Resonant antiferromagnetic spin wave excitation by terahertz magnetic near-field with split ring resonator

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Abstract: A spin wave of $HoFeO_3$ was excited by a terahertz magnetic near-field of a split ring resonator. The quantitative analysis shows that the spin wave was excited by the resonantly enhanced magnetic field.

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1. Introduction

Ultrafast control of spins in solids has attracted considerable attention from researchers because of its importance in fundamental physics and for technological applications such as spintronics and spin-based information processing. The direct, magnetic field–induced, ultrafast excitation and control of spin waves is most advantageous for these purposes. Recent terahertz (THz) pulse generation and detection techniques allow us to manipulate spins coherently and to elucidate spin dynamics [1]. Split ring resonator (SRR) enables us to achieve field enhancement and subwavelength field localization [2], which provide a good platform to study magnetic phenomena in condensed matter and also a route to developing electronically controlled hybrid spintronics and dynamic magnetooptic devices such as isolators. However, the coupling between magnetic excitation and SRR resonant mode has remained elusive because of complex magnetic field distribution in near-field regime. Here, we study the dynamics of antiferromagnetic spin waves in a $HoFeO_3$ crystal excited with THz electromagnetic pulses with SRR by near-field Faraday microscopy.

2. Experimental setup

Magnetization dynamics induced by the THz near-field of split ring resonators SRRs was studied using the time-resolved THz pump near-infrared (NIR) Faraday measurement setup shown in Fig. 1(a) and (b) [3]. As shown in the Fig. 1(a), a planar array of SRRs was fabricated on the surface of c-cut single crystal $HoFeO_3$. The incident THz electric field causes a current to flow circularly at the LC resonant frequency of the SRR, thereby inducing a magnetic near-field perpendicular to the surface (c-axis) [2]. Figures 1(c) and (d) show the spatial distribution of the magnetic field component H_z calculated from the THz electric field measured with an electro-optic sampling method and the THz magnetic field waveform in the time domain at the same position indicated by the circle in Fig. 1(c).

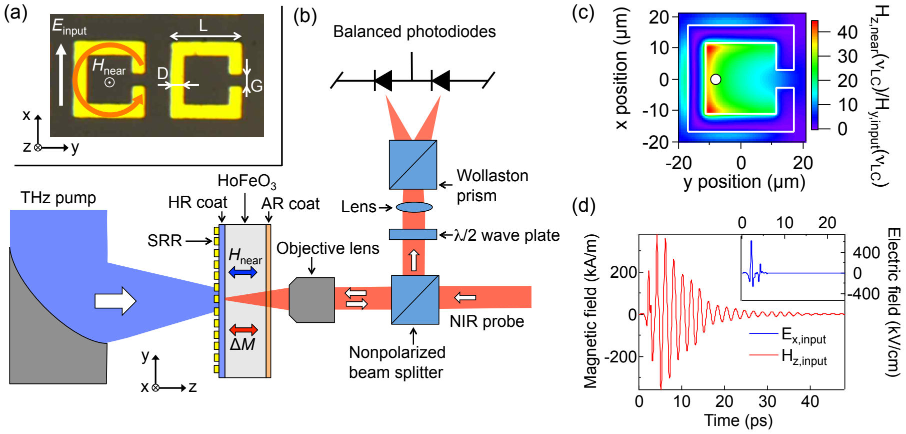

Fig.1. (a) The SRR fabricated on the ab-plane of $HoFeO_3$. (b) Schematic setup of THz pump-NIR Faraday rotation measurement. The experimental coordinate system is such that the x, y, and z axes are parallel to the crystal axes (a, b, c). The length of the ring L was 34 μm, the width D was 6 μm, and the split gap G was 6 μm. (b) Finite-difference time-domain method (FDTD) simulation of the magnetic field near the SRR. Two-dimensional distribution of z-directed magnetic field H_z at LC resonance frequency (ν_{LC}=0.5 THz) at the interface between the HR coat and $HoFeO_3$, plotted as the relative strength of the incident

magnetic field. The white dot indicates the probe position where the Faraday rotation is measured. (c) Temporal waveforms of the magnetic field component H_z (red line) calculated by using the THz electric field measured (blue line) by an electro-optic sampling method shown in the inset.

3. Results

$HoFeO_3$ is a typical weakferromagnet and well investigated on spin dynamics in THz frequency region. As shown in Fig. 2(a), the sample in the Γ_4 phase (T>58 K) has two iron sublattice magnetizations $\boldsymbol{m_i}$ ($\boldsymbol{i}$=1,2) which are almost antiferromagnetically aligned along the a-axis and slightly tilted toward the c-axis, giving rise to a spontaneous magnetization [4]. There are two spin-wave eigenmodes, called the anti-ferromagnetic-mode (AF-mode) and ferromagnetic-mode (F-mode). In our experimental setup, only the AF-mode can be excited by the THz magnetic near-field H_z, resulting in change of magnetization along the z-axis.

Figure 2(b) shows the temporal evolution of the Faraday rotation change induced by the generated THz magnetic near-field at several temperatures. The frequency of oscillation at each temperature is clearly assigned to that of the AF-mode [4]. To gain further insight into the spin motion and its driving force, we calculated the THz magnetic near-field induced magnetization dynamics and resultant polarization rotation of the probe pulse on the basis of the Landau-Lifshitz-Gilbert (LLG) equation [5]. We made numerical calculation with reported physical constants of $HoFeO_3$ and reproduced successfully the experimental results. One can see quite efficient build-up of AF-mode at 120 K, where the AF-mode is resonant with SRR mode, ν_{LC}=0.5 THz.

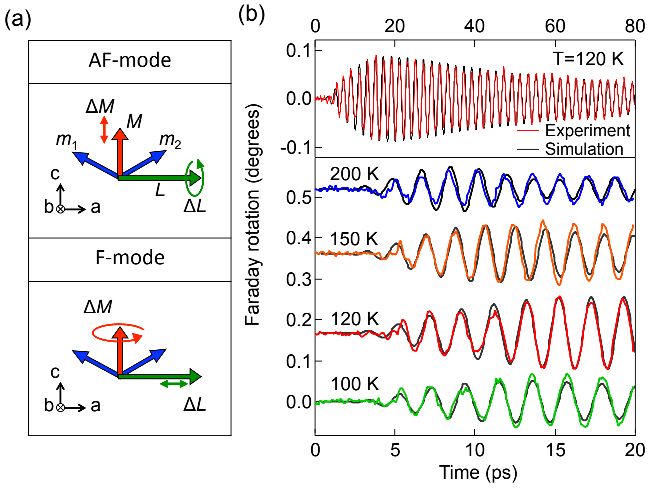

Fig.2. (a) Schematics of static configuration of Fe sublattice magnetization. Magnetization motions for two modes are shown using ferromagnetic vector $\boldsymbol{M}=\boldsymbol{m}_1+\boldsymbol{m}_2$ and antiferromagnetic vector $\boldsymbol{L}=\boldsymbol{m}_1-\boldsymbol{m}_2$. (b) Measured temporal change of Faraday rotation angle after THz pump pulse excitation measured and simulation results (black line).

4. Summary

We studied the excitation of antiferromagnetic spin waves in $HoFeO_3$ crystal coupled to a SRR by using THz pulses. The magnetic field in the vicinity of the SSR induced by the incident THz-electric-field component excites and the Faraday rotation of the polarization of a near-infrared probe pulse directly measures the oscillations that correspond to the antiferromagnetic spin resonance mode. The good agreement of the observed signals with Landau-Lifshitz-Gilbert equation based on the two-lattice model confirms that the THz magnetic near-field is resonantly enhanced by the SRR by 30 times in amplitude compared to that of the incident THz magnetic field.

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