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Nonlinear magneto-optical Kerr effect in gyrotropic photonic band gap structures: magneto-photonic microcavities

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Abstract

Nonlinear magneto-optical Kerr effect in second-harmonic generation is observed in the one-dimensional magneto-photonic microcavities built up of two nonmagnetic Bragg reflectors separated by a magnetic garnet half-wavelength spacer.

Keywords: Second-harmonic generation; NOMOKE; Magneto-photonic crystals

1. Introduction

The unique properties of photonic band gap (PBG) structures—photonic crystals and microcavities are associated with the possibility to control the light propagation [1]. The spectacular properties in PBG structures such as giant optical dispersion, bistability, and the localization of light define the perspectives of the applications of photonic crystals and microcavities in optoelectronics as all optical switches and transistors [2]. In one-dimensional (1D) case, the photonic crystal microcavity (MC) consists of two Bragg reflectors separated with a half-wavelength-thick spacer. The optical radiation resonant to the MC mode is strongly localized in the MC spacer. The resonant field enhancement at the MC mode leads to enhancement of nonlinear-optical response. The enhanced Raman scattering [3], second-harmonic generation (SHG) [4–9] and third-harmonic generation [10] have been observed in 1D microcavities. Recently, magnetic microcavities have been proposed for the enhancement of the linear magneto-optical effects [11]. In these PBG structures the localization of light and the multiple reflection interference in magnetic MC spacer lead to remarkable magneto-optical Kerr and Faraday rotations [12,13].

In this paper, for the first, to our knowledge, time the nonlinear optical magnetization-induced effects in 1D magneto-photonic MC are studied. The giant magnetization-induced rotation of the second-harmonic (SH) wave polarization in the geometry of the polar nonlinear magneto-optical Kerr effect (NOMOKE) is measured as the fundamental radiation in resonance with the MC mode. The strong spectral dependence of the angle of rotation of the SH wave polarization in the vicinity of the MC mode is observed.

2. Experimental

The samples of magneto-photonic microcavities are composed of two dielectric Bragg reflectors and an MC spacer. The Bragg reflectors are fabricated from six pairs of alternating quarter-wavelength-thick SiO_2 and Ta_2O_5 layers. The MC spacer is Bi-substituted yttrium–iron–garnet (Bi:YIG) layer with half-wavelength thickness. The samples were prepared by RF-magnetron sputtering. The Bi:YIG MC layers were subject to flush thermal annealing at approximately 720°C for 10 min. PBG gap

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is centered at approximately 800 nm and the MC mode is peaked at 840 nm under the normal incidence.

The linear polarized output of a tunable ns-parametric generator/amplifier (Spectra-Physics MOPO 710) operating from 730 to 1050 nm is directed onto the sample. The SHG signal is selected by filters and detected by a photomultiplier tube and gated electronics. To normalize the SH intensity spectrum over the laser fluence and the spectral sensitivity of the optical detection system a SH intensity reference channel is used with a slightly wedged z-cut quartz plate and with the detection system identical to the one in the sample channel. The DC-magnetic field up to 2 kOe is applied perpendicularly to the MC using a permanent Fe:Nd:B magnet. The angle of incidence for polar NOMOKE is 30°.

3. Results and discussion

Fig. 1 shows the spectra of the linear reflection coefficients R_s and R_p for the s- and p-polarized fundamental radiation, respectively. The high-reflectivity plateau observed for fundamental wavelength $hichlambda_{\omega}$ shorter than 780 nm is attributed to the PBG.

The narrow peaks at 825 nm for R_s and at 812 nm for R_p are associated with the MC mode. The MC mode for the p-polarized wave is blue-shifted at approximately of 12 nm with respect to the s-polarized fundamental radiation.

The dependences of the SH intensity on the analyzer angle (the SHG polarization diagrams) for p-polarized fundamental radiation are measured for opposite directions of the DC-magnetic field. These SHG polarization diagrams have an obvious magnetization-induced shift. The spectral set of such diagrams is measured for several fundamental wavelengths in the vicinity of the MC mode.

Fig. 2 shows the spectral dependence of the rotation angle of the SH wave polarization extracted from the fit of the SHG polarization diagrams. The SH intensity spectrum measured in the p-in, p-out polarization combination is shown for comparison. The rotation angle, $hichtheta_{SH}$, monotonically increases from 3° to 7° as $hichlambda_{\omega}$ increases from 790 to 830 nm. The spectral interval of the fundamental radiation tuning in the measurements of $hichtheta_{SH}$ is restricted by the small values of the SH intensity for fundamental wavelength at the wings of the MC modes and inside the PBG.

The SH intensity spectrum has a pronounced peak as fundamental radiation is in resonance with the MC mode at wavelength of 812 nm and no SHG enhancement is observed at the PBG edge in the vicinity of wavelength $\lambda = 890$ nm. The SHG resonance at the MC mode is attributed to the spatial localization of the fundamental radiation inside the MC spacer. At the PBG edge, the fundamental radiation is uniformly distributed across the MC and the enhanced SHG contributions from Bragg reflectors are expected due to the fulfillment of the phase-matching conditions. The small SHG signal at the PBG edge allows us to associate the whole SHG signal with the noncentrosymmetric Bi:YIG spacer and consider Bragg reflectors as centrosymmetric structures. The lack of the azimuthal anisotropy of the intensity of the s-polarized SH wave during sample rotation with respect to the normal allows the consideration of the Bi:YIG spacer as an in-plane isotropic medium. The quadratic nonmagnetic (crystallographic) polarization of the Bi:YIG layer is given by

$$P_i(2\omega) = \chi^{(2)}_{ijk} : E_j(\omega)E_k(\omega), \qquad (1)$$

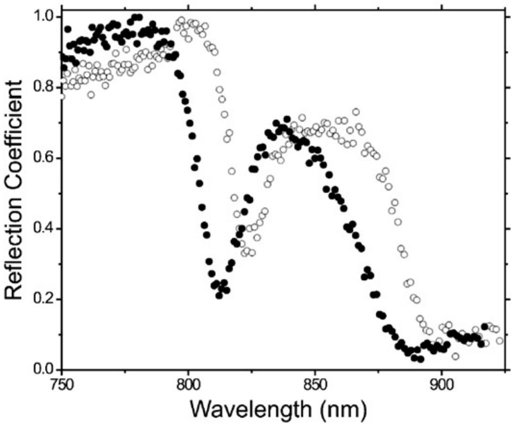

Fig. 1. Reflectivity spectra of the s-polarized (open circles) and p-polarized (filled circles) waves from Bi:YIG microcavity.

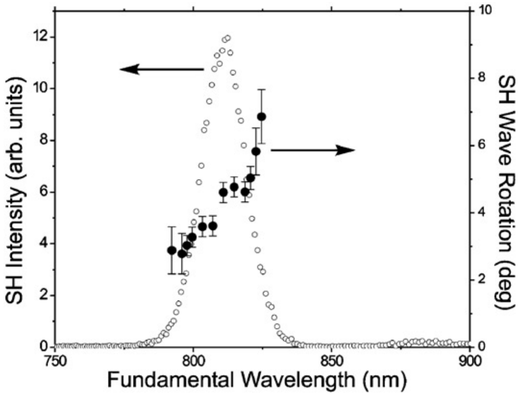

Fig. 2. Spectrum of rotation angle of the SH wave polarization for p-polarized fundamental radiation (filled circles) and the SH intensity spectrum measured in p-in, p-out polarization combination (open circles).

where $i, j, k = x, y, z$, axis z is the normal to the sample surface, xz is the plane of incidence and $E_j(\omega)$ is the jth component of fundamental field. The nonzero elements of the nonmagnetic quadratic susceptibility tensor $hichchi^{(2)}_{ijk}$ of the Bi:YIG layer are $hichchi^{(2)}_{zzz}$, $chi^{(2)}_{zxx} = \chi^{(2)}_{zyy}$ and $hichchi^{(2)}_{xzx} = \chi^{(2)}_{yzy}$. From Eq. (1) and the nonzero components of crystallographic nonlinear susceptibility one can derive that s-polarized nonmagnetic SHG is forbidden for the p-in, s-out polarization combination. Only one element of the magnetization-induced quadratic susceptibility tensor $hichchi^{(2)}_{ijk}(M)$, namely$hichchi^{(2)}_{yzx}(M)$, contributes to the polar NOMOKE for the p-polarized fundamental radiation [14]. This brings about the nonzero SHG signal in the p-in, s-out polarization combination. Thus, the total SH intensity for the given angle of the analyzer, $hichtheta$, is a superposition of the nonmagnetic p-in, p-out and magnetization-induced p-in, s-out SHG components

$$I^{2\omega}(\theta) \propto |E^{2\omega}_{\mathrm{pp}}(M)\sin\theta + E^{2\omega}_{\mathrm{ps}}(M)\cos\theta|^2, \qquad (2)$$

where $hichtheta = 0$ stands for the s-polarized SH wave. If the relative phase between the complex SHG components $E_{\mathrm{pp}}(2\omega)$ and $E_{\mathrm{ps}}(2\omega)$ is different from $\boldsymbol{\pi/2}$, the interference between these SHG contributions leads to the cross-term in the SH intensity that possesses the odd parity with respect to magnetization $\boldsymbol{M}$. This mechanism of the internal homodyne is similar to linear in magnetization variations of the magnetic-field-induced SH intensity which are observed in NOMOKE in magnetic films [15].

The rotation angle of the SH wave polarization is supposed to be spectral independent as long as the relative phase between $E_{\mathrm{pp}}(2\omega)$ and $E_{\mathrm{ps}}(2\omega)$ is a constant. Thus, the spectral dependence of $hichtheta_{\mathrm{SH}}$ can be associated with the Faraday rotation of the resonant fundamental radiation in the MC spacer, which is enhanced due to the multiple reflection interference. Initially, p-polarized fundamental wave becomes partially s-polarized inside the MC spacer. This mixed s,p-polarized fundamental radiation, coupling with *nonmagnetic* susceptibility components $hichchi^{(2)}_{zyy}$ and $hichchi^{(2)}_{yzy}$, gives *magnetic* contributions to the SHG components $E_{\mathrm{pp}}(2\omega)$ and $E_{\mathrm{ps}}(2\omega)$, respectively. Since the MC mode for the s-polarized fundamental radiation is red-shifted in comparison with the p-polarized wave, the best conditions for the Faraday rotation are achieved at the long-wavelength edge of the p-polarized MC mode. Thus, for $hichlambda_{\omega}$ in the vicinity of 800 nm, where the propagation of the s-polarized wave is forbidden by the PBG, $hichtheta_{\mathrm{SH}}(\lambda_{\omega})$ is entirely associated with the polar NOMOKE, while for $hichlambda_{\omega}$ near 825 nm the enhanced Faraday rotation of the resonant fundamental radiation is supposed to be dominant mechanism in the magnetization-induced rotation of the SH wave polarization.

4. Conclusions

In conclusion, the polar nonlinear magneto-optical Kerr effect in 1D photonic crystal microcavities with the magnetic Bi:YIG spacer is observed. The rotation of the SH wave polarization is studied as the fundamental radiation is in resonance with the microcavity (MC) mode. Two mechanisms are responsible for the observation of the magnetization-induced rotation of the SH wave polarization and spectral dependence of observed NOMOKE. The first one is the appearance of the magnetization-induced s-polarized SH wave, forbidden in non-magnetized sample and significantly enhanced due to the localization of the resonant fundamental radiation inside the magnetic MC spacer. The second mechanism is the Faraday rotation of the fundamental radiation that is enhanced in the spectral vicinity of the MC mode due to the multi-pass propagation of the fundamental wave through the magnetic MC spacer.

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