Time evolution of domain-wall motion induced by nanosecond laser pulses

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The time evolution of the magnetization normal component change in a garnet film with a labyrinthine domain structure under the action of circularly and linearly polarized laser pump pulses (the pulse duration is 5 ns; the wavelength is 527 nm) has been studied. The dynamic state of the magnetic film was registered using an induction method with a time resolution of 1 ns. It was found that for the initial state of the magnetic film with an equilibrium domain structure, the form of the photomagnetization pulse reflects the time evolution of a domain-wall motion. The domain-wall motion initiated by the circularly polarized laser pump pulse continues in the same direction for a time more than an order of magnitude exceeding the laser pulse duration. In general, the time evolution of the domain-wall movement occurs in three stages. The separation of the contributions to the photomagnetization from the polarization-dependent and polarization-independent effects was carried out. The photomagnetization pulses that reflect the contributions by the aforementioned effects differ by form, and more than two orders of magnitude by duration. Their form doesn't change under a magnetic bias field change, only the photomagnetization pulse amplitude does: for the polarization-dependent contribution, it's an even function of the field, and for the polarization-independent contribution, it's an odd function. The interconnection between the polarization-dependent and polarization-independent effects, on the one hand, and the domain-wall displacement and the change of the film's saturation magnetization, on the other hand, was identified and described.

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I. INTRODUCTION

The problems associated with various aspects of domain-wall dynamics in magnetic materials attract attention of both theoreticians and experimentalists [1–3]. Currently, such attention is largely due to applied issues of spintronics [4,5], which explains why the experimental study of domain-wall dynamics in submicron objects is important. Some interesting results have been obtained in this field: there can be no effect of nanowire transverse dimensions on domain-wall dynamics [6,7], and domain-wall mobility in nanowires is close to that in continuous films. Studying nanometer scale dynamics of domain walls requires high spatial and time resolution simultaneously [8–11]. A magnet dynamic state can be modified by field-induced [9,10,12], current-induced [13], and laser-induced [14–21] actions. An infrared-pump-induced change of a spin structure within static domain walls in Co/Pt multilayers on a subpicosecond time scale was observed [22]. In our view, there are some very interesting works [20,23] (and references therein) which discuss important problems of the magnetization reversal effect dependence on a polarization state of laser radiation.

In certain situations, an initially demagnetized multidomain magnet can be magnetized under the action of circularly polarized light. Such a photomagnetization seems to be caused by modification of a domain structure [24]. Until recently, domain structure modification caused by domain-wall motion and unrelated to temperature changes of a saturation magnetization was considered to be hypothetically possible. Nevertheless, convincing experimental proof of its observation was absent. In Ref. [25] it was concluded that it is possible to distinguish between the two contributions to the photomagnetization — the first one is from changes in the domain magnetization and the second one is from changes in the domain structure.

Registering only the amplitude values of the photomagnetic response (like in Ref. [25]) is not enough for verification of the conclusion about the two contributions in photomagnetization processes. A photomagnetization pulse form (the time evolution of the magnetization change) must be known for obtaining information on possible development scenarios of those processes in the magnetic film depending

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on its *initial state* (from polydomain to monodomain). The photomagnetization pulse form contains information on the duration of the photomagnetization processes and allows extracting the contributions from each of them to the resulting change of the sample magnetization. Obtaining and analyzing the time evolution of the magnetization change helps us to draw the conclusion on the participation of domain walls in the photomagnetization and on the time evolution of their movement.

In this work, an experimental study of time evolution of a magnetic garnet film's magnetization change under the action of laser pump pulses was done. The duration of circularly and linearly polarized pump pulses is 5 ns; the wavelength is 527 nm. The dynamic state of the magnetic film with different initial states (from a regular domain structure to a monodomain state) was registered using an induction method with a temporal resolution of 1 ns.

II. PHENOMENOLOGICAL DESCRIPTION

This section is devoted to a phenomenological description of a domain structure modification under the photomagnetization of a polydomain magnet. The description is quite general and, in our opinion, simplifies understanding of the article (particularly of Sec. IV).

Analysis of the experimental data obtained in Ref. [25] shows that the garnet film photomagnetization under the action of a circularly polarized laser pump pulse is caused by the following effects: the *polarization-dependent* (*p.dep*) photomagnetization (the circularly polarized pump pulses of opposite helicities excite the photomagnetization responses of opposite polarity) and the *polarization-independent* (*p.ind*) photomagnetization (the photomagnetization response polarity stays constant). The first of those effects was observed at a polydomain sample initial state, the second one at a monodomain sample initial state.

Let us illustrate the possible correlation of aforesaid effects with the domain's magnetization change and with the change of the magnetic film's domain structure. The easy magnetic axis of the film is directed along the normal to its surface. The magnetic field normal component (bias field) is denoted as H_b (for clarity's sake $H_b > 0$ if not stated explicitly). The field change allows changing domain widths $w_\uparrow(H_b)$ and $w_\downarrow(H_b)$ in the domain structure. Hereinafter the characters $\uparrow$ and $\downarrow$ shall indicate the direction of the domain spontaneous magnetization along and against the normal to the film plane, respectively. That is, for $H_b \geqslant 0$, $w_\uparrow(H_b) \geqslant w_\downarrow(H_b)$, and for $H_b \leqslant 0$, $w_\uparrow(H_b) \leqslant w_\downarrow(H_b)$. The field change allows us to control the domain structure filling factor ρ_0 in the initial state of the sample, i.e., before the pump pulse:

$$\rho_0 = \frac{w_\uparrow(H_b)}{w_\uparrow(H_b) + w_\downarrow(H_b)}. \tag{1}$$

Hereinafter the symbol 0 denotes the sample initial state. The average value of the sample magnetization normal component in the initial state corresponding to (1) may be written as

$$M_0 = M_s \frac{w_\uparrow(H_b) - w_\downarrow(H_b)}{w_\uparrow(H_b) + w_\downarrow(H_b)} \equiv M_s(2\rho_0 - 1), \tag{2}$$

where M_s is the saturation magnetization value in domains. Hereinafter only the sample magnetization normal component will be considered.

Under the action of the circularly polarized pump pulse, domain magnetizations $M_\uparrow(t)$ and $M_\downarrow(t)$ become time dependent, as well as domain width $w_\uparrow(t)$ and $w_\downarrow(t)$ become time dependent. Therefore the sample magnetization average value could be written as

$$M(\rho_0,t) = \frac{M_\uparrow(t)w_\uparrow(t) + M_\downarrow(t)w_\downarrow(t)}{w_\uparrow(t) + w_\downarrow(t)}, \tag{3}$$

and the time-dependent filling factor is

$$\rho(t) = \frac{w_\uparrow(t)}{w_\uparrow(t) + w_\downarrow(t)}. \tag{4}$$

Expressions (3) and (4) are of a most general nature.

Under the action of the pump pulse, regardless of its helicity, the magnetizations of adjacent domains are changing but stay equal in the absolute value (which is confirmed, within the available accuracy, by the experimental results), i.e.,

$$M_\uparrow(t) = -M_\downarrow(t). \tag{5}$$

It is quite probable that such a change is caused by photoinduced heating of the sample. Considering (5) and (3), we have

$$M(\rho_0,t) = M_\uparrow(t)\frac{w_\uparrow(t) - w_\downarrow(t)}{w_\uparrow(t) + w_\downarrow(t)}. \tag{6}$$

and then a pulsed magnetization change

$$\Delta M(\rho_0,t) = M(\rho_0,t) - M(\rho_0). \tag{7}$$

First let's consider the case when the initial state is a polydomain with zero remanent magnetization [$H_b = 0$, $\rho_0(H_b) = 0.5$, and $M(\rho_0) = 0$]; see Eqs. (1) and (2). Using (6) and (7) we get that for $M(\rho_0 = 0.5) = 0$ the photomagnetization pulse will be described by the expression

$$\Delta M(\rho_0 = 0.5,t) = M_\uparrow(t)\frac{w_\uparrow(t) - w_\downarrow(t)}{w_\uparrow(t) + w_\downarrow(t)}. \tag{8}$$

It is seen from (8) that $\Delta M(\rho_0 = 0.5,t) \neq 0$ only at $w_\uparrow(t) \neq w_\downarrow(t)$; in other words, photomagnetization occurs because the domain dimensions with opposite magnetization directions become different under the action of the pump pulse. But under the initial state of $\rho_0 = 0.5$, the photomagnetization is a completely p.dep effect which is quite obvious and is confirmed by experimental results. For the circularly polarized pump pulses of opposite helicities [right- (R) and left-handed (L)]:

$$\Delta M^R(\rho_0 = 0.5,t) = -\Delta M^L(\rho_0 = 0.5,t). \tag{9}$$

Then from (8) follows

$$w_\uparrow^R(t) - w_\downarrow^R(t) = -[w_\uparrow^L(t) - w_\downarrow^L(t)], \tag{10}$$

which corresponds to such a restructuring of the domain structure under the photomagnetization at which the helicity change of the circular polarized pump pulse (R $\Leftrightarrow$ L) leads to the domain-wall movement direction change. Hereinafter symbols R and L will be used to indicate a polarization state of the circularly polarized pump pulse in the places where their omission may lead to misunderstanding.

Now let's consider the second case when the initial state is a polydomain structure with $0.5 < \rho_0 < 1$ (nonzero remanent magnetization). In this case the photomagnetization effect is a combination of the p.dep and p.ind effects. The expression for domain magnetization changes caused by the pump pulse is

$$\Delta M_{\uparrow}(t) = M_{\uparrow}(t) - M_s, \tag{11}$$

$$\Delta M_{\downarrow}(t) = M_{\downarrow}(t) + M_s. \tag{12}$$

At the same time, according to (5):

$$\Delta M_{\uparrow}(t) = -\Delta M_{\downarrow}(t). \tag{13}$$

Notice here that the values of $\Delta M_{\uparrow,\downarrow}(t)$ don't depend on the pump-pulse helicity because the values of $M_{\uparrow,\downarrow}(t)$ don't depend on the pump-pulse helicity. The filling factor ρ is also changing under the action of the laser pump pulse:

$$\Delta\rho(t) = \rho(t) - \rho_0. \tag{14}$$

The values of $\Delta M_{\uparrow}(t)$, $\Delta M_{\downarrow}(t)$, and $\Delta\rho(t)$ are relatively small, so in their first order of smallness the expression for the photomagnetization pulse as function of ρ (or H_b) and t can be obtained from (2), (3), (7), and (13):

$$\Delta M(\rho_0,t) \approx \Delta M_{\uparrow}(t)[2\rho_0 - 1] + 2M_s\Delta\rho(t). \tag{15}$$

The value of $\Delta M_{\uparrow}(t) \neq 0$ is independent of the pump-pulse helicity. Therefore the first term in the right part of (15) gives the contribution only to the p.ind effect conditioned by the saturation magnetization change under the laser-induced heating. Thus, the contribution to the p.dep effect could be related only to the second term in the right part of (15). This second term is proportional to $\Delta\rho(t)$; thereby $\Delta\rho(t)$ will inevitably contain the part which depends on the pump-pulse helicity. Apparently, such a dependence is related to the domain-wall movement direction change under the circularly polarized pump-pulse helicity change (like the case when $\rho_0 = 0.5$).

Notice that $\Delta\rho(t)$ also contains a part independent of the pump-pulse helicity. The point is that when $H_b \neq 0$ the value of $\Delta\rho(t)$ is changing because of the saturation magnetization change (e.g., [3]) as well. But, as shown above, the domain magnetization change is independent of the pump-pulse helicity. Hence the second term in the right part of (15) gives the contribution to the p.ind effect as well.

Thus, the two contributions to the photomagnetization are phenomenologically described: the first one is due to the domain-wall movement and the second one is due to the domain magnetization change (because of heating). It is necessary to find out the photomagnetization pulse form—the time evolution of the magnetization change—to prove that the description is right and it corresponds to the observed photomagnetization process. Our results of the registration of a photomagnetization pulse form (that depends on the sample initial state) and analysis of the results are given below in the experimental section of the work.

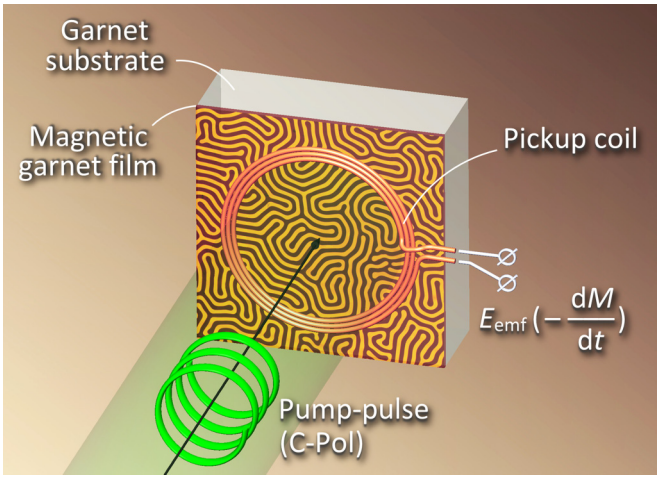

FIG. 1. Scheme of the experiment for the pulsed photomagnetization: the garnet film with a labyrinthine domain structure, a circularly polarized (C-Pol) laser pump pulse, and an inductive transducer (a pickup coil).

III. EXPERIMENTAL SECTION

A. Characteristics of the sample

The sample under study is a $(Bi,Lu)_3(Fe,Ga,Al)_5O_{12}$ garnet film with a large perpendicular anisotropy grown on the (111) oriented $Gd_3Ga_5O_{12}$ substrate. A through-thickness equilibrium labyrinthine domain structure with oppositely magnetized domains (Fig. 1) has a period of $P_0 = 32\,\mu$m (see Fig. 2). The magnetization in the domains is perpendicular to the film plane, and the domain walls are 180° domain walls. Our sample has a thickness of $h = 8{,}3\,\mu$m, a saturation magnetization of $4\pi M_s = 97$ G, an anisotropy field of $H_k = 5.5$ kOe, a coercive force of $H_c = 0.7$ Oe, and a bubble collapse field of $H_0 = 32$ Oe. The magnetic parameters of the sample (Fig. 3) were measured using a vibrating sample magnetometer (EZ11).

The sample is a typical uniaxial magneto-optical material. Various domain structures [1,3,26,27], including spatially ordered [28–34] ones, may form in such materials.

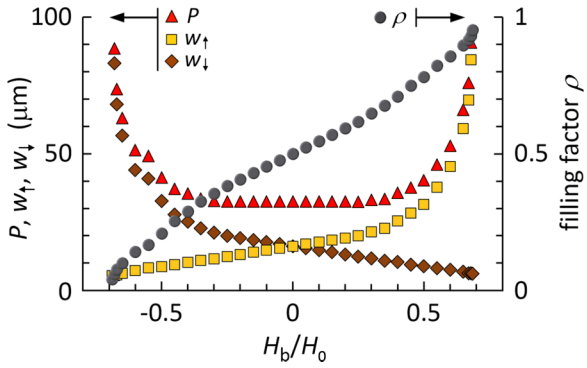

FIG. 2. Normalized field dependences of the domain structure period P (triangles), the oppositely magnetized domain widths $w_\uparrow$ (squares) and $w_\downarrow$ (diamonds), and the domain structure filling factor ρ (circles) of the sample. The bias field H_b is directed along the normal to the sample surface and normalized to the bubble collapse field H_0.

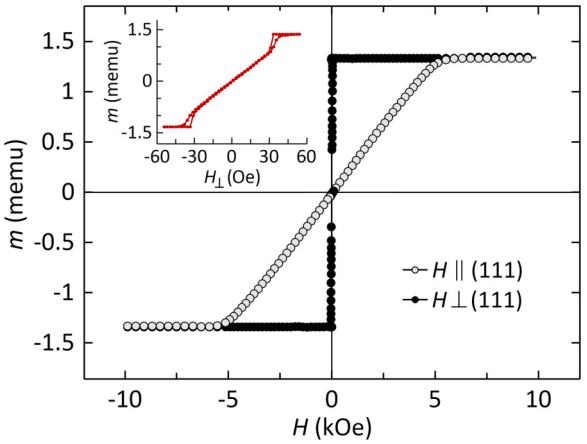

FIG. 3. Magnetic hysteresis loops $m(H)$ of the garnet film for two directions of the magnetic field: parallel ($H_{\parallel}$, gray circles) and perpendicular ($H_{\perp}$, black circles) to the film plane. Inset: the magnetic hysteresis loop $m(H_{\perp})$ when the field $H_{\perp}$ varies in a range of ± 100 Oe.

B. Magnetic field and domain structure filling factor

The domain structure filling factor ρ_0 in the sample initial state [and consequently the magnetization average value $M(\rho_0)$] was controlled by the dc magnetic field H_b (see Sec. II). Notice that the domain structure period $P_0 = w_{\uparrow}(H_b) + w_{\downarrow}(H_b)$ remains constant in a field range of $H_b < 0.3H_0$ (that indicates constancy of domain density). At the same time, the filling factor changes in the range of $0.36 < \rho < 0.64$ (Fig. 2).

In this work special attention was given to the preparatory stage of the experiment, which is forming of the sample initial state before the laser pump pulse. To achieve that, before each pump pulse the domain structure was "annealed" (the magnetic film was demagnetized by an ac field with a field frequency of 500 Hz and with an amplitude exponentially decreasing to zero) for restoration of the sample initial state. The magnetic field strength vectors of the ac and dc magnetic fields are collinear vectors.

C. Induction method of photomagnetization research

Induction methods are the basic methods for research of magnetic materials, allowing us to obtain integral properties of the research object [35–39]. In the experimental setup of the present work (Fig. 4), the photomagnetization signal was registered using an induction method with a pulse-induction technique for a passive transformation. The passive transformation is realized in a dynamic (pulsed) mode under the action of the laser pump pulse (Fig. 1). In this mode the interconnection between the magnetic flux Φ (input value) created by the photomagnetized part of the sample and the electromotive force $E_{\text{emf}} = -\mathrm{d}\Phi/\mathrm{d}t$ (output value) is implemented. The electromotive force is induced in the primary inductive transducer — the induction sensor in the form of a miniature pickup coil (Fig. 1). The signal registration by the induction method confirms explicitly that the laser pump pulse leads to the magnetization change of the material in the optically excited area—the average value of the sample magnetization $M(\rho_0,t)$ becomes time dependent under the action of the pump pulse. At the same time, the magnetic

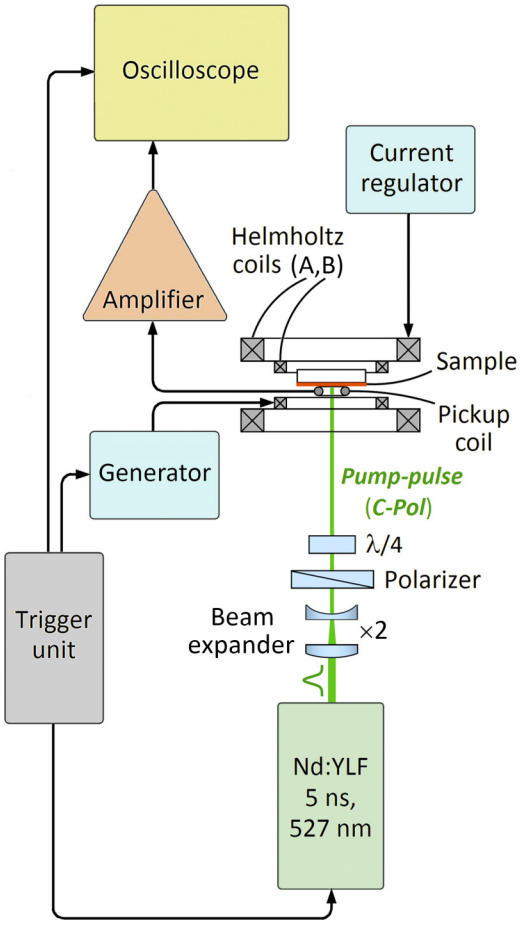

FIG. 4. Block diagram of the experimental setup for the photomagnetization study by the induction method. Optical elements: a pulsed laser (5 ns/527 nm), a beam expander, a polarizer, and a plate $\lambda/4$. A magnetic system: two Helmholtz coil systems to generate dc (A, together with the current regulator) and ac (B, together with the generator) magnetic fields. The sample is located in the center of the magnetic system. The elements of signal measuring and synchronization: a pickup coil, an amplifier, an oscilloscope, and a trigger unit.

flux change $\Delta\Phi(\rho_0,t)$ created by the pulsed magnetization change $\Delta M(\rho_0,t)$ [see Eq. (7)] induces the registered signal $E_{\text{emf}}(\rho_0,t) \sim -\mathrm{d}M(\rho_0,t)/\mathrm{d}t$ in the induction sensor.

The registration of the signal $E_{\text{emf}}(\rho_0,t)$ in the study of the pulsed photomagnetization phenomenon is complicated by the fact that the induction sensor transfer function is changing because of measuring circuit resonances [39]. This leads to the signal distortion and its registration as periodic damped oscillations [25].

The effect of the resonance phenomena in the measuring LC circuit on the form of the registered signal is attenuated in this work. Due to reduction of the pickup coil inductance L and, as a consequence, increase of the registering systems resonance frequency (the frequencies of the parasitic resonances is outside the signal bandwidth) we have eliminated the periodic damped oscillations in the registered signals $E_{\text{emf}}(\rho_0,t)$ (Fig. 5, left).

The induction signal $E_{\text{emf}}(\rho_0,t)$ has a differential form so a time integral of the signal allowed us to obtain the

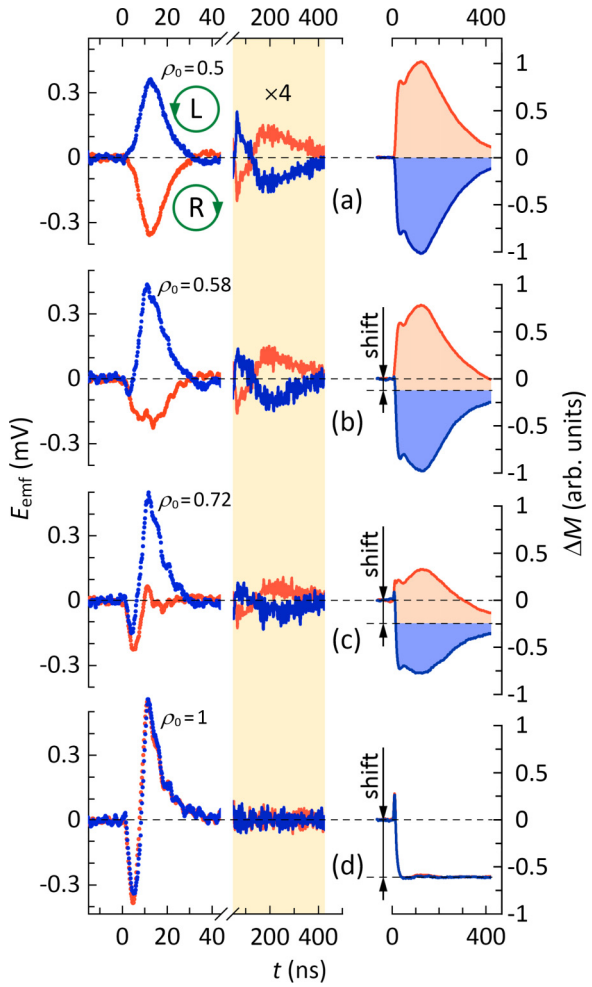

FIG. 5. Left: the induction signals $E_{emf}(\rho_0,t)$ induced by a laser pump pulse with right- (R) and left-handed (L) circular polarizations; portions of the signals are marked within a range of $t=50$ to 400 ns; their amplitude is quadrupled. Right: the photomagnetization pulses $\Delta M(\rho_0,t)$ obtained by integrating the corresponding induction signals (time integral of electromotive force). The bias field H_b and the domain structure filling factor ρ_0 for the initial state of the magnetic film are (a) $H_b=0$, $\rho_0=0.5$; (b) $0<H_b<H_0$, $\rho_0=0.58$; (c) $0<H_b<H_0$, $\rho_0=0.72$; and (d) $H_b>H_0$, $\rho_0=1$.

time evolution of the sample magnetization change, i.e., the photomagnetization pulse $\Delta M(\rho_0,t)$ (Fig. 5, right).

D. Experimental setup

In the experiment we used a Nd:YLF nanosecond Q-switched laser (DTL-419QT) as a source of photomagnetizing pump pulses (Fig. 4). Pump-pulse parameters are wavelength is 527 nm, pulse duration is 5 ns, beam diameter is 1 mm (a laser beam expander was used), pulse energy instability is less than 3.0%, pulse repetition rate is 10 Hz. The low repetition frequency of the laser pump pulses is selected for a possibility of the domain structure "annealing" by the ac magnetic field before each pump pulse. A laser pulse fluence of 23 mJ/cm^2 was selected to improve the signal/noise ratio in the recording channel of the experimental setup and to prevent thermal annealing processes in the sample. The linearly polarized laser pump pulse is converted to a circularly polarized one and incident normal to the sample surface. Some experiments utilized linearly polarized laser pulses as well.

The sample is located in the center of the two systems of Helmholtz coils (Fig. 4). They are intended for the generation of the dc (A) and ac (B) magnetic fields perpendicular to the sample plane. The induction sensor with an inner diameter of 1 mm and an inductivity of $L=80$ nH is located directly on the magnetic film surface (Fig. 1).

The signal $E_{emf}(\rho_0,t)$ was registered by an oscilloscope in real time as a reaction to the single pump pulse (Fig. 5, left). A time resolution of ~1 ns was achieved by using a low-inductance transducer, an active differential probe (AP033) with a bandwidth of 500 MHz, and an oscilloscope (HDO6104) with a bandwidth of 1 GHz and a high dynamic range (12 bit).

Since the domain structure period P_0 is 32 μm and the pump-pulse spot diameter is 1 mm, all the experimentally observed values should be regarded as averaged over a large number of domains. Approximately 10^3 cycles of pulsed photomagnetization were averaged at each experimental condition to accumulate sufficient statistics. The photomagnetization process is highly repetitive from cycle to cycle due to domain structure "annealing" before each pump pulse.

IV. RESULTS AND DISCUSSION

A. Description of experimental results

The induction signal $E_{emf}(\rho_0,t)$ (Fig. 5, left) shows the time evolution of the rate of the sample magnetization change. The photomagnetization pulse $\Delta M(\rho_0,t)$ (Fig. 5, right) shows the time evolution of the sample magnetization change. All the signals represented on Fig. 5 are obtained for the same sample area that was under the action of the laser pump pulse. Data on Figs. 5(a)–5(d) indicate the transformation of the signals $E_{emf}(\rho_0,t)$ and $\Delta M(\rho_0,t)$ because of the domain structure filling factor ρ_0 change and because of the laser pump-pulse helicity change (R $\Leftrightarrow$ L).

Let's consider the sample in the initial state with the equilibrium domain structure ($\rho_0=0.5$). In this case under the pump-pulse helicity change, the signals $E_{emf}(\rho_0,t)$ and $\Delta M(\rho_0,t)$ change their polarity but save their form [Fig. 5(a)], and the signal $\Delta M(\rho_0,t)$ tends to zero.

The filling factor grows ($0.5<\rho_0<1$) under the action of the bias field H_b, and the pump-pulse helicity change leads to changes of both the polarity and form of the signals $E_{emf}(\rho_0,t)$ and $\Delta M(\rho_0,t)$ [Figs. 5(b), 5(c)]. Nevertheless, in the time interval from 50 to 400 ns, the signal form $E_{emf}(\rho_0,t)$ stays constant (Fig. 5, marked part in the center). With the increasing of filling factor ρ, only the amplitude of that part of the signal is decreasing. The value of $\Delta M(\rho_0,t)$ over time tends to some intermediate value of $\Delta M^{shift}(\rho_0)$ which is independent of the pump-pulse helicity and grows with the increasing of filling factor ρ_0.

When the magnetic film initial state is monodomain ($H_b>H_0$, $M_0(H_b)=M_s$, $w_\downarrow(H_b)=0$, $\rho_0=1$), both the polarity and form of the signals $E_{emf}(\rho_0,t)$ and $\Delta M(\rho_0,t)$ are independent of the pump-pulse helicity [Fig. 5(d)]. Furthermore, both the polarity and form of the signal $E_{emf}(\rho_0,t)$ and the

photomagnetization pulse $\Delta M(\rho_0,t)$ stay constant after the transition from the circular to linear pump-pulse polarization.

Thus, depending on the initial state of the magnetic film, the p.dep ($H_b=0$, $\rho_0=0.5$) or p.ind ($H_b>H_0$, $\rho_0=1$) photomagnetization effects are taking place. Under the bias field less than a film saturation field ($0.5<\rho_0<1$), the combined contribution of the aforesaid effects to the photomagnetization is observed.

The mathematical processing of the photomagnetization pulses $\Delta M(\rho_0,t)$ is done with those apparent combinations:

$$\Delta M^{p.dep}(\rho_0,t) = 0.5[\Delta M^R(\rho_0,t) - \Delta M^L(\rho_0,t)], \quad (16)$$

$$\Delta M^{p.ind}(\rho_0,t) = 0.5[\Delta M^R(\rho_0,t) + \Delta M^L(\rho_0,t)]. \quad (17)$$

where $\Delta M^R(\rho_0,t)$ and $\Delta M^L(\rho_0,t)$ are the photomagnetization pulses $\Delta M(\rho_0,t)$ under the action of the laser pump pulses of opposite helicities. The mathematical processing allowed us to separate the contributions to the photomagnetization from the p.dep and p.ind effects under the arbitrary sample initial state (under the arbitrary values of ρ_0). The separation of the contributions allowed us to track the transformation of the photomagnetization pulse form, represented on Fig. 6. The

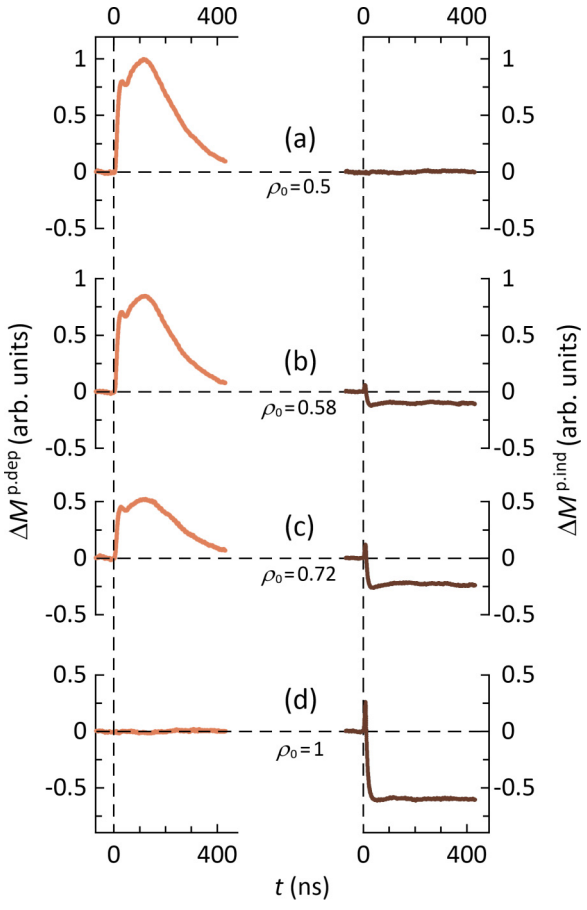

FIG. 6. Time evolution of the sample's magnetization normal component change corresponding to the contributions to the photomagnetization from the polarization-dependent [$\Delta M^{p.dep}(\rho_0,t)$, left] and the polarization-independent [$\Delta M^{p.ind}(\rho_0,t)$, right] effects after the mathematical processing of the photomagnetization pulses $\Delta M(\rho_0,t)$ (Fig. 5).

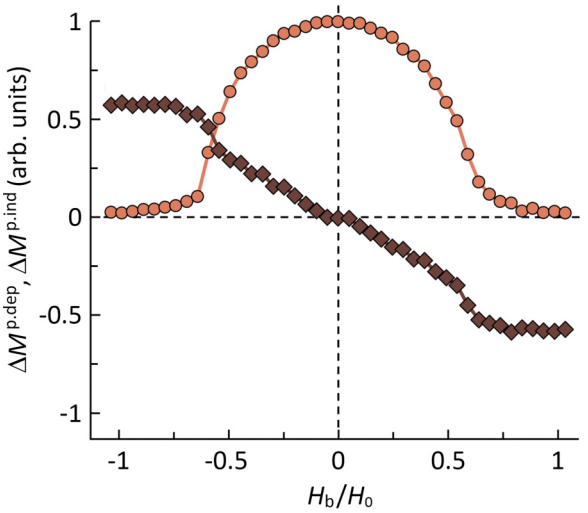

FIG. 7. Normalized field dependences of the photomagnetization pulses amplitudes $\Delta M^{p.dep}(\rho_0,t)$ and $\Delta M^{p.ind}(\rho_0,t)$ caused by the polarization-dependent (circles) and the polarization-independent (diamonds) effects, respectively. The bias field H_b is normalized to the bubble collapse field H_0.

photomagnetization pulses $\Delta M^{p.dep}(\rho_0,t)$ and $\Delta M^{p.ind}(\rho_0,t)$ show the time evolution of the sample magnetization change separately for each of the aforesaid contributions to the photomagnetization.

The form of the photomagnetization pulses $\Delta M^{p.dep}(\rho_0,t)$ and $\Delta M^{p.ind}(\rho_0,t)$ is independent of the sample initial state. Only their amplitude changes are observed (Fig. 7): for the p.dep contribution it's an even function H_b, and for the p.ind contribution it's an odd function H_b.

The form difference of the photomagnetization pulses $\Delta M^{p.dep}(\rho_0,t)$ and $\Delta M^{p.ind}(\rho_0,t)$ indicates that the p.dep and the p.ind effects have different natures.

B. Discussion and interpretation of the results

The optimization of the primary inductive transducer parameters performed in this work allowed us to avoid the signal $E_{emf}(\rho_0,t)$ distortion caused by influence of measuring circuit resonances on the induction sensor transfer function and to achieve a time resolution of 1 ns at the registration of the induction signals. Another feature of the experimental technique is the domain structure "annealing" by an ac magnetic field before each laser pump pulse. At the same time an initial thermodynamically equilibrium domain structure is formed, which allowed achieving high repetitiveness of the photomagnetization processes.

(i) For detection of the domain-wall movement contribution to the photomagnetization, it is important to analyze the photomagnetization in the absence of the external magnetic field. In this case, the magnetic film initial state is an equilibrium domain structure with filling factor $\rho_0=0.5$ which corresponds to zero total film magnetization. Therefore, the only process that could lead to nonzero total film magnetization is a domain-wall movement. As a result, the domain structure filling factor is changed.

Notice that a possible increase of a film temperature as a result of the laser pulse action (the laser wavelength falls into

the film's absorption spectrum [25,26]) does not lead to the total magnetization change: in this case the compensation of the magnetization change in the domains with equal volumes and opposite magnetization directions occurs. The experimental results showed that the registered signal $E_{\mathrm{emf}}(\rho_0,t)$ [Fig. 5(a), left] and the corresponding photomagnetization pulse $\Delta M(\rho_0,t)$ [Fig. 5(a), right] are caused only by the p.dep photomagnetization effect. There is no contribution from the p.ind effect: $\Delta M^{p.ind}(\rho_0=0.5,t)\to 0$ [Fig. 6(a), right]. Note that the amplitude of the photomagnetization pulse $\Delta M^{p.dep}(\rho_0,t)$ is maximal in the absence of the external magnetic field [Fig. 6(a), left].

The polarity change of the induction signal $E_{\mathrm{emf}}(\rho_0,t)$ [Fig. 5(a), left] under the laser pump-pulse helicity change also supports the domain-wall movement contribution to the photomagnetization. The domain-wall velocity vector reverses with the domain-wall movement direction change. That leads to the total magnetization direction change and is registered in the experiment as the polarity change of the induction signal $E_{\mathrm{emf}}(\rho_0=0,t)$. This signal reflects the time evolution of a domain-wall velocity. Thus, the p.dep photomagnetization effect is caused exactly by the domain-wall movement.

Let's consider in more detail the form of the photomagnetization pulse $\Delta M(\rho_0,t)$ for the sample initial state with $\rho_0=0.5$ [Fig. 5(a), right and Fig. 6(a), left]. The photomagnetization pulse is characterized by having three parts that reflect the stages with different maximum rates of the sample magnetization change. In the first stage ($t<30$ ns), $\Delta M(\rho_0,t)$ is rapidly increasing. In the second stage ($30<t<120$ ns), $\Delta M(\rho_0,t)$ continues to increase but with less rate. In the third stage ($t>120$ ns), the relaxation process begins and $\Delta M(\rho_0,t)$ is decreasing for $\sim 10^3$ ns.

Such a form of the photomagnetization pulse reflects the time evolution of the domain-wall movement. In the first stage, the domain-wall velocity is more than an order of magnitude greater than the velocity in the second stage. This may be explained by a spin structure transformation of domain walls during the transition to the second stage. The time of the domain-wall movement in one direction (in the first and second stages) is more than an order of magnitude greater than the laser pump-pulse duration. The third stage corresponds to the process of relaxation to the initial state, at the same time the domain-wall movement direction is inverted. The values of the domain-wall velocities on the second and third stages are almost equal (Fig. 5, marked part in the center). In general, the observed picture of the domain-wall movement's time evolution under the action of a circularly polarized laser pump pulse is similar to the domain-wall movement under the action of a magnetic field pulse that exceeds a critical field of domain-wall linear dynamics [1,3]. In this case, features of the domain-wall movement are high velocity in the beginning of the motion (the first stage), the Walker breakdown (the breakdown of the stationary domain-wall movement accompanied by some decrease in velocity), and the transition to the domain-wall nonlinear dynamics with a saturation velocity of domain walls (the second stage).

(ii) Now let's discuss the study results of the sample photomagnetization whose initial state is the monodomain state ($\rho_0=1$) [Fig. 5(d) and Fig. 6(d)]. The induction signal form and therefore the photomagnetization pulse form have two specific parts that reflect the stages of the magnetization change. On the first part, the magnetization changes (decreases) during $t<30$ ns. On the second part, changes of the magnetization were not registered within the available measurement accuracy [Fig. 5(d), marked part in the center]. We evaluate the duration of the second part as $>10^4$ ns, which corresponds to slow cooling of the optically excited area after the pump pulse.

The duration of the first part is in accordance with typical times (a nanosecond time scale) of a spin system heating up via phonon-magnon interactions in magnetic dielectrics [14]. Thus, the magnetization changes during the whole pump pulse $\tau_p=5$ ns. Notice that a crystal lattice heating up (increasing of the sample temperature) is a consequence of electron-phonon interactions. Typical times for such processes in magnetic dielectrics are $\leqslant 1$ ps [14]. Thus, the sample temperature change is the process that changes the monodomain sample magnetization.

As the experimental results have shown, the registered signal $E_{\mathrm{emf}}(\rho_0,t)$ [Fig. 5(d), left] and the corresponding photomagnetization pulse $\Delta M(\rho_0,t)$ [Fig. 5(d), right] are caused only by the p.ind photomagnetization effect. There is no contribution from the p.dep effect [see Fig. 6(d), left]. Note that the amplitude of the photomagnetization pulse $\Delta M^{p.ind}(\rho_0,t)$ is maximal in the monodomain sample initial state [Fig. 6(d), right]. Moreover, in such an initial state of the magnetic film both the form and polarity of the signals $E_{\mathrm{emf}}(\rho_0=1,t)$ and $\Delta M(\rho_0=1,t)$ are independent of the laser pump-pulse polarization state. This also indicates that this contribution to the photomagnetization is caused by the saturation magnetization change due to the sample heating.

(iii) Let's consider the photomagnetization of the sample with a domain structure in the presence of the magnetic field H_b not exceeding a film saturation field ($0.5<\rho_0<1$). In this case, the results of the mathematical signal processing indicate that the p.dep and p.ind photomagnetization effects are occurring in the film at the same time. The separation of their contributions allowed us to track the form transformation of the photomagnetization pulses $\Delta M^{p.dep}(\rho_0,t)$ (Fig. 6, left) and $\Delta M^{p.ind}(\rho_0,t)$ (Fig. 6, right) with the change of ρ_0 and to find out the transformation of the contributions to the photomagnetization from two mechanisms—domain-wall movement and saturation magnetization change. The photomagnetization pulse $\Delta M^{p.dep}(\rho_0,t)$ reflects the time evolution of the domain-wall movement. The photomagnetization pulse $\Delta M^{p.ind}(\rho_0,t)$ reflects the time evolution of the saturation magnetization change due to the sample heating.

V. CONCLUSIONS

In this work, we demonstrated that for the magnetic film whose initial state is an equilibrium domain structure at zero external magnetic field (with the filling factor $\rho_0=0.5$ and zero total film magnetization), the polarization-dependent effect entirely defines the film's photomagnetization under the action of a circularly polarized laser pump pulse. It was shown that the effect is caused by a domain-wall movement. Such a movement initiated by the laser pump pulse continues in one direction for a time that is more than an order of magnitude longer than the pump-pulse duration (identification of mechanisms causing such an inertial domain-wall behavior require

additional research using time-resolving spectroscopy). In general, the time evolution of the domain-wall movement goes in three stages.

The separation of the contributions to the photomagnetization from the polarization-dependent (a domain-wall movement) and polarization-independent (a spin system heating up) effects was performed for an arbitrary initial state of the magnetic film. It was shown that the photomagnetization pulses that reflect the polarization-dependent and polarization-independent contributions differ by form, and more than two orders of magnitude by duration. The photomagnetization pulse form for both contributions does not change under the magnetic field change, only the photomagnetization pulse amplitude does: for the polarization-dependent contribution, it's an even function of the magnetic field, and for the polarization-independent contribution, it's an odd function.

We emphasize that domain-wall movement induced by the laser pump pulse, which is studied in this work, could be of interest for practical applications in spin-photonics devices [40].

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