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ABSTRACT

We demonstrate the measurement of the magnetization dynamics at femtosecond time scales using a split helix resistive magnet reaching magnetic field strengths up to 25 T. The high frequency resolution achieved by ultrafast lasers coupled with the high magnetic fields that can achieve magnetization oscillations in the hundreds of gigahertz makes this a very valuable experimental tool. We demonstrate the technique by using time-resolved magneto-optic Kerr effect spectroscopy to measure the spin dynamics of the ferrimagnet (FeCo)_{1-x}Gd_x at magnetic fields up to 25 T for different magnetic field orientations. Three orientations were used to investigate the magnetization dynamics, perpendicular to the sample plane, parallel to the sample plane, and 20° off the sample plane. The polar time-resolved magneto-optic Kerr effect data show different dynamics depending on the alignment of the external magnetic field with the rare earth or transition metal magnetization. In time-resolved magneto-optic Kerr effect measurements with magnetic fields at 20° off the sample plane, we obtain oscillations due to the precession of the net magnetization. The oscillation frequency increases linearly with the external magnetic field, reaching 500 GHz at 20 T. When the magnetic field is applied parallel to the sample plane, the observed magnetization dynamics undergoes a 180° phase shift when the magnetic field direction is reversed. The different magnetic field orientations with respect to the sample lead to very different magnetization dynamics, which probe different aspects of the magnetic properties of the alloy, emphasizing the importance of the versatility of the present instrumentation.

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I. INTRODUCTION

The high temporal resolution of modern femtosecond lasers makes ultrafast manipulation of magnetic states of technological importance in innovative magnetic storage. Ultrafast lasers can resolve spin oscillation frequencies of hundreds of gigahertz (GHz), which are difficult to measure using traditional methods.¹ Magneto-optic spectroscopy is used to take advantage of the high temporal resolution of ultrafast lasers and achieve all-optical spin switching.^{2,3} Such magneto-optical techniques include the magneto-optical Kerr effect (MOKE)/Faraday spectroscopy, magnetic Raman scattering, and magnetically induced second harmonic generation and have provided new insights into magnetic excitations.^{4–20} Time-resolved MOKE in particular has been essential in understanding the spin

dynamics at ultrafast time scales and spin switching approaching the terahertz (THz) frequency range. These high spin switching frequencies can occur in antiferromagnets, which are thought to have great potential for application in antiferromagnetic spintronics and opto-spintronics^{21–25} and may require much larger external magnetic fields to investigate or manipulate due to large exchange energies.^{26–30} An alternative to antiferromagnets is provided by ferrimagnetic materials that have magnetization and can be measured via MOKE. Interest in ferrimagnetic materials has recently grown considerably, as ferrimagnets have unique properties with important spintronic applications.³¹ The properties of ferrimagnets, including the saturation magnetization, spin polarization, and anisotropy, can be tuned across a wide range. The high frequency properties of ferrimagnets are widely studied, as ferrimagnets combine some of the

attractive aspects of high-frequency applications of antiferromagnets with the convenience of a net magnetic moment for alignment under an external field. Of particular interest to all ferrimagnetic systems are the spin dynamics at ultrafast timescales, which are conveniently probed with laser-based optical techniques. A noteworthy and closely related phenomenon in rare earth (RE)/transition metal (TM) alloys is the reversal of magnetization following an ultrafast optical excitation, also referred to as all optical magnetization switching.^{32,33}

It has been demonstrated that the time scale of the spin response to a femtosecond laser excitation can be controlled by varying the Curie temperature, the atomic magnetic moment of the chemical elements, and the intensity of the excitation.^{7,9,34} In RE/TM metal alloys such as $(\text{FeCo})_{1-x}\text{Gd}_x$, on the rare-earth atoms, the intra-atomic exchange integrals favor ferromagnetic alignment between the spin moments on the 4f orbitals, positioned several eV away from the Fermi level, and the less than half filled 5d electrons that comprise the conduction band. Hybridization between the rare-earth 5d states and the Fe, Co 3d electrons promotes antiparallel alignment of the transition metal and Gd moments.^{35,36} The net magnetic moment can point in the direction of either the Gd or the Fe, Co moments, depending on which sublattice has the larger total moment. The ratio of Gd total magnetization to the Fe, Co total magnetization can be adjusted either by changing the Gd content x or the measurement temperature.^{31,37–40} Furthermore, the question whether high magnetic fields can also affect the time scale of the ultrafast spin response to a femtosecond laser excitation has been of great interest.⁴¹ Previous studies have estimated the period of the precession of the electron spin to be 28 GHz/T.^{42–45} Therefore, in order to affect the spin response in the range of 1–10 ps, one has to apply magnetic fields above 10 T. However, combining high magnetic fields with ultrafast magnetization dynamics experiments has so far been very limited.

We present below all-optical studies of spin dynamics in $(\text{FeCo})_{1-x}\text{Gd}_x$ probed with pump–probe techniques. These studies are important for a variety of reasons. The RE/TM alloys have large Verdet constants, which can lead to a large magneto-optical Faraday rotation. Furthermore, one can have a large change in the orbital component of magnetization by selecting different RE elements. There are a number of optical and ultrafast optical studies on ferrimagnetic alloys that have provided important insights into their opto-magnetic and magnetization dynamics.^{41,46–61} However, using large magnetic fields, we are able to generate spin dynamics with an oscillation period of ~ 2 ps. These studies were enabled by new instrumentation that allows the application of external magnetic fields up to 25 T using MOKE geometries. We were able to apply magnetic fields perpendicular to the sample plane in the polar configuration and longitudinal MOKE with magnetic fields at 20° and parallel (0°) to the sample plane. Time-resolved and static MOKE measurements up to 30 T in a resistive high-field magnet were previously achieved in the polar configuration.⁴¹ However, the current instrumentation demonstrates great flexibility, allowing different MOKE configurations.

II. EXPERIMENT

Bitter magnets are resistive magnet designs that are capable of much higher magnetic fields than superconducting magnets. These

magnets are constructed using an interlocking stack of helical copper disks that circulate large currents around a small central space where the sample is located. The magnet is usually several meters in length in order to create a uniform high magnetic field at the sample location, leading to a large distance from the outer windows.⁶² Furthermore, stray fields require any instrument containing ferromagnetic components to be placed far away from the magnet. Therefore, Bitter magnets usually require the use of optical fibers to couple light sources and detectors into and out of the magnetic field.^{63,64} Fiber-coupled experiments are suitable for continuous wave visible and near-infrared studies.⁶⁵ However, it is much more challenging for time-resolved experiments using femtosecond broadband pulsed lasers because dispersion and higher-order nonlinearities of optical fibers distort the laser pulse, making the data analysis challenging. Furthermore, polarization-maintaining fibers are difficult to handle.

Pulsed magnets can reach higher magnetic fields, but for a very short amount of time that lasts only milliseconds with a limited number of cycles, they are not suitable for the time-resolved MOKE measurements presented here, where the data collection takes on average approximately thirty minutes. The split helix magnet system at the National High Magnetic Field Lab is capable of sustained operation at fields as high as 25 T.^{63,66} A schematic of the magnet is shown in Fig. 1(a). The electrical power consumption of this resistive magnet is 32 MWh, but the ability to maintain a high magnetic field enables the time consuming femtosecond time-resolved experiments.⁶⁷ The split helix has a 39 mm bore and uses a custom-constructed cryostat that can reach a base temperature of ~ 12 K. The resistive split helix magnet generates a magnetic field up to 25 T and allows optical access through two windows, perpendicular to the direction of the magnetic field. The magnetic field is generated in the vertical direction, perpendicular to the optical axis, which complicates experiments in the Faraday geometry. In this configuration, for the sample to face the optical windows, the magnetic field would be in the sample plane.

In order to overcome this limitation, we designed the sample holders shown in Figs. 1(b)–1(d). The first mount in Fig. 1(b) is the simplest design, which enables MOKE measurements with magnetic fields parallel to the plane of the sample. The pump and probe beams are sent in at a small incidence angle. They are focused with long focal length lenses and reflected out of the bore. However, in order to pull the magnetization out of the plane and measure the precession of the magnetization, the external magnetic field needs to be applied at an angle with respect to the sample plane. The sample holder shown in Fig. 1(c), where the sample is mounted directly on the copper holder at 20° with respect to the vertical fixed magnetic field direction. The angles of incidence are determined by the sample holder geometry but can be varied slightly. The beams are reflected by the sample surface and reflected out of the bore by the top mirror. One could design a similar copper holder at a different angle with respect to the vertical direction to achieve intermediate angles with respect to the magnetic field. Finally, we have designed a mirror mount for the polar MOKE geometry, where the magnetic field is applied perpendicular to the sample surface. The schematic is shown in Fig. 1(d), where a fixed mirror mounted at 45° guides the focusing beams perpendicular to the surface of the sample. The beams are reflected back from the sample surface and directed toward the detectors.

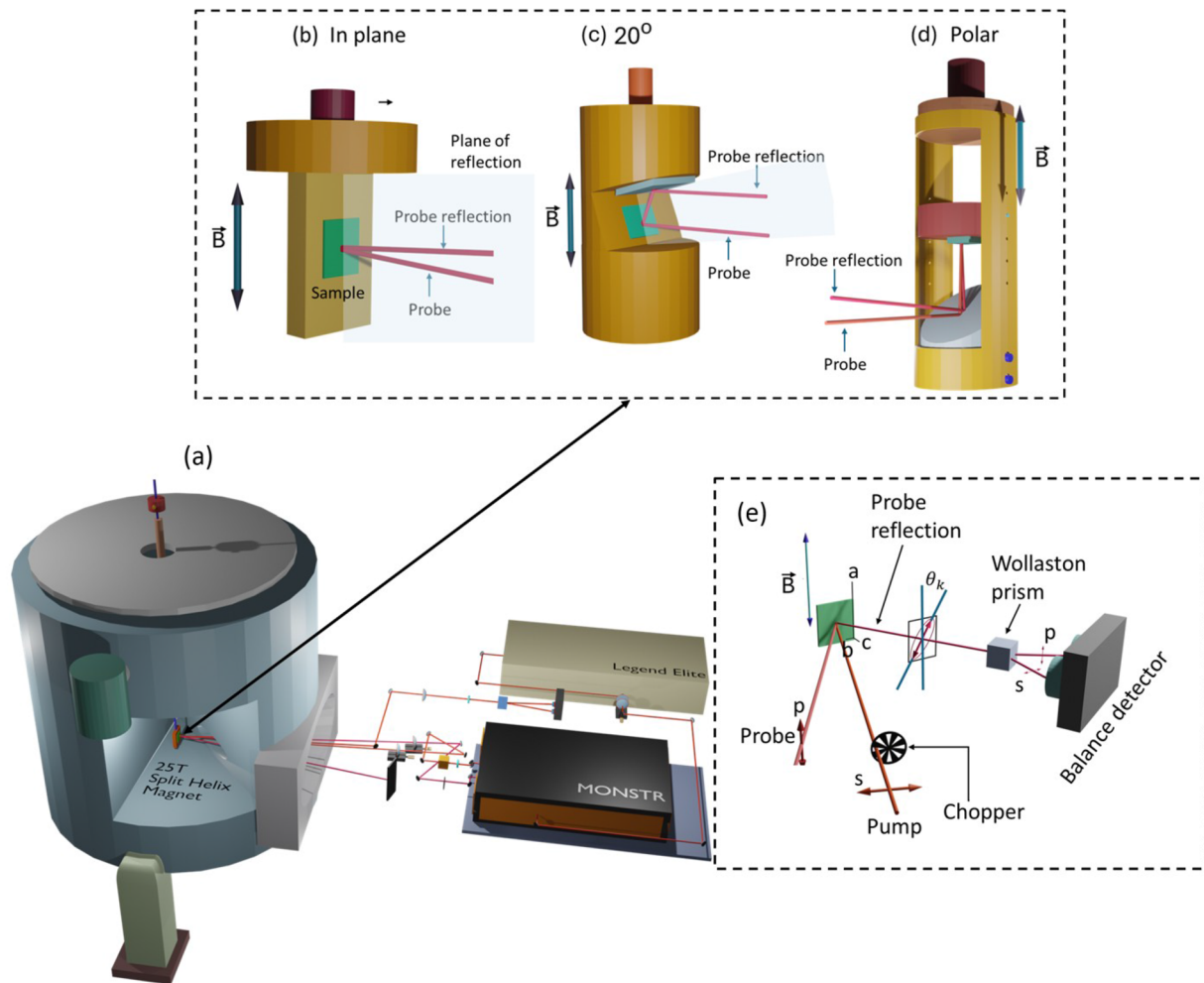


FIG. 1. (a) Experimental setup used for the time-resolved Magneto-Optic Kerr Effect (MOKE) experiments. The magnet system used is the resistive split helix, whereas the pump and probe beams are provided by the multidimensional optical nonlinear spectrometer (MONSTR).^{68,69} The MONSTR splits the laser beam originating from the Legend Elite regenerative amplifier and generates a time delay between pump and probe beams. The magnetic field generated by the split helix can reach up to 25 T, and the magnetic field direction is fixed vertically. In order to achieve different variable magnetic field directions, special sample holders are made. (b) The sample holder used for measurements where the magnetic field is applied in-plane. The plane of reflection is vertical along the magnetic field direction. (c) The sample holder used for measurements where the magnetic field is applied at 20° with respect to the sample plane. The plane of reflection is vertical along the magnetic field direction. (d) The sample holder used for polar time-resolved MOKE. The magnetic field is perpendicular to the plane of the sample. (e) Schematic of the experiment: the pulse and the probe beams are focused and overlap on the sample. The linearly polarized probe beam is reflected from the sample surface. The polarization experiences a slight rotation due to the magneto-optic Kerr effect. This rotation is detected by splitting the probe beam into the s- and p- components using a Wollaston prism and recording them with a balance detector. Small rotation angles θ_k of the linear polarization induced by the pump beam can lead to an imbalance between the s- and p- components and be detected.

The method used in implementing the time-resolved MOKE spectroscopy here is the MONSTR apparatus, which is a compact and portable platform. The apparatus splits the laser beam and generates the time delay between the pump and probe beams. The original implementation was introduced in Ref. 69 and was further developed to use commercially available optical mounts and broadband optics for wider tunability.⁶⁸ The MONSTR platform

described in Ref. 68 was used to perform a variety of time-resolved femtosecond spectroscopy measurements,^{70–80} whereas the time-resolved MOKE detection setup shown in Fig. 1(e) was used in recent studies.^{35,36,81–83} The ability to move the setup quickly in the cell without needing major alignment is crucial in a user facility where the magnet time using the split helix is limited to one week of preparation time and one week of experimentation. Such

capability is provided by the MONSTR instrument. The experiments presented complement recent instrumentation developments in the near infrared and terahertz.^{63,84}

The laser system used in this experiment is a Coherent Legend Elite femtosecond laser amplifier that generates 25 fs pulses with a maximum pulse energy of 5 mJ and a center wavelength of 800 nm (1.55 eV), with a transform-limited bandwidth of 64 meV. The output of the titanium:sapphire laser amplifier is split into four beams by the multidimensional optical nonlinear spectrometer (MONSTR), where only two are used to perform these experiments. One beam is used to pump the sample in a pump-probe experimental configuration and is horizontally polarized, whereas the second beam probes the magnetization via the magneto-optical Kerr effect and is vertically polarized. The laser beam configuration is shown in Fig. 1(e). High extinction polarizers are used in the probe beam to detect small rotations and ellipticity generated by the magnetization of the sample. In the absence of perturbation by the probe beam, the reflected beam is rotated by 45° using a half-wave plate and sent to a Wollaston prism, which splits the beam equally into its s- and p-components. The two equal intensity beams are detected by balanced detectors. The pump beam generates a change in the sample magnetization, which could be due to different mechanisms depending in part on the sample properties. The changes in magnetization lead to a rotation of the probe polarization via the magneto-optic Kerr effect, which leads to a detectable imbalance of the s- and p-components split by the Wollaston prism. The pump beam is modulated by an optical chopper, and the pump induced changes in the probe beam are obtained via lock-in detection.^{1,85}

III. RESULTS AND DISCUSSION

When an ultrashort laser pulse interacts with an ordered ferromagnetic material, the angular momentum of the system is redistributed between the electron, lattice, and spin systems. As a result, the magnetic moment of the system quenches rapidly, and ultrafast demagnetization occurs within ≈ 200 fs.^{4–9} Following the rapid electron demagnetization, the lattice and spin relaxation starts, which occurs in time scales from a few ps to ns. In the present study, the spin dynamics in the $(\text{FeCo})_{1-x}\text{Gd}_x$ system is investigated with time-resolved magneto-optical Kerr effect (TR-MOKE) measurements using ultrafast (~ 25 fs) laser pulses at 800 nm. The light penetration depth at these wavelengths is expected to be ~ 20 nm. The net magnetic moment of this alloy can be compensated by tuning the concentration of the RE and TM, and magnetic compensation in the films occurs at a Gd concentration of $\approx 26\%$. However, temperature can also be used to achieve magnetic compensation.

The sample used in the present study is a single $(\text{FeCo})_{1-x}\text{Gd}_x$ layer of thickness ~ 30 nm. The Ta 10 nm|Fe(60)Co(10)Gd(30)30 nm|Ta 5 nm amorphous ferrimagnetic alloy film was deposited on a Si/SiO_x substrate using magnetron co-sputtering from elemental Fe, Co, and Gd targets at room temperature in a high-vacuum chamber with a base pressure of $\sim 2.66 \times 10^{-8}$ mBar and an Ar working pressure of $\sim 7 \times 10^{-3}$ Torr. The films were grown in a configuration of Ta (10 nm)/(FeCo)_{1-x}Gd_x (30 nm)/Ta (5 nm). The bottom Ta layer was used as a buffer to promote adhesion to the substrate and improve the uniformity of the subsequently deposited $(\text{FeCo})_{1-x}\text{Gd}_x$ layer, while the top Ta layer serves as a protective cap

to prevent oxidation. The elemental composition of the films was verified using energy-dispersive x-ray spectroscopy (EDS), confirming that the samples are close to the intended nominal composition within experimental uncertainty. The film thickness and structural uniformity were characterized by low-angle X-ray reflectivity (XRR) measurements using Cu K α radiation over an angular range of 0°–5°, yielding thickness values consistent with the nominal layer design. The growth led to a (Gd) rare-earth-rich alloy with an in-plane easy axis, where the TM and RE magnetic moments aligned in opposite directions. As the low energy magneto-optical response of the $(\text{FeCo})_{1-x}\text{Gd}_x$ films is determined by the spin polarization near the Fermi level, the dominant magnetic sublattice is probed, and the net spin dynamics can be tracked with time-resolved MOKE using the visible/near IR light pulse. We measured the magnetic moment of the $(\text{FeCo})_{1-x}\text{Gd}_x$ sample as a function of temperature using the low temperature physical property measurement system (PPMS), and the compensation temperature appears around 215 K. The time resolved MOKE measurements presented here were taken at 15 K, well below the compensation temperature. Therefore, at this temperature, the magnetization is expected to be dominated by the rare earth. Importantly, our sample structure is comprised of a single ferrimagnetic layer with an in-plane easy axis.

We use three magnetic field orientations with respect to the sample plane to measure the magnetization dynamics using time-resolved MOKE at magnetic fields up to 25 T. The time-resolved MOKE in the absence of magnetic fields is shown in Fig. 2(a) as a reference and shows a well-known rapid demagnetization and magnetization recovery within 1 ps.^{4,5,7,9} We start the discussion with the external magnetic field applied perpendicular to the sample plane and perpendicular to the RE or TM magnetization. The time-resolved MOKE was measured at opposite magnetic field directions for several field strengths, with representative measurements at ± 25 T shown here. The schematic of the sample, the external magnetic field *B*, rare earth magnetization *M_R*, and transition metal magnetization *M_T* are shown in Fig. 2(b). When external magnetic fields are applied in the polar configuration, a much longer magnetization dynamics is observed, which is different with respect to the external magnetic field direction +*B* and –*B*. The time-resolved MOKE data for +25 T and –25 T are shown in Figs. 2(c) and 2(d), respectively, and some qualitative similarities with the earlier observed dynamics in the polar configuration⁴¹ are explained by going through the spin-flop transition as the electronic temperature produced by the laser temporarily increases.

However, the details of the dynamics differ here. Particularly, a temporal reorientation to the transition metal-dominated region is observed with +25 T, followed by a slower relaxation toward the Gd-dominated state. With –25 T, the system seems to be directly pushed into the FeCo-dominated state. In the measured timescale, the initial state is not recovered in either case, suggesting a very slow magnetization relaxation process. While we are measuring at low temperatures, a high magnetic field applied in different directions can affect the magnetization compensation point; its change is not sufficiently large to induce a strong effect. The slow relaxation observed in this case points to laser pulse induced (almost) complete demagnetization and the appearance of nucleation centers with magnetization up or down that grow into a domain pattern as the system cools down. This would be a transient state with perpendicular domains, where the number of domains up would be larger for

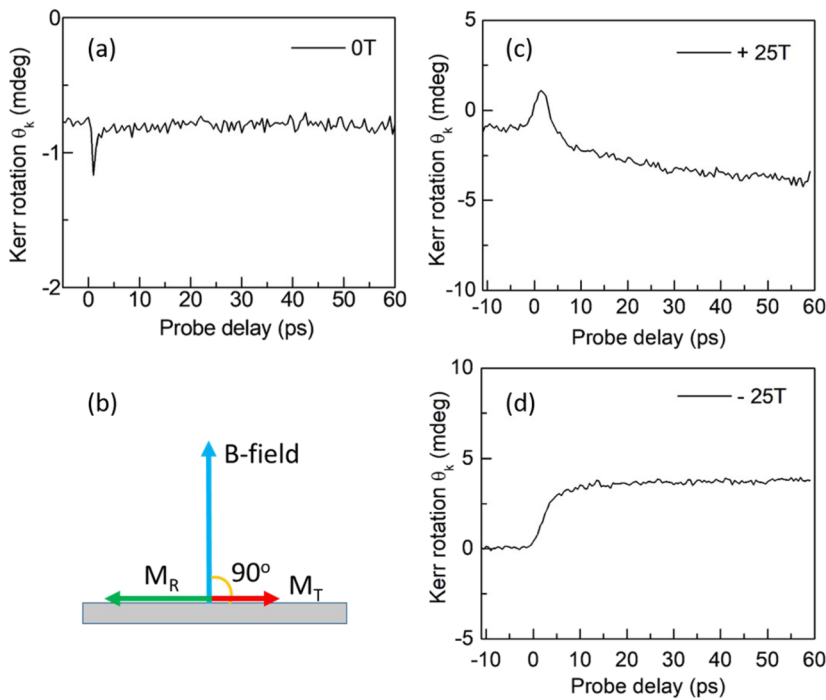


FIG. 2. Polar time-resolved MOKE at 15 K. (a) Zero magnetic field time-resolved MOKE data. (b) Schematic of the sample, external magnetic field B , rare earth magnetization M_R , and transition metal magnetization M_T . The external magnetic field has been applied in two opposite directions $\pm B$, shown by the solid blue arrow. The green and red arrows represent the rare earth magnetization M_R and the transition metal magnetization M_T , respectively. (c) and (d) Time resolved MOKE data for ± 25 T. The magnetization dynamics between $(-B)$ and $(+B)$ is anisotropic.

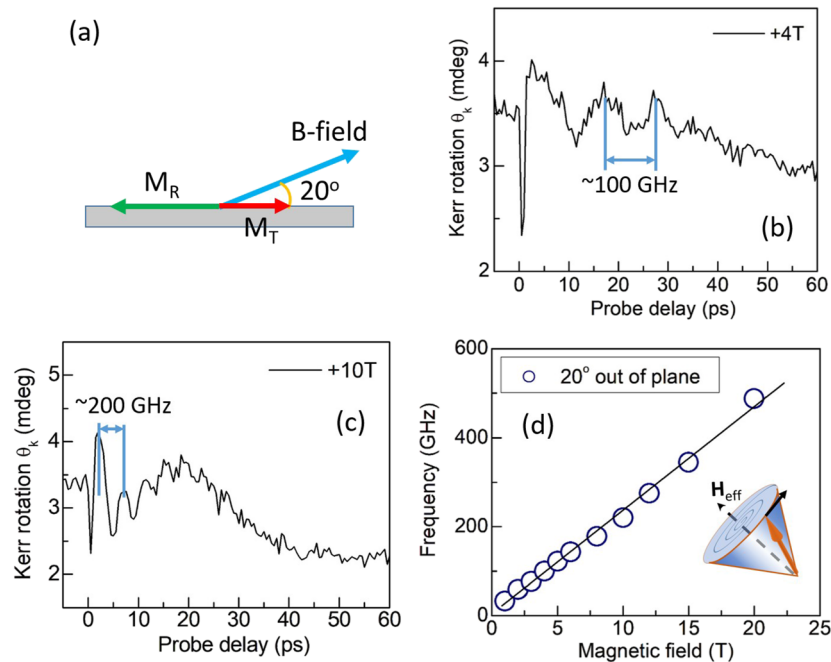


FIG. 3. (a) Longitudinal time-resolved MOKE at 15 K, where the external magnetic field is applied at a 20° angle with respect to the sample plane. The external magnetic field has been applied in two opposite directions, $\pm B$, shown by the solid blue arrow. The green and red arrows represent the rare earth magnetization M_R and the transition metal magnetization M_T , respectively. [(b) and (c)] Time resolved MOKE data for 4 and 10 T, respectively. (d) Oscillation frequency vs the magnitude of the magnetic field applied. The magnetization dynamics shows oscillations that increase in frequency from 33 to 500 GHz with increasing magnetic fields from 1 to 20 T, respectively. The oscillations are phase shifted by 180° between the $(-B)$ and $(+B)$ directions of the external magnetic field. The error in determining the oscillation frequency increases with the magnetic field due to small precession cone angles and a limited number of fringes. We estimate the error in determining the frequency of the oscillations at high magnetic fields above 10 T to be <20 GHz. The precession of the net magnetization (brown arrow) around the effective magnetic field H_{eff} (black arrow) is schematically shown in the inset.

one field direction with one of the sublattices and smaller for the opposite field direction with the other sublattice.

We proceed by measuring the magnetization dynamics in the longitudinal configuration. We attempt to pull the net magnetization out of the sample plane by applying the external magnetic field at 20° with respect to the sample plane. The schematic of the sample, RE and TM magnetization, and the external magnetic fields are shown in Fig. 3(a). At lower magnetic fields, starting at 1 T, oscillations in the magnetization dynamics start to appear. These oscillations are thought to originate from the precession of the net magnetization around the effective magnetic field.⁵ Representative time-resolved MOKE data for this magnetic field orientation are shown in Figs. 3(b) and 3(c) for magnetic fields of 4 and 10 T, respectively. The oscillation frequency starts at ~ 33 GHz at 1 T and reaches ~ 250 GHz at 12 T. The observed oscillations persist at higher magnetic fields and increase in frequency with increasing magnetic fields, reaching ~ 500 GHz at 20 T. Finally, we plot the frequency of the observed oscillations as a function of the applied magnetic field. The data are shown in Fig. 3(d), where the blue circles are frequencies obtained experimentally by fitting the oscillations of the time-resolved MOKE data with magnetic fields applied at 20° with respect to the sample's plane.

Upon optical excitation, the magnetic moment is perturbed and deflected from its equilibrium direction. The magnetization $\mathbf{M}$ experiences a torque and precesses around the effective magnetic field, $\mathbf{H}_{\text{eff}}$, following the Landau–Lifshitz–Gilbert (LLG) equation as given by

$$\frac{\partial \mathbf{M}}{\partial t} = \gamma \mathbf{M} \times \mathbf{H}_{\text{eff}} - \frac{\alpha}{M} \left(\mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} \right), \quad (1)$$

where α is the phenomenological damping constant, $\gamma = 2.8 \times \pi \times g$ MHz/Oe is the gyromagnetic ratio of the electron, and g is the Landau splitting factor.⁸⁶ The first term describes the magnetization precession, and the second term, also known as Gilbert's term, leads to damping. The precession frequency as a function of the in-plane magnetic field can be described by the Kittel equation^{87,88}

$$f = \frac{\gamma}{2\pi} \sqrt{H(H + 4\pi M_s)}, \quad (2)$$

where H is the magnetic field and M_s is magnetization. For polar MOKE and arbitrary angles, the general expression for the magnetic field dependence of the oscillation frequency has been discussed in recent publications.^{89,90} The measured precession frequency is plotted as a function of the magnetic field together with curves fit using Eq. (2), approximating a linear relationship of the oscillation frequency with increasing applied magnetic field, and is fit by the black line.

Finally, the external magnetic field is applied parallel to the sample plane. The schematic of the sample, external magnetic field B , rare earth magnetization M_R , and transition metal magnetization M_T is shown in Fig. 4(a). The external magnetic field has been applied in two opposite directions, $\pm B$, and is schematically shown by a solid blue arrow. The green and red arrows represent the rare earth magnetization M_R and the transition metal magnetization M_T , respectively. The time-resolved MOKE data are shown in Figs. 4(b) and 4(c) for magnetic fields of $+10$ and -10 T, respectively. At 10 T, a highly damped oscillation is observed that experiences an 180° phase shift when the magnetic field direction is reversed.

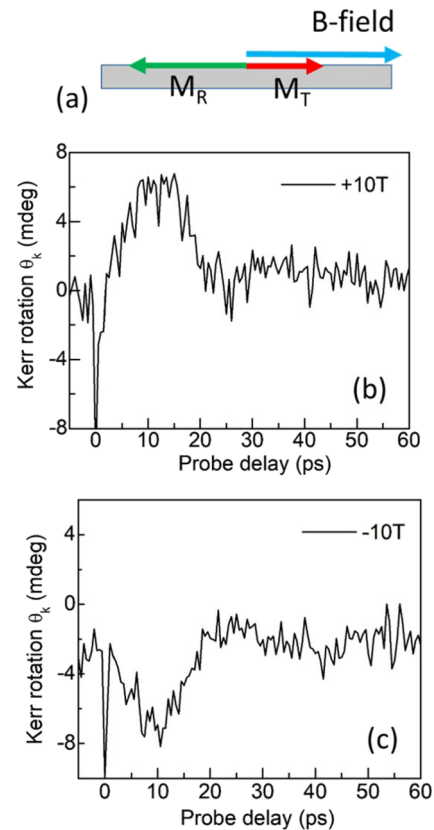


FIG. 4. Longitudinal time-resolved MOKE at 15 K, where the external magnetic field is applied parallel to the sample plane. (a) Schematic of the sample, external magnetic field B , rare earth magnetization M_R , and transition metal magnetization M_T . The external magnetic field has been applied in two opposite directions, $\pm B$, shown by the solid blue arrow. The green and red arrows represent the rare earth magnetization M_R and the transition metal magnetization M_T , respectively. [(b) and (c)] Time-resolved MOKE data for ± 10 T, respectively. The observed magnetization dynamics undergoes a 180° phase shift when the magnetic field direction is reversed.

IV. CONCLUSIONS

We measured the magnetization dynamics with extremely high temporal resolution using a split helix resistive magnet reaching magnetic field strengths up to 25 T. The high frequency resolution coupled with the high magnetic fields that can achieve magnetization oscillations in the hundreds of gigahertz makes this a very valuable experimental tool. The split coil magnet with a sample space accessible by optical windows allows for time-resolved optical measurements with different field orientations with respect to the sample. We demonstrate the technique by using time-resolved MOKE spectroscopy to measure the spin dynamics of the ferromagnet $(\text{FeCo})_{1-x}\text{Gd}_x$ at magnetic fields up to 25 T for different magnetic field orientations. Three orientations were used to investigate the magnetization dynamics in this system, perpendicular to the sample plane, parallel to the sample plane, and 20° off the sample plane. The flexibility to measure at different magnetic field orientations with respect to the sample makes this

instrumentation development unique. The polar time-resolved magneto-optic Kerr effect data show anisotropic dynamics depending on the alignment of the external magnetic field with the rare earth or transition metal magnetization. In time-resolved magneto-optic Kerr effect measurements with magnetic fields at 20° off the sample plane, we obtain oscillations due to the precession of the effective magnetization around the external field. As expected in this configuration, the oscillation frequency increases linearly with the external magnetic field, reaching 500 GHz at 20 T. When the magnetic field is applied parallel to the sample plane, the observed magnetization dynamics undergoes a 180° phase shift when the magnetic field direction is reversed. The high magnetic fields are very important for materials with substantial exchange interactions such as antiferromagnets, whereas the femtosecond resolution of the laser can resolve the much higher resonance frequencies that can be achieved. The different magnetic field orientations with respect to the thin film alloy lead to very different magnetization dynamics, emphasizing the importance of the versatility of the present instrumentation. This technique would be used to study materials that are important for antiferromagnetic spintronics and opto-spintronics.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Arup Barua: Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Writing – original draft (equal). **Sean Knapp:** Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal). **Noha Alzahrani:** Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal). **Diego Enrique Gomez:** Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal). **Oksana Chubykalo-Fesenko:** Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal). **Dmitry Semenov:** Investigation (equal); Methodology (equal); Resources (equal). **Stephen A. McGill:** Investigation (equal); Methodology (equal); Resources (equal). **Darío Arena:** Funding acquisition (equal); Investigation (equal); Methodology (equal); Resources (equal). **Denis Karaiskaj:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Project administration (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon request.

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