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Femtosecond time-resolved Faraday rotation in thin magnetic films and magnetophotonic crystals

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Femtosecond time-resolved Faraday rotation is studied in magnetic garnet films and magnetophotonic crystals. Femtosecond dynamics of Faraday angle governed by multiple reflection interference and Faraday effect non-reciprocity is revealed by using polarization-sensitive ultrafast correlation technique. © *2012 American Institute of Physics*. [doi:10.1063/1.3679452]

I. INTRODUCTION

Magneto-optical effects such as Faraday polarization rotation and its dynamics are intensively studied in various composite and multilayered media due to their prospectives for light control applications.[1,2] The Faraday rotation enhancement can be achieved by multiple reflection interference in a thin film,[3] or a Fabry-Perot resonator with silver mirrors[4] utilizing non-reciprocity of the effect. The natural development of magneto-optical enhancement topic are magnetophotonic crystals and microcavities (MPC and MMC) with $\lambda/2$-thick cavity layer (where λ is operating wavelength) and distributed Bragg reflectors yielding higher quality factor together with more compact full size of the device. Both the enhancement of Faraday rotation[1] and of nonlinear magneto-optical effects[5,6] are observed in MPC and MMC.[1,7]

Time-resolved magneto-optical experiments are being developed intensively last decade due to a row of fundamental problems of ultrafast magnetization dynamics in a medium and ultrafast magnetization switching.[8] One of the key experiments in the field is ultrafast magnetization reversal by an intense femtosecond pulse leading to, inter alia, picosecond-scale magneto-optical response dynamics.

However, time modulation of magneto-optical effect at subpicosecond scale is possible without changes in the state of the media. A layered optical material can modulate electric field amplitude and phase of a femtosecond pulse in space and, consequently, in time. For example, Faraday rotation value of the initial part of the pulse may differ in times from that of its tail and from a steady-state value.

In this paper femtosecond dynamics of Faraday effect is demonstrated experimentally in a layered magnetic material by using recently developed[9] polarization-sensitive time-resolved correlation technique.

II. CALCULATIONS

Let a femtosecond laser pulse with a Gaussian temporal profile propagate through a magnetic multilayered medium under the normal incidence. The input laser pulse is decomposed into right and left circular polarized normal modes of the magnetic film. Then, for each of the normal modes Fourier transform converts the input pulse from time domain into frequency domain. The spectra of the right- and left-polarized components of the input pulse are multiplied by the complex transmission coefficients obtained by 4×4 transfer-matrix formalism.[10] Optical properties of the medium are assumed to be constant in time in the experimentally important case of magnetic dielectrics, while the ultrafast demagnetization processes should be included into consideration for magnetic metals heated by an intense femtosecond pulse.[8] Thus, the spectra of normal modes amplitudes behind the media can be calculated. Then, using backward Fourier transform one obtains the time dependence of the normal modes amplitudes. Due to the linearity of the problem, the resulting temporal response including transmittance and Faraday angle can be transformed into the original basis.

The algorithm was used for typical cases distinguished by ratio of a film optical thickness nd to spatial pulse length l: $nd > l$, $nd \sim l$, as well as for quasi-steady-state case $nd \ll l$ and for real experimental samples parameters, where n is refractive index and d—physical thickness. Figure 1 shows time dependence of Faraday angle (Figs. 1(b) and 1(d)) calculated for a femtosecond pulse transmitted through a magnetic film together with the envelopes of incoming (Figs. 1(a), 1(c), dot curve) and transmitted (Figs. 1(a), 1(c), solid curve) light intensities. The calculations are performed for $\epsilon' = 7$, $\epsilon'' = 0.001$, $g' = -0.0033$, $g'' = 0$, where ϵ', ϵ'' are real and imaginary parts of dielectric constant, g', g'' are real and imaginary parts of gyration, respectively. The parameters correspond to a 20 μm-thick (Figs. 1(a) and 1(b)) and 9 μm-thick (Figs. 1(c) and 1(d)) Bi-substituted yttrium iron garnet films, $nd = 53$ μm and $nd = 23$ μm, respectively. Pulse duration is $\tau = 100$ fs (spatial length $l = 34$ μm) and central wavelength is $\lambda_0 = 1550$ nm.

Steady-state Faraday angle, which is the same for the quasi-steady-state case $nd \ll l$, is given by the dash-dot horizontal lines in Figs. 1(b) and 1(d). The results for $nd = 53$ $\mu m > l$ case are shown in Figs. 1(a) and 1(b). The envelope of the optical field intensity behind the film is a sequence of pulses of decreasing intensity rescattered inside the film. For

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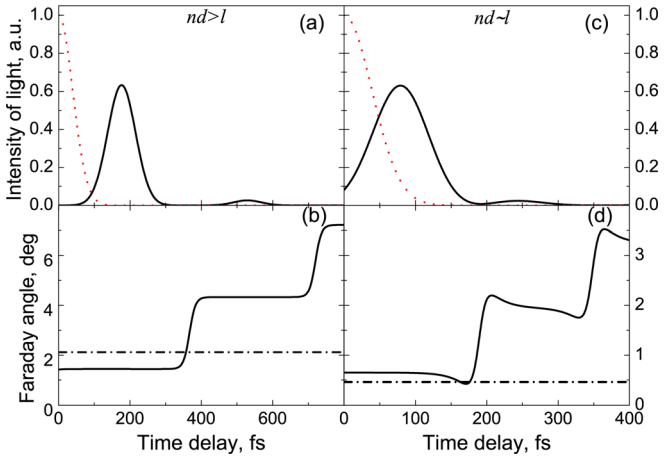

FIG. 1. (Color online) (a and c) The envelope of incoming (dot curve) and transmitted (solid curve) intensities, (b and d) Faraday angle calculated as the functions of time delay. The calculations are plotted for a (a and b) 20 μm-thick magnetic film, $nd > l$ and (c and d) 9 μm-thick magnetic film, $nd \sim l$. Dash-dot lines in Figs. 1(b) and 1(d) show steady value of Faraday effect.

the case $nd > l$ (Figs. 1(a) and 1(b)), the pulses do not overlap in space. Therefore, Faraday rotation within a single pulse is constant and increases by 2θ with each subsequent pulse, where θ is Faraday rotation angle of the first transmitted pulse. As a result, the time dependence of Faraday rotation is a step-like function with a step length determined by the time delay between adjacent pulses. Experimentally, time scale covers the first few pulses with detectable intensity. Faraday angle as a function of time can be both less and greater than its steady-state value (dash-dot lines). Figures 1(c) and 1(d) shows the envelope of the light intensity (Fig. 1(c)) and time dependence of Faraday angle (Fig. 1(d)) for a magnetic film thickness comparable with the spatial pulse duration $nd = 24$ μm $\simeq l$ (Figs. 1(c) and 1(d)). Compared to the previous case, the ranges of negative derivative within the steps appear. The steps are associated with large phase shifts between consecutive pulses leading to their destructive interference, although

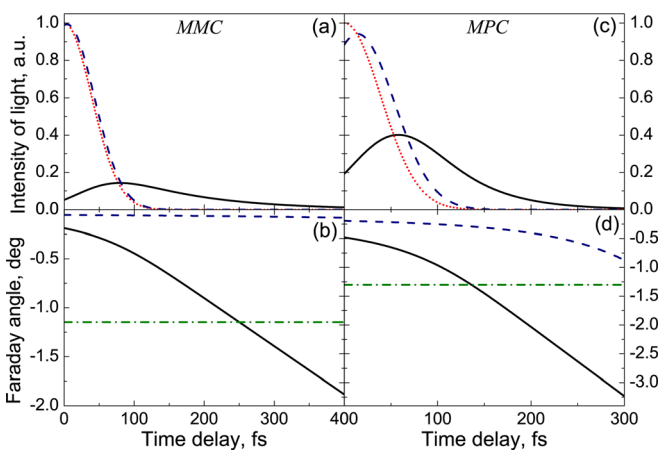

FIG. 2. (Color online) (a and c) The envelope of incoming (dot curve) and transmitted (solid curve) intensities of light, (b and d) Faraday angle (solid curve) calculated as the functions of time delay . The calculations are plotted for a (a and b) MMC and a (b and d) MPC. Dash curves show (a and c) transmitted pulse and (b and d) Faraday rotation for films with equivalent thickness of magnetic material. Dash-dot curves show steady Faraday angle value at pulse central wavelength microcavity mode position in MMC and photonic bandgap edge in MPC.

at first glance, it does not fit the idea of non-reciprocity of Faraday effect, implying a monotonic increase of the rotation angle in time. The negative-derivative steps can appear only in spectral vicinity of interference minima of transmittance.

Figure 2 shows the envelope of light intensities (Figs. 2(a) and 2(c)) and time dependence of Faraday angle (Figs. 2(b) and (d)) for a MPC and a MMC. The MPC consists of 10 bilayers of magnetic and nonmagnetic dielectrics with optical thickness of $\lambda/4$, where λ is the wavelength of light. The calculation parameters correspond to Bi:YIG and SiO_2 layers. Dielectric constant of nonmagnetic layers is $\epsilon' = 2.1$, $\epsilon'' = 0$, that of magnetic layers is $\epsilon' = 7$, $\epsilon'' = 0.0025$, gyration $g' = -0.0054$, $g'' = 0$ and pulse duration is of 100 fs. The pulse central wavelengths $\lambda = 1539$ nm and $\lambda = 1516$ nm correspond to the spectral position of MMC microcavity mode and to photonic bandgap edge of the MPC, respectively. The MMC is a $\lambda/2$-thick magnetic layer squeezed between two non-magnetic dielectric Bragg mirrors made from 5 pairs of SiO_2 and Ta_2O_5 layers, for numerical simulations we assumed that Ta_2O_5 parameters are equal to $\epsilon' = 4$, $\epsilon'' = 0$. For comparison, the results for a magnetic film with the thickness equal to the total thickness of all magnetic layers of MMC (MPC) are shown by dash lines. Bragg reflectors of MMC increase drastically the quality factor of the cavity in comparison with that of a single-layer film. The transmitted pulse is retarded strongly both in MMC and MPC being a fingerprint of "frozen light" effect inside the media. The increased light-matter interaction time yields up to order-of-magnitude Faraday effect enhancement in comparison with the thin film value.[1,11] The angle achieves its steady-state value (dash-dot line) after approximately 200 fs and doubled steady-state value after 400 fs. In MPC (Figs. 2(a) and 2(b)) larger values of Faraday angle and its larger changes in time are seen due to the strong artificial dispersion of ϵ at the photonic bandgap edge.

Figure 3 shows calculated femtosecond dynamics of Faraday angle in thin film as a function of central wavelength of a 130-fs pulse in the range from 1500 to 1550 nm. The film parameters used for simulations are $d = 30$ μm, $\epsilon = 4.0$ and $g = -0.0033$. The development of the spectral interference patterns with time is seen: there are no spectral oscillations earlier then approximately 350 fs. The interference oscillations are clearly seen for delays longer than 360 fs. The time derivative sign is different for maxima and minima of spectral interference oscillations. The Faraday angle increases with time in the case of constructive interference, i.e., spectral transmittance maximum, while it decreases if consequent rereflected pulses interfere destructively in the vicinity of 1550 nm.

III. EXPERIMENTAL

An infrared femtosecond Er^{3+}-fiber laser with 70-MHz repetition rate, average intensity of 130 mW, wavelength of 1.55 μm and pulse duration of 130 fs is used as a source of radiation in the polarization-sensitive correlation scheme. A Glan prism splits a laser pulse into orthogonally linearly polarized signal and gate pulses. A signal pulse with approximate beam diameter 1 mm goes at normal incidence through

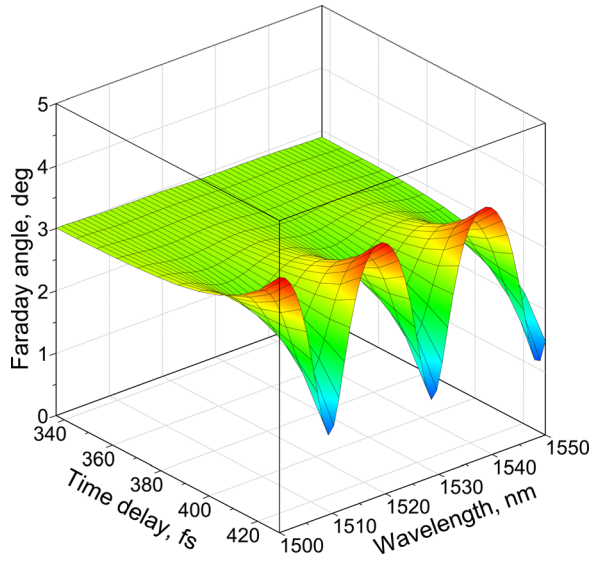

FIG. 3. (Color online) Femtosecond dynamics of Faraday angle calculated for a 30 μm-thick film with central wavelength of a 130-fs pulse in the range from 1500 to 1550 nm.

the sample placed in magnetic field of 1 kOe oriented parallel to light propagation direction and through a 47-KHz photoelastic modulator. The time shift of the gate pulse relative to the signal pulse can be varied by the optical delay line in the gate-pulse channel. The polarizations of both the signal and the gate pulses are projected to the 45°-oriented axis by a Glan prism and focused at the same spot into a nonlinear BBO crystal. If the pulses overlap in time and space in the nonlinear crystal, noncollinear second-harmonic generation occurs, which intensity is proportional to the pulses correlation function $u(\tau) = \int I(t) I_{gate}(t-\tau) dt$, where $I(t)$ is intensity of the transmitted signal pulse, $I_{gate}(t-\tau)$ is intensity of the gate laser pulse, and τ is a time delay between them. For small Faraday angle θ and for PEM delay value of 2.405 rad used in experiment: $J_0 = 0$ and the intensity of the signal pulse modulated with PEM can be written as[12] $I(t)[1 + 4J_2\theta(t)\cos(2\omega t)]$, where ellipticity term is omitted, J_0, J_2 are zero- and second-order Bessel functions at 2.405 rad. The PEM modulation frequency $\omega \ll c/l$. Thus, $u(\tau) = u_{dc}(\tau) + u_{2\omega}(\tau) = \int I(t) I_{gate}(t-\tau) dt + 4J_2 \cos(2\omega t) \int \theta(t) I(t) I_{gate}(t-\tau) dt$. The signal pulse is delayed and retarded, and if the changes in Faraday rotation are slower than the gate pulse duration, one can consider Faraday angle dynamics $\theta(t)$ as averaged within the gate pulse $\theta(\tau)$. Then the correlation function measured at the double PEM frequency is given by: $u_{2\omega}(\tau) = 4J_2\theta(\tau) \int I(t) I_{gate}(t-\tau) dt \equiv 4J_2\theta(\tau) u_{dc}$. Correlation functions detected by Si photodiode both dc and locked-in to the double PEM frequency 2ω give us the temporal behavior of Faraday angle: $\theta(\tau) \approx \frac{\sqrt{2} u_{2\omega}(\tau)}{4 J_2 u_{dc}(\tau)}$.

Figure 4 shows experimental time dependence of Faraday angle for the 30-μm-thick $Tm_{2.21}Bi_{0.79}Fe_{3.85}Ga_{1.15}O_{12}$ film. The negative derivative of the dependence results from the phase shift leading to its destructive interference with the first pulse tail. This corresponds to the second step in calculations (for example, see Fig. 1(d)). The curve in Fig. 4 is the

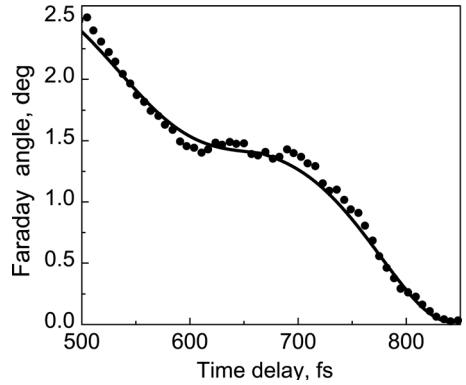

FIG. 4. Faraday rotation dynamics extracted from correlation function of a reference 130-fs pulse and a 130-fs pulse with central wavelength of 1564 nm transmitted through a 30 μm-thick film.

fit of the model time dependence of Faraday angle calculated by the algorithm given in Sec. II to the experimental data. Film thickness $d = 30$ μm, pulse duration of 130 fs, gyration $g' = -0.0006$ are taken from steady-state experiments and fixed. A good agreement of the calculations and measurement is achieved for the following adjustable parameters: $\epsilon' = 4.005$, $\epsilon'' = 0.011$, $g'' = 0.0001$, which are consistent with literature data. Steady-state measurements of Faraday effect give a 2.5° rotation angle at 1550 nm.

In conclusion, Faraday rotation dynamics is studied experimentally and numerically in a layered magnetic medium. Despite the conventional view of monotonic increase of Faraday angle yielded by the non-reciprocity of Faraday effect, the time dependence of the rotation angle can be not only increasing, but also decreasing, nonmonotonic, and even can change the sign. Such effects are a consequence of the structural features of the medium leading to multiple interference in the film and to large phase shifts between different parts of a single femtosecond pulse.

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