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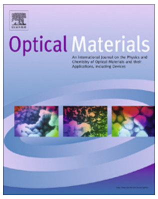

Magnetooptics of single and microresonator iron-garnet films at low temperatures

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ABSTRACT

We have investigated the low-temperature behavior of the optical and magneto-optical properties of (Bi, Gd, Al)-substituted yttrium iron-garnet films that are either single or microresonator, i.e. sandwiched between two dielectric Bragg mirrors. It was shown that the magneto-optical properties of the microresonators with a magnetic film core are mainly determined by the properties of the constituent magnetic films. Special attention was paid to the compositions possessing magnetic compensation temperatures. The phenomenon of the temperature hysteresis was found and discussed for several samples. This testifies the fact that the magnetic moment reorientation in a magnetic field occurs by the full cycle of the first-order phase transitions “collinear phase – non-collinear phase – collinear phase”. The Faraday hysteresis curves at around magnetic compensation temperatures are demonstrated to be very informative concerning composition of a sample. In particular, the hysteresis curves measured for the magnetic films on the garnet substrates showed bursts that indicates formation of a transition layer.

1. Introduction

The high transmissivity and large magneto-optical (MO) response of the multilayered periodic structures (photonic crystals) based on Bi-substituted yttrium–iron-garnet (Bi: YIG) films in optical range allow their applications for nonreciprocal MO devices such as isolators, circulators and modulators [1–11]. Therefore, within the last years their unique properties have attracted a great deal of attention of numerous research groups [12–24].

Usually, microcavity photonic crystals consisting of a magnetic film sandwiched between two nonmagnetic Bragg mirrors (BM) are considered. Light transmitted through the MO microcavity structure is controlled via external magnetic field. However, the temperature could be also a parameter allowing one to control the MO properties of the photonic crystals, especially in the case when MO layers have a composition with a magnetic compensation temperature T_{comp}. Noted should be a lack of information about temperature dependence of the optical and MO properties of the magneto-photonic crystals, only a few reports are available in scientific literature [25–27]. Recently, we have studied the low-temperature behavior of the optical and MO properties of the one-dimensional magneto-photonic crystals with iron garnet layers [27] and observed no noticeable dependence of the optical resonances on temperature. Additionally, we found a kind of temperature hysteresis of the Faraday effect. In order to fully understand physical origin of this phenomenon it should be studied in detail. Furthermore, a comparison of the low temperature behavior of the optical and MO properties of the microcavity MOMR and single magnetic films is vital, since the properties of the magneto-photonic crystals are mainly determined by the corresponding single films. Therefore, the aim of this work is to experimentally study the temperature dependences of the optical transmittance and Faraday rotation of the magneto-optical microresonator (MOMR) and single MO layers of different compositions including compositions with magnetic compensation temperature.

2. Methods

Three types of the (Bi, Gd, Al)-substituted iron-garnet films and microcavity MOMRs with cavity layers of the similar compositions

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were prepared and investigated. The nominal compositions of these MO films are $Bi_{1.0}Y_{0.5}Gd_{1.5}Fe_{4.2}Al_{0.8}O_{12}$ (M1), $Bi_{2.8}Y_{0.2}Fe_5O_{12}$ (M2) and $Bi_{2.5}Gd_{0.5}Fe_{3.8}Al_{1.2}O_{12}$ (M3). Correspondingly, three types of the MOMR on their bases were fabricated:

$GGG/(TiO_2/SiO_2)^4/M1/(SiO_2/TiO_2)^4$ (MOMR-I),

$GGG/(TiO_2/SiO_2)^4/(M1/M2)/(SiO_2/TiO_2)^4$ (MOMR-II),

$GGG/(TiO_2/SiO_2)^4/(M1/M3)/(SiO_2/TiO_2)^4$ (MOMR-III).

Here GGG is substrate of (111) gadolinium–gallium garnet $Gd_3Ga_5O_{12}$, M1 is MO cavity monolayer, M1/M2 and M1/M3 are double MO cavity layers. The M1 layer was used in the MOMR-I as the main MO layer and in the MOMRs-II and -III – as a MO sub-layer. The M2- and M3 layers were used in the MOMRs-II and -III as the main MO layers. Schematics of three types of the MOMR are presented in Fig. 1. Each MOMR consists of two dielectric Bragg mirrors (BM-1 and BM-2) and MO cavity layers. Each BM has four pairs of TiO_2 and SiO_2 layers.

The double MO layers M1/M2 and M1/M3 are used instead of single M2 and M3 layers because of some technical difficulties related to deposition and crystallization of garnet films with a high Bi content on non-garnet substrates (or layers), particularly on SiO_2 layers. Therefore, in the case of MOMR-II and III the M1 sub-layer with a lower Bi content was deposited on SiO_2 prior to deposition of the M2 and M3 main layers with a higher Bi content. After its crystallization the M2 or M3 layers were deposited.

Since Gd-ion is magnetic and has magnetization opposite to the magnetization of the iron-sublattice, MO films containing Gd^{3+} ions possess magnetic compensation temperature T_{comp}. Consequently, the phenomenon of the magnetic compensation should be observed in M1 and M3 single films as well as layers inside the MOMRs.

The single MO films on GGG substrates as well as the cavity mono- and double layers in the MOMRs were fabricated by reactive ion beam sputtering of corresponding targets in argon–oxygen mixture with subsequent crystallization in air (the preparation details are described elsewhere [28,29]). For better adhesion before deposition of the single MO films the GGG substrates were processed by argon ions at 1 keV energy and 2.5 mA cm^{-2} current density during 2 min. The films in the double cavity layers in the MOMRs were sputtered and crystallized separately. The TiO_2/SiO_2 BM were fabricated by electron beam evaporation at substrate temperature of about 673 K with optical monitoring of their thicknesses. The optical thicknesses of the M1 cavity sub-layer and TiO_2 and SiO_2 layers were chosen as $\lambda_R/4$, and of the main cavity layers – $\lambda_R/2$ in the MOMR-I and $3\lambda_R/4$ – in the MOMRs-II and III. Here λ_R is a resonant wavelength for each MOMR (defined as the photonic band gap center).

Optical and magneto-optical measurements were performed using diffraction grating monochromators, MDR-6 and MDR-4. Spectral measurements of the Faraday rotation angle (Θ_F) were performed by the standard modulation null-method with using the polarization plane modulator working at 515 Hz and based on the Faraday Effect in the Bi: YIG film grown by liquid phase epitaxy. The spectral resolution of the grating monochromator was near 2.0 nm in the measurements of Faraday rotation angle. The light signal was detected by a photomultiplier. For low temperature measurements, the optical liquid helium cryostat with warm windows was used [30].

The Faraday hysteresis loops (FHL) of each MOMR and corresponding film were measured at their λ_R to determine the coercivity force H_C, saturation magnetization field H_S, squareness ratio K_S (as relation of residual Θ_F to saturation Θ_{Fmax}) and other parameters of the samples.

The MO figure of merit Q for MOMR was defined as $Q = 2|\theta_F|/\alpha$, where θ_F is the specific Faraday rotation, $\alpha = -ln(T_o)/h$, T_o is transmittance coefficient, and h is the thickness of the magnetic layer.

3. Results

Optical transmittance spectra of the MOMRs at room temperature (300 K) and magnetic field $H = 7.8$ kOe demonstrate a photonic band gap at the wavelength range of 580–780 nm and Fabry–Perot resonances at $\lambda_{R1} = 641$ nm for the MOMR-I, $\lambda_{R2} = 655$ nm for the MOMR-II and $\lambda_{R3} = 675$ nm for the MOMR-III. The values of the Faraday rotation Θ_F at the resonances λ_{R1}, λ_{R2} and λ_{R3} and are 1.2°, 8.3° and 4.3°, respectively. They are approximately 9, 11 and 10 times more than the Θ_F values for the monolayer M1 and double M1/M2, M1/M3 films at the corresponding wavelengths. A GGG substrate gives some contribution to Θ_F signals for all types of the samples. The peak transmittances for corresponding MOMR are 42%, 11% and 13%, respectively. For the MOMRs-I and -III the values of Q are 10, 30 and 20, respectively.

Accordingly to the Faraday hysteresis loops of the MOMRs at their λ_R and $T = 300$ K the MOMR-I has the uniaxial anisotropy, the MOMR-II has in-plane magnetic anisotropy, and the MOMR-III has the "angle phase" anisotropy, i.e. its magnetization is inclined to the film plane.

Let us consider the temperature dependences of the Faraday rotation angle Θ_F in the MOMRs and single films. Fig. 2 represents the experimental data of the measured temperature dependences of Θ_F of the single magnetic films and MOMRs at their λ_R and magnetic field of 10 kOe. The single M1 and M3 films on GGG substrates and in the MOMRs are of the same thickness. Temperature dependence of Θ_F for the M3 film is shown in detail at the low temperatures in the inset of Fig. 2.

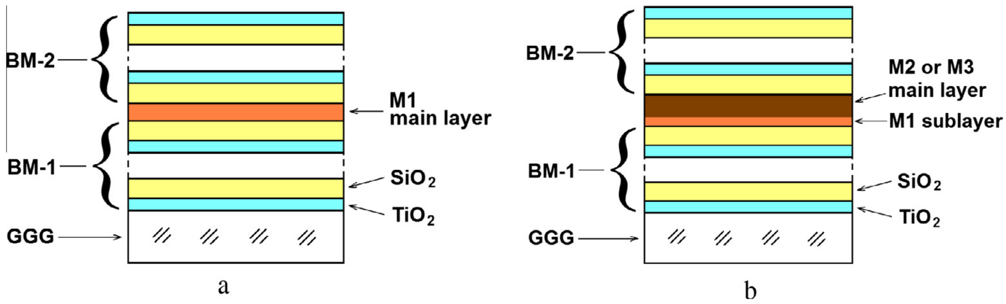

Fig. 1. Schematics of the investigated MOMR samples: (a) MOMR-I with a single M1 cavity layer, (b) MOMR-II- or III with double M1/M2 or M1/M3 cavity layers. BM-1 and BM-2 are bottom and top dielectric Brag mirrors, respectively.