Optical bistability in one-dimensional magnetic photonic crystal with two defect layers

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One-dimensional magnetic photonic crystal with two magnetic defect layers is theoretically studied. The dependence of defect modes inside photonic band gap on the distance between defect layers is investigated. It is shown that the cubic nonlinear optical response of a two-defect MPC leads to the effect of bistability on the frequencies of defect modes. © 2008 American Institute of Physics. [DOI: 10.1063/1.2832351]

Magnetic photonic crystals (MPCs) are very promising for applications in modern photonics, since they possess an additional and continuously tunable degree of freedom. These MPCs can be presented as periodic one-, two-, and three-dimensional structures composed of at least two different magnetic and nonmagnetic or two magnetic materials with different refractive indices. The difference in refractive index of MPCs (like in conventional photonic crystals) leads to the appearance of so-called photonic band gaps (PBGs) in the spectra of normal electromagnetic waves (EMWs), i.e., to forbidden regimes where EMWs cannot propagate through the photonic structure. The linear and nonlinear optical and magneto-optical (MO) properties of MPCs have already been investigated in numerous publications (see, for example, Refs. 1 and 3 for reviews). Quadratic nonlinear optical effects of MPCs, such as optical second harmonic generation, were well studied. Cubic optical nonlinearity can lead to different phenomena such as third harmonic generation and optical self-action. An intriguing issue is the effect of optical bistability, which was well studied for nonmagnetic photonic crystals and for which preliminary results were obtained for a MPC with one defect layer. Recently, the effects of self-action in a dielectric photonic crystal with a single magnetic defect layer was reported. In regular photonic structures, the presence of a defect layer leads to the so-called defect mode (narrow peak with a high transmittivity) inside the PBG. The number of defect modes depends on the number of defects in the photonic structure and can be changed by varying the distance between the defects and by their thicknesses. The linear optical and magneto-optical properties of MPCs with two defects were studied in Refs. 11 and 12.

In this paper, we present the results of a theoretical investigation of the optical bistability in a one-dimensional MPC with two defect layers. Taking into account the nonlinear optical susceptibility, we studied analytically and numerically the nonlinear optical response of a two-defect MPC upon intensive optical radiation in the polar MO configuration for normal incidence of light. The intensity dependence of the defect modes as well as the sign of the nonlinear part of the refractive index are calculated.

Consider a one-dimensional MPC composed of alternating nonmagnetic gadolinium gallium garnet (GGG) $\text{Gd}_3\text{Ga}_5\text{O}_{12}$ and magnetic yttrium iron garnet (YIG) $\text{Y}_3\text{Fe}_5\text{O}_{12}$ layers with two magnetic defect YIG layers constructed as $(MN)^a(DM)(NM)^b(DM)(NDM)(NM)^c$ (Fig. 1). Here, $M$ denotes the magnetic layer with thickness $d_1$, $N$ is the nonmagnetic layer of thickness $d_2$, and $D_M$ is magnetic defect layer of thickness $d_{\text{Def}}$, respectively, and $a$, $b$, and $c$ are numbers of $(NM)$ bilayers with thickness $D=d_1+d_2$. The magnetization vector in all the magnetic layers is oriented perpendicular to the layers, as shown in Fig. 1.

The nonlinear optical polarization of the magnetic $\mathbf{P}_{\text{NL}(1)}$ and nonmagnetic $\mathbf{P}_{\text{NL}(2)}$ layers can be presented as follows:

![FIG. 1. Schematic of a MPC with two magnetic defects (dark). Big arrows show the directions of incident and transmitted EMWs. Small arrows inside YIG layers indicate the direction of magnetization.](image-url)
where $E(\omega)$ is the electric field of the incident EMW with frequency $\omega$, $e_{ij}^{(i)}$ and $\chi_{ijkl}^{(i)}$ are the dielectric permittivity tensor and nonlinear optical susceptibility tensor for $M$ ($i=1$) and $N$ ($i=2$) layer respectively. In Eq. (1), we omit terms quadratic in $E(\omega)$ describing optical second harmonic generation because we consider the nonlinear optical response at the fundamental frequency $\omega$.

For the polar MO configuration as shown in Fig. 1, the dielectric permittivity tensors for both types of layers (magnetic and nonmagnetic) can be presented as follows:

$$
e^{(1)}_{ij} = \begin{pmatrix} e^{(1)}(1) & 0 \\ 0 & e^{(1)}(2) \end{pmatrix}, \quad e^{(2)}_{ij} = \begin{pmatrix} e^{(2)}(1) & 0 \\ 0 & e^{(2)}(2) \end{pmatrix},$$

where $e^{(1)}$ and $e^{(2)}$ are magnetization-independent components of the permittivity tensor in the $M$ and $N$ layers, respectively, $f$ is the linear MO constant and $m_Z$ is the $z$ component of the unit magnetization vector $m=M/M_s$, where $M_s$ is the saturation magnetization. The tensor $\chi_{ijkl}^{(1)}$ for the magnetic layers can be presented in the standard form

$$
\chi_{ijkl}^{(1)} = \chi_{ijkl}^{(3;1)} + \chi_{ijkl}^{(3;2)},
$$

where $\chi_{ijkl}^{(3;1)}$ and $\chi_{ijkl}^{(3;2)}$ are magnetization-independent and magnetization-dependent parts of $\chi_{ijkl}^{(1)}$, respectively. Nonlinear optical properties of GGG are not taken into account.

For the calculations of transmission characteristics of the MPC, we used a transfer matrix method developed for nonlinear multilayers in Ref. 16. Similarly to the procedure used in our earlier paper, 12 we present the transfer matrix for the MPC shown in Fig. 1 in the following form:

$$
\hat{T} = (\hat{P})^n \hat{A}_1 \hat{E}_1(d_{\text{inc}})(\hat{A}_1)^{-1}(\hat{P})^n \hat{A}_1 \hat{E}_1(d_{\text{inc}})(\hat{A}_1)^{-1}(\hat{P})^n, \quad (4)
$$

where

$$
\hat{P} = \hat{A}_2 \hat{E}_2(d_2)(\hat{A}_2)^{-1} \hat{A}_1 \hat{E}_1(d_1)(\hat{A}_1)^{-1}. \quad (5)
$$

The indices 1 and 2 correspond to the YIG and GGG, respectively. $E_i(z)$ is the propagation matrix of the eigenmodes inside the layer $i$ and $\hat{A}_i$ relates to the total electric $E_{ex,y}$ and magnetic $H_{x,y}$ fields at the boundary of the layer to the amplitude of the eigenmodes. The explicit formulas for the $\hat{A}_i$ matrices elements, as well as for the wave numbers $k_z$ are obtained from the Maxwell equations. 17

Using expressions (4) and (5), we calculated numerically the transmission spectra for a two-defect MPC and obtained two defect modes inside the PBGs. For numerical simulations, we used the following values for the tensors in Eqs. (2) and (3): $e^{(1)}=4.886$, $f=0.009$, $e^{(2)}=3.709$, for $\lambda=1.15 \mu m$, 13 and $\chi_{xxz}^{(3;1;0)}=1.8 \times 10^{-18}(m^2/V^2)$, $\chi_{xxz}^{(3;1;1)}=0.36 \times 10^{-18}(m^2/V^2)$, $\chi_{xxx}^{(3;1;2)}=0.1 \times 10^{-18}(m^2/V^2)$, and $\chi_{xxx}^{(3;1;3)}=0.1 \times 10^{-18}(m^2/V^2)$. 9 The position of these defect modes was also analyzed as a function of the distance $d$ between the defects inside the MPC. Numerical calculations showed that increasing the distance between the defects leads to a decreasing distance between the defect modes. The corresponding results of the numerical calculations are presented in Fig. 2.

Nonlinear polarization induced by a cubic optical nonlinearity can lead to a nonlinear behavior of EMWs transmitted through the MPC, since the refractive index of the nonlinear media depends on the intensity of the transmitted light as

$$
n = n_0 + n_2 I, \quad (6)
$$

where $n_0$ is the refractive index in the linear (or low-intensity) situation, and $n_2$ is an optical constant that characterizes the strength of the optical nonlinearity.

Here, $I=(n_o c/8\pi)E_0^2$ is the intensity of the incident EMW with amplitude $E_0$ and $c$ is the speed of light in vacuum. The results of the calculations are summarized in Fig. 3 that shows a strong nonlinear dependence of the output intensity as a function of the intensity of the incident light, giving rise to optical bistability. The latter can be controlled by an external magnetic field, giving rise to interesting new applications.

Figure 3 shows that the intensity dependence of the transmission of the left-handed circularly polarized transmit-
tied light varies much stronger in comparison with right-handed polarized light. This fact can be explained by different combinations of cubic nonlinear optical tensor components which determine the intensity-dependent refractive index.

In conclusion, we have considered the influence of cubic optical nonlinearity on the behavior of transmitted normal incidence light for a MPC with two defect layers. It was shown that the positions (or frequencies) of the defect modes inside the photonic band gap strongly depend on the distance between defect layers in MPC. The nonlinear cubic polarization leads to bistability effects in the transmitted light.

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