Gigantic spin waves induced by ultrashort laser pulses

Recently, spintronics, a field of electronic engineering utilizing the degrees of freedom of both electrons and spins of materials, has been actively studied. In particular, its application to information transmission techniques that use spin waves is highly expected.

In this study, we discovered remarkable spin waves with more than ten times the amplitude of those previously reported. This was realized by temporally and spatially observing the behavior of spins in a ferrimagnetic Gd–Fe–Co thin film immediately after the irradiation of ultrashort laser pulses [1].

Usually, spin directions can be switched by applying magnetic fields or electric pulses. Likewise, spin waves can be generated by applying radio-frequency magnetic or electric fields. In this study, however, we applied a recently developed method to manipulate spins by using ultrafast laser pulses (pulse width: ~100 fs). Because light-induced spin wave generation is theoretically a nonthermal process, it may lead to the development of new electronic devices with lower power consumption. Conversely, the discovery of new magnetization control methods, for example, spin manipulation using spin-lattice coupling, is also expected by making use of thermal activation by laser beams.

To effectively control spin directions, ferrimagnetic Gd–Fe–Co alloy films are used as materials because of their strong magneto-optical interaction. Gd–Fe–Co alloys have different angular-momentum compensation temperatures (T_A) depending on their composition. In addition, it is known that anomalously strong precession damping takes place at T_A. Therefore, as shown in Fig. 1, light-induced spin dynamics depends on the ambient temperature of the sample relative to its T_A; when T_A is below or above the experimental temperature, we expect prolonged magnetization precession and rapid magnetization reversal, respectively [2].

Experiments were performed at SPring-8 **BL25SU** soft X-ray beamline [3] by visualization of the X-ray magnetic circular dichroism effect using a photoemission electron microscope (XMCD-PEEM) combined with a pump-probe technique [4]. Figures 2(a) and 2(b) show time-dependent XMCD-PEEM images of $Gd_{26}Fe_{66}Co_8$ and $Gd_{22}Fe_{70}Co_8$ thin films, respectively. In the $Gd_{26}Fe_{66}Co_8$ sample (Fig. 2(a)), the magnetization mostly settled to its final state approximately 1 ns after the excitation. However, in the $Gd_{22}Fe_{70}Co_8$ sample (Fig. 2(b)), a packet of wavelike spin modulation propagated isotropically along the radial direction from 800 ps to 5 ns post-irradiation. Precise analysis of the modulation of the XMCD signals revealed that precession angle of the spin waves was extremely large, approximately 20° (±10°) (Fig. 2(c)). Taking into account the temporal resolution of the present study, the actual precession angle may be approximately double this value up to ~40° (±20°). This value is orders of magnitude higher than that ever observed in spin waves generated by either electric fields or optical excitation, where precession angles are typically in the range of ~0.1–1°.

We proved by some other simulations and comparative experiments that this unusual phenomenon is triggered by resonant magnetization precession as

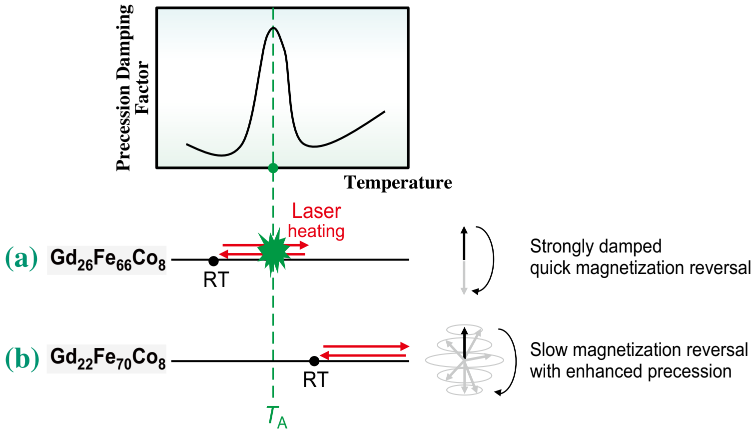

Fig. 1. Schematic of magnetization reversals induced by laser pulses of Gd–Fe–Co thin films. When the Gd content is 26% ($Gd_{26}Fe_{66}Co_8$, T_A>RT), smooth spin reversal with strong damping is expected. When the Gd content is 22% ($Gd_{22}Fe_{70}Co_8$, T_A<RT), the sample temperature does not intercept T_A and long-lasting spin precession is expected.

explained in Fig. 1(b). However, nonzero propagation momentum (*traveling* of the wavefronts) is likely produced by extrinsic factors such as lateral shifting of the precession phase due to a laser-induced radial heat gradient, considering (i) the large wavelength (on the order of 10 μm), which cannot be explained by intrinsic magnons generated in metallic systems, (ii) the limitation of the observed modulation to the irradiated spot, and (iii) the contraction and inward movement of the wavefronts toward the center of the spot (note that backward-volume magnetostatic waves are ruled out by the experimental geometry, which directs the magnetization perpendicular to the propagation direction of the waves). Nevertheless, we believe that the present observation provides a new point of view regarding how to generate spin waves. Considering that this phenomenon occurs as a consequence of a mixture of spin precession and heat excitation, experimental and theoretical searches for the possibility of spin-phonon coupling may also be worthwhile.

In fact, the Gd–Fe–Co system has previously been regarded as a good candidate capable of "ultrafast spin switching" (Fig. 1(a)), in other words, a "low" T_A condition (Fig. 1(b)) has been thought to be unfavorable for this purpose. In this study, however, we unexpectedly discovered a completely new functionality in Gd–Fe–Co ferrimagnets, *giant spin waves*, under this condition. Discoveries of highly pronounced novel phenomena sometimes accelerate the development of practical devices. For example, the giant magnetoresistance (GMR) effect was first reported as a tiny effect. Meanwhile, a phenomenon with the same mechanism was found by another research group at nearly the same time but the magnetoresistance ratio was approximately ten times larger than that observed by the other group [5]. The series of discoveries attracted much attention, leading to the development of GMR recording heads as well as the exponential improvement of recording density. We believe that the gigantic spin waves introduced here can serve as a trigger for the development of high-speed on-chip magnetic signal processing and control in spin-electronics applications.

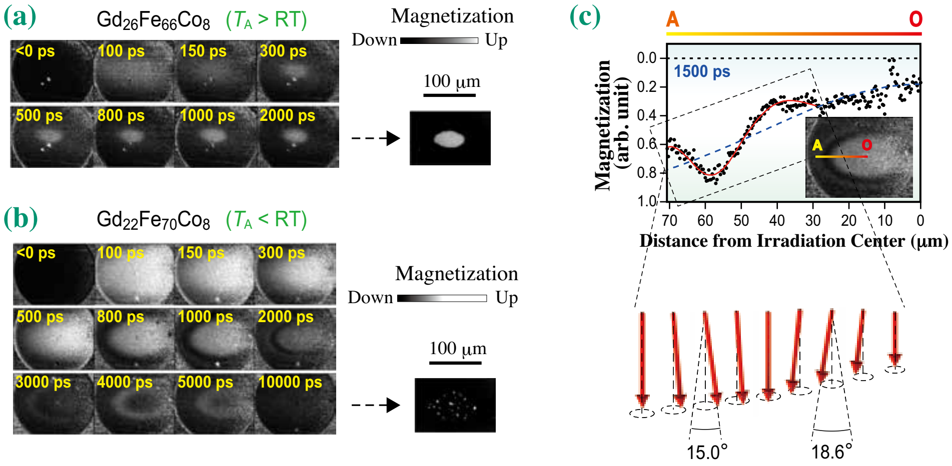

Fig. 2. Time-dependent magnetic images of the **(a)** $Gd_{26}Fe_{66}Co_8$ and **(b)** $Gd_{22}Fe_{70}Co_8$ samples. In the $Gd_{26}Fe_{66}Co_8$ sample, clear spin reversal is observed. However, in the $Gd_{22}Fe_{70}Co_8$ sample, wavelike magnetization modulation propagated isotropically along the radial direction. **(c)** Spin distribution of the $Gd_{22}Fe_{70}Co_8$ sample 1500 ps after the laser pulse duration. A line profile of the magnetization distribution (main graph), an XMCD-PEEM image snapshot (inset image), and the calculated distribution of spin directions (lower drawings) are shown. One can see propagating spin waves whose precession angle is in the range of 20° (±10°).

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References

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