region from 1400 nm to 1800 nm with a band gap of about $\Delta\lambda = 400$ nm.

In Fig. 2 (b) there is an increase in the value of the Faraday rotation at the edges of the photonic band gap. Indeed, a first peak is observed at the lower edge towards a wavelength of 1400 nm and a second larger peak is observed at the upper edge towards a wavelength of 1800 nm.These enhances are because of optical Borrmann effect [26].

Thestructureusedin thispartiscalledthe "micro-cavitystructure"(Fig. 3).It consistsof an alternation of magneto-opticallayers ($SiO2/ZrO_2$ or SiO_2/TiO_2)with a high refractive index andlowindexairlayers.Thecentrallayercorresponds to a defectcharacterized bya width ($d_{def} = 2^* d_1$) that allows lightto passthrough thecenterof thephotonic band gap.

Fig. 4 shows the spectral response of the micro-cavity formed by defecting one layer obtained with the RCWA method of the impulse response for values of refractive index

Fig. 4 (a) shows a resonance of the value of the transmittance as well as Fig. 4 (b) shows an increase in the value of the Faraday rotation within the photonic band gap (≈ 1580 nm). Indeed, the value of the Faraday rotation is greater than that of a reference

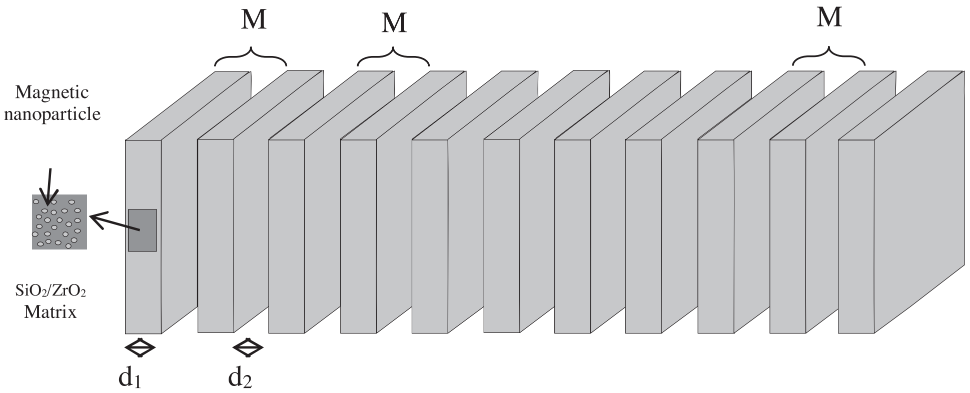

Fig. 1. Schematic of 1D photonic crystal structure made with magneto-optic layers without defect.

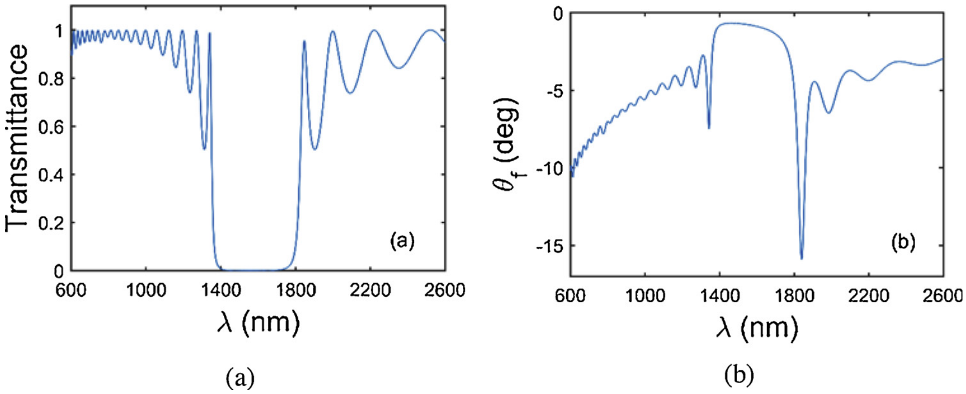

Fig. 2. Transmittance (a) and the Faraday rotation (b)spectra of 1D photonic crystal made with magneto-optic layers without defect.

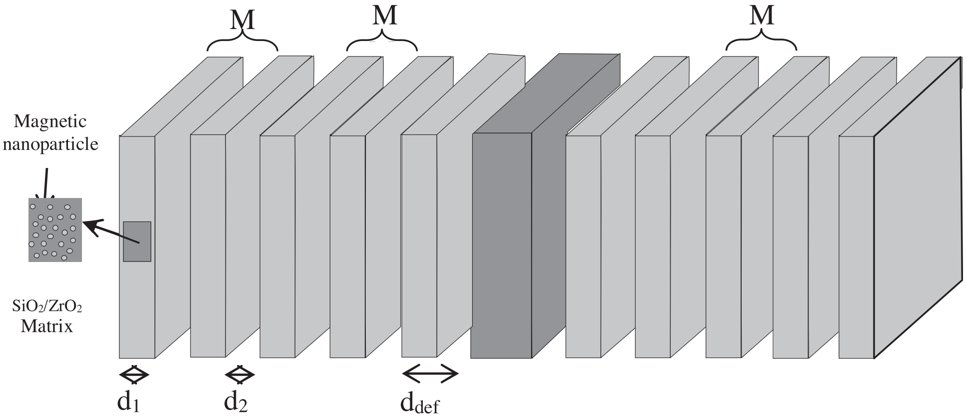

Fig. 3. Schematic of 1D photonic crystal structure made with magneto-optic layers with one defect.

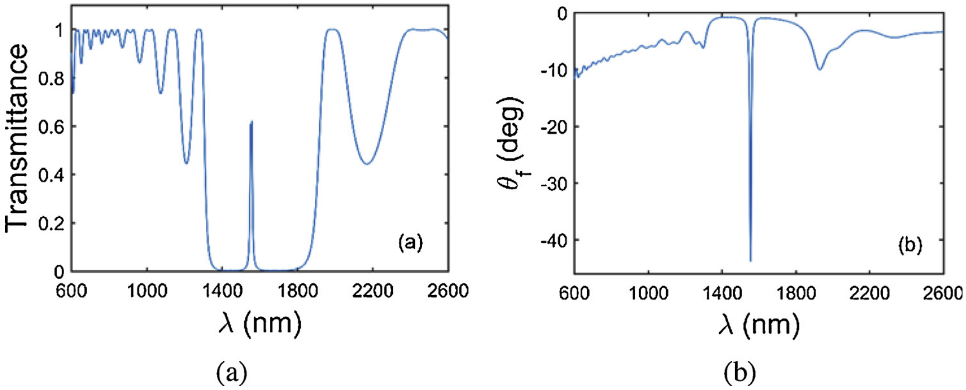

Fig. 4. Transmittance (a) and the Faraday rotation (b)spectra of 1D photonic crystal made with magneto-optic layers with defect.

layer. The simulation results are in agreement with experimental results [15].

3. Results and discussions

In order to study the influence of the material on the Faraday rotation effect in 1D MPCs, we varied the concentration of magnetic nanoparticles VF%of the structures, and introduced a defect to different locations. Then two defects and finally three defects are considered. The simulations are carried out under the Rigorous Coupled Wave Analysis (RCWA) (RSoft Design Group, Diffract Mode, Inc. 200 Executive Blvd. Ossining, NY 10,562).

Table 1
The concentration of magnetic nanoparticles VF% of the structures: magneto-photonic layer realized by sol-gel process.

VF(%)	Im(εxy)
1	0000267857
2.04	0000546429
11	0003214287
21	0005357144
42	0016250003

3.1. *The effect of the variation of the concentration of magnetic nanoparticles VF% of the structures*

In this part, the structure we have varied the concentration of magnetic nanoparticles VF% of the structures: magneto-photonic layer realized by sol-gel process, and we study the influence of volume fraction VF% on the Faraday rotation and transmittance for (one defect at 6th layer air/(A/B)11/air) (Table 1).

Fig. 5 show the Faraday rotation and transmittance of both as functions of volume fraction VF% for the case of perpendicular incident light.

In the following, we study the wavelength dependence of magneto-optical responses of the structures introduced in the case of different volume fractions. Thus, Fig. 5 illustrates transmittance and Faraday rotation spectra of the structure for different volume fractions and in the case of perpendicular incident light.

As can be seen, the structure exhibits maximum Faraday rotation and high transmittance.Therefore, these SiO_2 / ZrO_2 or SiO_2 / TiO_2 matrices doped with MPCs based on $CoFe_2O_4$ magnetic nanoparticles can be used in integrated magneto-optical devices such as filters and isolators. Since the operating bandwidth is one of the most important functional characteristicsof devices based on MPC [27,28]. To obtain such devices, a Faraday rotation value of 45° must be achieved.

This value of the Faraday rotation is necessary for the realization of a Faraday isolator for example [29,30] is obtained with a concentration of nanoparticles of 42%.

3.2. *The effect of defects layer*

In order to investigate the properties of photonic band gap and defect mode(s) of the structure regarding the various magneto-optical defect layer positions, we produced the Fig. 6. This figure shows the transmittance and Faraday rotation spectra of the considered structure for different positions of defect layer.

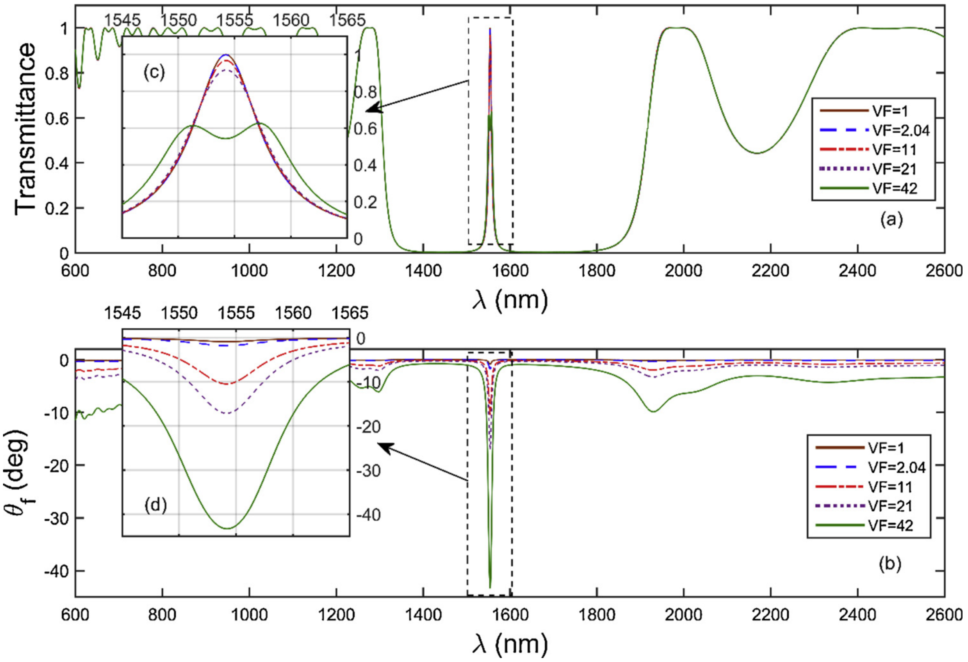

Fig. 5. Transmittance and Faraday rotation spectra of 1D photonic crystal structure made with magneto-optic layers with one defect for different volume fractions.

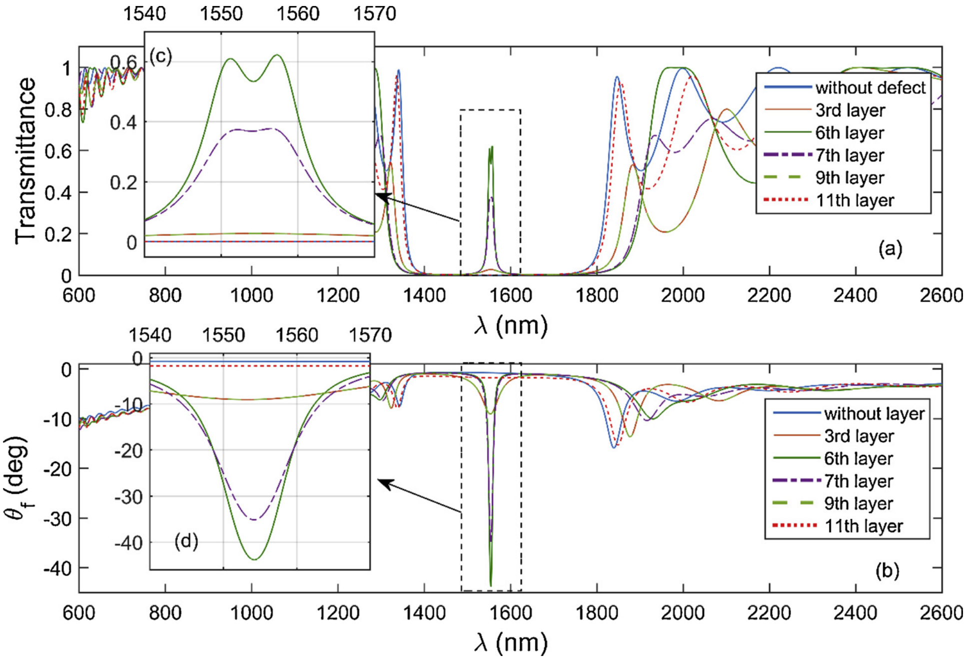

Fig. 6. Transmittance and Faraday rotation spectra of 1D photonic crystal structure made with magneto-optic layers with one defect at different positions.

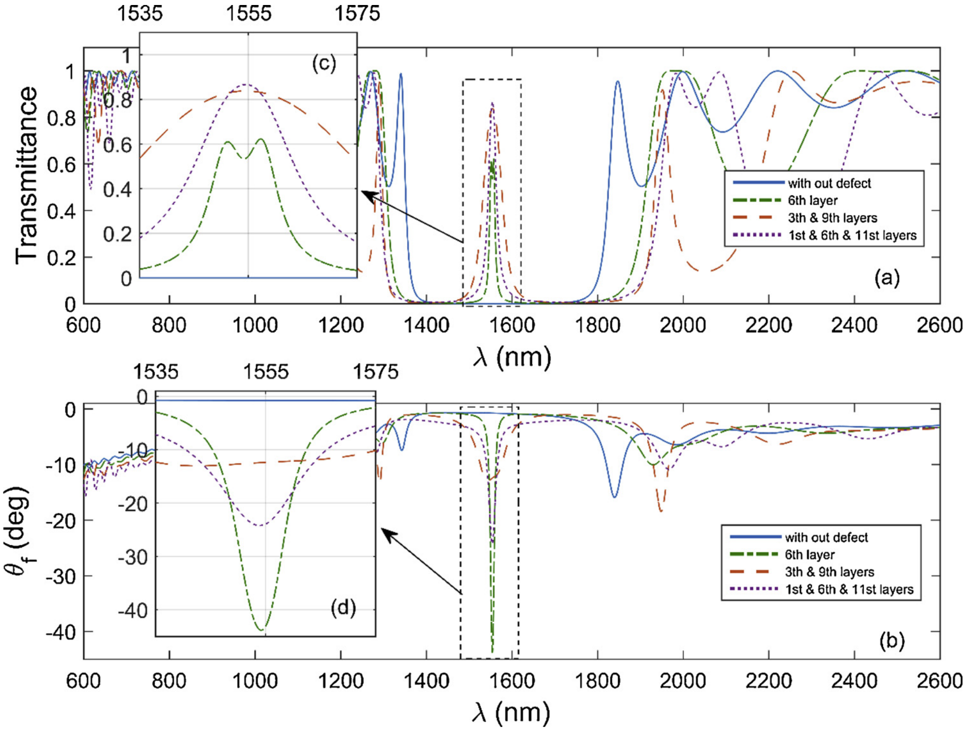

Fig. 7. Transmittance and Faraday rotation spectra 1D photonic crystal structure made with magneto-optic layers with one, two and three defects at different positions.

The preceding results show that the central position of the photonic band gap can be controlled by modifying the position of the defect layer. Moreover, it is seen that the peak value of the transmittance and Faraday rotation are dependent of the position of the defect layer.As expected for such a periodic structure, the increase in the value of the Faraday rotation is observed in the center of the photonic band gap. At 1560 nm, the value of the Faraday rotation of the studied micro-cavity structure is increased compared to that of the reference magneto-optical layer. Nevertheless, the peak transmittance of all of them is affected by the defect layer position.

In this section, we sought to optimize the exaltation of magneto-optical effects in 1D MPC. Thus, several defects (two and three defects) are introduced into different locations in the periodic structure to achieve a "multi-cavity" structure (Fig. 7).

From the results obtained, we observe a resonance of the value of the transmittance and the Faraday rotation and their value are strongly influenced by the presence of the defects and their locations.

From these works it is retained that the periodic structuring is an effective means for exalting the value of the Faraday rotation at the edges of the photonic band gap. In addition, the introduction of defects within this structure leads to exaltation within the photonic band gap.

4. Conclusion

In this paper, we represent a new design for magneto-photonic crystal platform. we have used a new kind of artificial magneto-optical materials (SiO_2/ZrO_2 or SiO_2/TiO_2 matrix doped with magnetic nanoparticles) in magneto-photonic crystals as a magnetic defect layer, characterized by low refractive index material 1.51. This magnetic layer can be realized by sol-gel process. In addition, we have studied the effect of the concentration of magnetic nanoparticles VF% of the structures and the defects at different locations on the resonance of the value of the transmittance of micro-cavities and the Faraday rotation in a 1D magneto-photonic crystals.

The value of the transmittance in the bandgap and the Faraday rotation are sensitive to the concentration of magnetic nanoparticles VF% of the structures the locations and number of photonic crystal cavity. Hence, we have also investigated the influence of defects at different locations on the optical response of transmission-type one-dimensional MPCs.

References

[1] E. Yablonovitch, Inhibited spontaneous emission in solid-state physics and electronics, Phys. Rev. Lett. 58 (1987) 2059–2062, https://doi.org/10.1103/PhysRevLett.58.2059.

[2] S. John, Strong localization of photons in certain disordered dielectric superlattices, Phys. Rev. Lett. 58 (1987) 2486–2489, https://doi.org/10.1103/PhysRevLett.58.2486.

[3] J.D. Joannopoulos, S.G. Johnson, J.N. Winn, R.D. Meade, Photonic Crystals Molding the Flow of Light, Princeton University Press, Princeton, New Jersey, 2007.

[4] B.E.A. Saleh, M.C. Teich, Fundamental of Photonics, 2nd edition, Wily Interscience, 1991.

[5] J.D. Joannopoulos, P.R. Villeneuve, S. Fan, Photonic crystals, Solid StateCommunications 102 (1997) 165–173, https://doi.org/10.1016/S0038-1098(96)00716-8.

[6] K. Nozaki, T. Tanabe, A. Shinya, S. Matsuo, T. Sato, H. Taniyama, M. Notomi, Sub-femtojoule all-optical switching using a photonic-crystalnanocavity, Nat. Photon. 4 (2010) 477–483, https://doi.org/10.1038/nphoton.2010.89.

[7] H.M. Lee, J.C. Wu, Transmittance spectra in one-dimensional superconductor-dielectric photonic crystal, J. Appl. Phys. 107 (2010), https://doi.org/10.1063/1.3362935 09E149-09E149-3.

[8] S.A. El-Naggar, Enlarged omnidirectional photonic gap in one dimensional ternary plasma photonic crystals that contain metamaterials, Eur. Phys. J. 67 (2013) 54–60, https://doi.org/10.1140/epjd/e2013-30669-5.

[9] J.D. Joannopoulos, S.G. Johnson, J.N. Winn, R.D. Meade, Photonic Crystals: Modeling the Flow of Light, 2nd edition, Princeton University Press, 2008, pp. 197–203.

[10] P. Markos, C.M. Soukoulis, Wave Propagation: From Electrons to Photonic Crystals and Left-handed Materials, Princeton University Press, 2008.

[11] E. Abdel-Rahman, A. Shaarawi, Defect mode in periodic and quasiperiodic one-dimensional photonic structures, J. Mater. Sci. Mater. Electron. 20 (Suppl 1) (2009) 153–158, https://doi.org/10.1007/s10854-007-9496-x.

[12] E. Lotfi, K. Jamshidi-Ghaleh, F. Moslem, H. Masalehdan, Comparison of photonic crystal narrow filters with metamaterials and dielectric defects, Eur. Phys. J. 60 (2010) 369–372, https://doi.org/10.1140/epjd/e2010-00207-4.

[13] K. Jamshidi-Ghaleh, Z. Ebrahimpour, One-way absorption behaviour in defective 1D dielectric-metal photonic crystal, Eur. Phys. J. 67 (2013) 27–30, https://doi.org/10.1140/epjd/e2012-30383-x.

[14] I.L. Lyubchanskii, N.N. Dadoenkova, M.I. Lyubchanskii, E.A. Shapovalov, T. Rasing, Magnetic photonic crystals, J. Phys. D Appl. Phys. 36 (2003) R277–R287, https://doi.org/10.1088/0022-3727/36/18/R01.

[15] M. Inoue, R. Fujikawa, A. Baryshev, A. Khanikaev, P.B.Lim, H. Uchida, O. Aktsipetrov, A. Fedyanin, T. Murzina, A. Granovsky, J. Phys. D Appl. Phys. 39 (2006) R151–R161, https://doi.org/10.1088/0022-3727/39/8/R01.

[16] H.F. Zhang, S.B. Liu, X.K. Kong, B.X. Li, Photonic band gap of three dimensional magnetized photonic crystal with Voigt configuration, Eur. Phys. J. 67 (2013) 169–181, https://doi.org/10.1140/epjd/e2013-40193-3.

[17] N. Bahlmann, M. Lohmeyer, O. Zhuromskyy, H. Dotsch, P. Hertel, Nonreciprocal coupled waveguides for integrated optical isolators and circulators for TM-modes, Opt. Commun. 161 (1999) 330–337, https://doi.org/10.1016/S0030-4018(99)00027-9.

[18] N. Bahlmann, M. Lohmeyer, O. Zhuromskyy, H. Dotsch, P. Hertel, Integrated magneto-optic Mach-Zehnder interferometer isolator for TE modes, Electron. Lett. 34 (1998) 2122–2123, https://doi.org/10.1049/el:19981485.

[19] A. Hocini, M. Bouras, H. Amata, Theoretical investigations on optical properties of magneto-optical thin film on ion-exchanged glass waveguide, Opt. Mater. 35 (9) (2013) 1669–1674, https://doi.org/10.1016/j.optmat.2013.04.026.

[20] F. Royer, D. Jamon, J.J. Rousseau, H. Roux, D. Zins, V. Cabuil, Magneto-optical nanoparticle-doped silica-titania planar waveguides, J. Lightwave. Technol, Applied Physics Letters. 86 (2005) 011107, , https://doi.org/10.1063/1.1844038.

[21] M. Inoue, M. Levy, A.V. Baryshev, Magnetophotonics: From Theory to Applications, Springer Heidelberg, New York Dordrecht London, 2013.

[22] T. Hamon, S. Buil, E. Popova, P.R. Dahoo, N. Keller, Investigation of a one-dimensional magnetophotonic crystal for thestudy of ultrathin magnetic layer, J. Phys. D Appl. Phys. 39 (2006) 1012–1017, https://doi.org/10.1088/0022-3727/39/6/003.

[23] Reza Abdi-Ghaleh, Mohsen Asad, Design of one-dimensional magnetophotonic crystals operating at visible wavelengths, Eur. Phys. J. D 69 (2015) 13–19, https://doi.org/10.1140/epjd/e2014-50618-0.

[24] Ahmed Kahlouche, Abdesselam Hocini, Djamel Khedrouche, Band-gap properties of 2D photonic crystal made by silica matrix doped with magnetic nanoparticles, J. Comput. Electron. 13 (2014) 490–495, https://doi.org/10.1007/s10825-014-0559-y.

[25] Mounir Bouras, Abdessalem Hocini, Mode conversion in magneto-optic rib waveguide made by silica matrix doped with magnetic nanoparticles, Opt. Commun. 363 (2016) 138–144, https://doi.org/10.1016/j.optcom.2015.11.024.

[26] A.B. Khanikaev, A.B. Baryshev, P.B. Lim, H. Uchida, M. Inoue, A.G. Zhdanov, A.A. Fedyanin, A.I. Maydykovskiy, O.A. Aktsipetrov, Nonlinear Verdet law in magneto-photonic crystals: interrelation between Faraday and Borrmann effects, Phys. Rev. B 78 (2008) 193102-1–193102-4, https://doi.org/10.1103/PhysRevB.78.193102.

[27] M. Zamani, M. Ghanaatshoar, Adjustable magneto-optical isolators with flattop responses, Opt. Express 20 (2012) 24524–24535, https://doi.org/10.1364/OE.20.024524.

[28] M. Zamani, M. Ghanaatshoar, High performance reflection-type 1D magnetophotonic crystals with flat-top responses, Photonics Nanostruct. 11 (2013) 234–240, https://doi.org/10.1016/j.photonics.2013.04.002.

[29] M.J. Steel, M. Levy, R.M. Osgood, High transmission enhanced Faraday rotation in one-dimensional photonic crystals with defect, Ieee Photonics Technol. Lett. 12 (2000) 1171–1173, https://doi.org/10.1109/68.874225.

[30] M.J. Steel, M. Levy, R.M. Osgood, Photonic bandgaps with defects and the enhancement of faraday rotation, J. Light. Technol. 18 (2000) 1297–1308, https://doi.org/10.1109/50.871709.