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# Polarization control of emitted THz waves using spintronic emitters with anisotropic magnetic layers & birefringence characterization of Quartz

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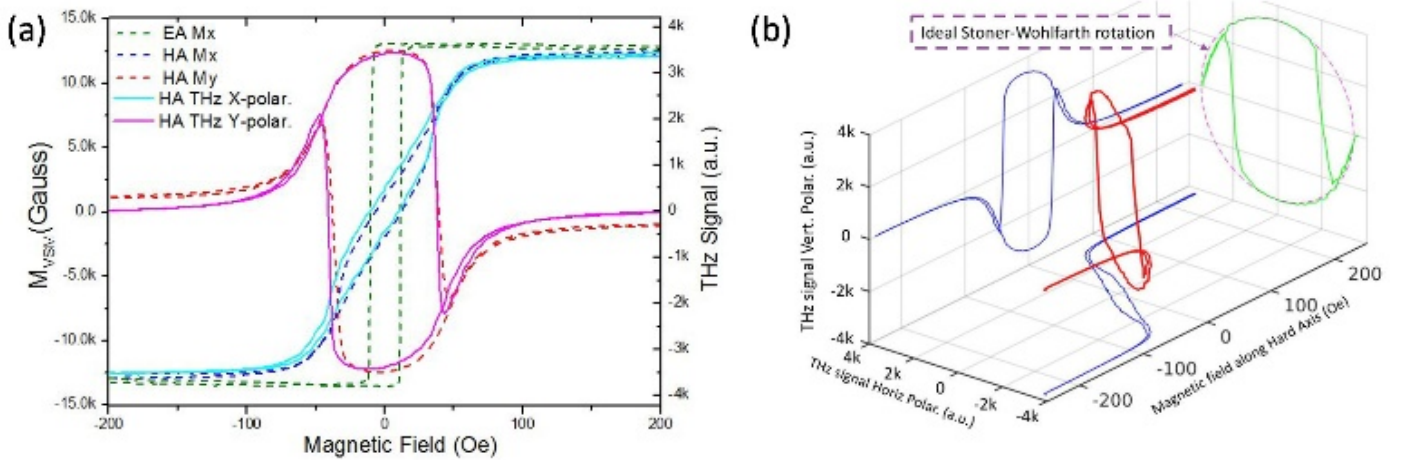
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**Abstract**—We demonstrate that spintronic TeraHertz emitters using uni-axial anisotropic FeCo/TbCo<sub>2</sub>/FeCo ferromagnetic layers allow the polarization control of the THz emitted wave thanks to the Stoner-Wohlfarth coherent rotation of magnetization when submitted to a magnetic field along hard axis. The determination of birefringence parameters of a quartz half-wave plate is described as an application example.

## I. INTRODUCTION

THE TeraHertz frequency band presents many potential applications in a wide variety of fields, from non-invasive control to spectroscopy. However, the current THz generation technologies based on semiconductors are limited in their applications due to the narrow THz bandwidth or gaps due to phonon absorption. Typical TDS spectra are cut-off maximally at 6THz. THz spintronic emitters, introduced by Kampfrath et al., offer a new approach to THz wave emission [1]. Exciting a 5d/3d non-magnetic (NM)/ferromagnetic (FM) multilayer by IR fs-pulses generates a spin-polarized current that upon diffusion in the NM metal undergoes strong spin-orbit coupling. The action of the inverse spin-Hall effect transforms the spin-current into a charge current dipole transversely oriented to the spin direction. The ultrafast relaxation times and absence of phonon absorption bands typical of metals allow the generation of THz pulses Fourier-limited by the IR pulse. The polarization state is intrinsically linked to the magnetization direction in the FM layer. Thus, the control of the THz polarization is possible with the rotation of magnetization. Up to now, it was done by rotating the applied magnetic field [2].



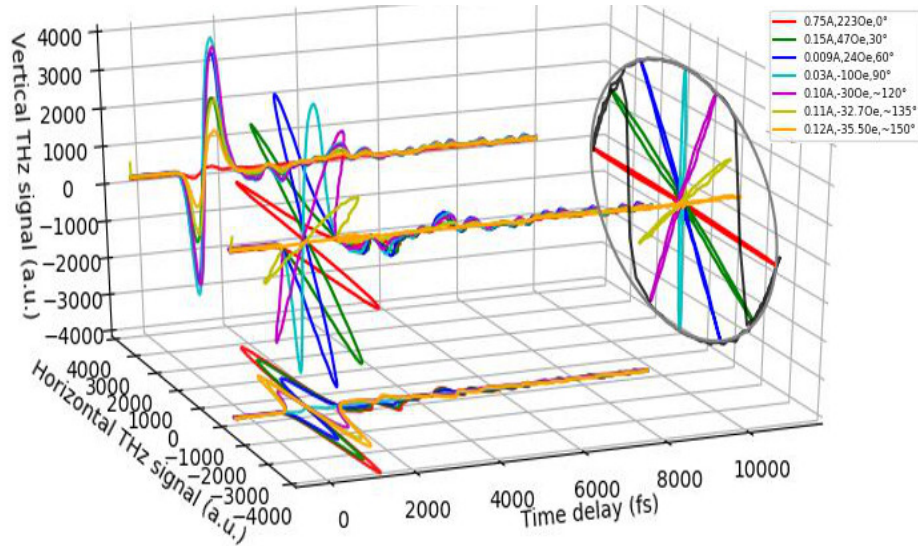
**Fig. 1** (a) Comparison between VSM measured magnetic loops (dashed lines) and THz-TDS measurement (full lines) on the maximal peak position. The hysteresis loop with the field applied along the easy axis for the longitudinal component (green) is also presented. (b) 3D representation of the longitudinal and transversal components of the THz emission vs. magnetic field.

## II. POLARIZATION CONTROL

The use of a ferromagnetic layer with uni-axial anisotropy allows to coherently rotate the magnetization by varying the applied field ONLY along the hard axis between its saturation values. We deposited a W(2nm)/ FeCo(0.5nm)/ TbCo<sub>2</sub>(0.8nm)/ FeCo(0.5nm)/ Pt(2nm) emitter stack on a c-cut Sapphire substrate by RF sputtering in a LEYBOLD Z550 equipment. During the growth, a magnetic field was applied in the plane of the substrate to induce the anisotropy. Thanks to the exchange coupling

between the layers, the result is a magnetically anisotropic and soft material with low saturation field around 100Oe. The spintronic emitter was then investigated under a normal incidence transmission configuration of a time domain spectroscopy (TDS) setup,

exposed by a 100fs infrared pulse with a central wavelength of 820nm and a repetition rate of 80MHz. The longitudinal and transverse component of the THz emission are measured by combining two linear polarizers placed between the emitter and a horizontal dipole photoconductive antenna; one polarizer set at 45°, to be able to detect vertical and horizontal polarization, and a rotating polarizer between 0 and 90° to select the horizontal or vertical components to be observed. By setting up the delay line of the TDS setup at the point of maximum THz emission, it was possible to measure it as a function of the applied field. Both THz components are shown on figure 1a (full lines) and are perfectly consistent with the VSM measurements. Fig. 1b shows the 3D representation of both THz components as well as the Stoner–Wohlfarth-like rotation of the magnetization (hence THz polarization). It is now possible to set a determined polarization angle simply by setting the magnetic field at the appropriate value. Figure 2 shows a 180° rotation of the polarization for specific values of the magnetic field (form positive to negative saturation). By varying the magnetic field along the magnetic hard axis direction, we demonstrate a full 360° rotation of the THz polarization.



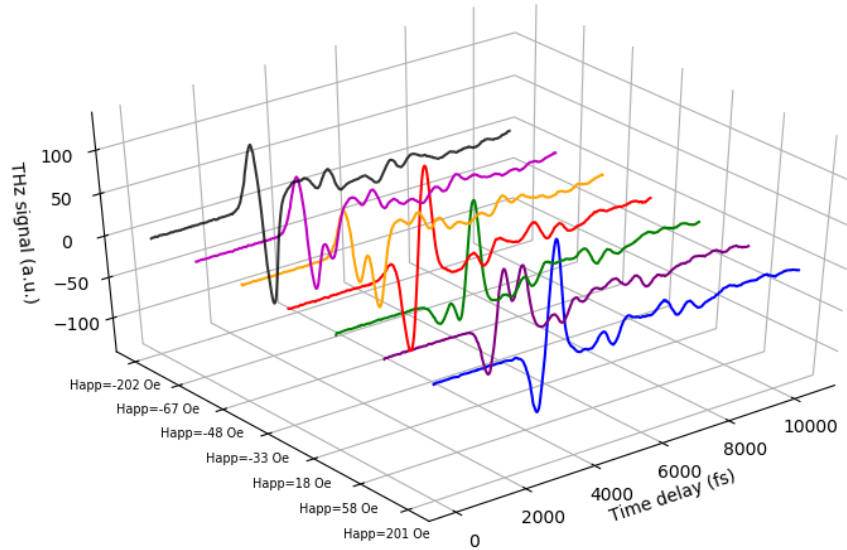
**Fig. 2.** 3D representation of THz-TDS scan under different magnetic fields to show the rotation of the polarization of the emitted radiation. The electric field remains constant during the operation, apart from an artifact around 300e caused by the anisotropic layers.

### III. APPLICATION TO BIREFRINGENCE CHARACTERIZATION

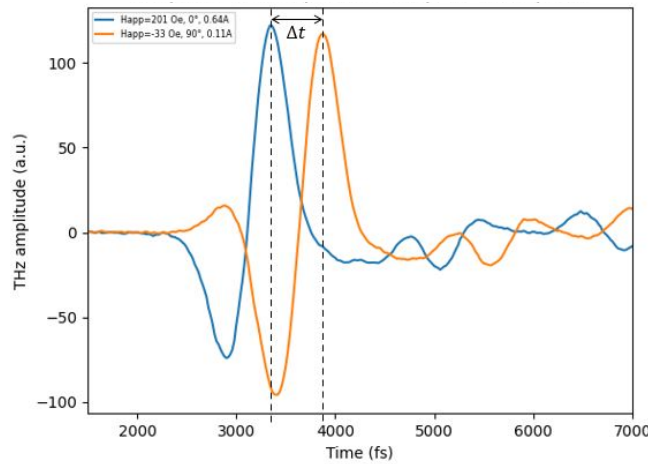
As an application of the coherent rotation control, we determined the birefringence properties of a quartz half-wave plate in the THz band. Quartz is a well-known optically anisotropic material that presents two light propagation axes, the ordinary and extraordinary axes. With the polarization control of our emitters, the difference of refractive index between the two axes can be easily evaluated in the THz range thanks to our Time Domain Spectroscopy setup. Few modifications on the previously used setup are made to experimentally study the quartz birefringence; the rotating polarizer is replaced by the quartz waveplate. It would no longer allow for both horizontal and vertical components to be observed, but the reconstructed sum of the THz “slow” and “fast” signals.

Figure 3 depicts the behavior of the emitted THz waves that propagates through a 3mm quartz half-wave plate with a 90° orientation of the ordinary axis with the horizontal plane. By varying the magnetic field from 201 Oe to -200 Oe, it is possible to observe the contribution of each axis of propagation, and the temporal shift resulting in the index difference in the crystal. The shape of the THz pulse is unaffected when the polarization is fully aligned with either ordinary or extraordinary axes. In our case that would be for a 0° (horizontal) and a 90° (vertical polarization. Figure 4 shows the temporal shift between the horizontal and vertical polarization. The temporal shift is determined by the temporal difference between the two positive maxima of the emission.

The temporal shift between the observed peaks gives the index difference:  $\Delta n = \Delta t \times \frac{c}{d}$ , with  $\Delta t$  the temporal shift,  $c$  the speed of light and  $d=3\text{mm}$  the thickness of the quartz crystal. With a  $\Delta t = 520\text{fs}$ , the resulting index difference obtained is  $\Delta n = 0.052$  between ordinary and extraordinary axis, which is consistent with values found in literature [3,4].



**Fig. 3.** Temporal traces of THz emission from a multilayer spintronic device with in-plane magnetic anisotropy. For different values of an externally applied magnetic field, the polarization of the THz pulse rotates, hence allowing to see the temporal shift caused by the birefringence of the quartz.



**Fig. 4.** Temporal traces of THz emission from a multilayer spintronic device with in-plane magnetic anisotropy. Temporal shift of the THz pulse for a horizontal (fast) and vertical (slow) polarization.

#### IV. SUMMARY

We present an improved scheme to achieve coherent polarization rotation without multipolar or rotating external magnetic bias nor complex cascaded emitters. This is achieved by exploiting recent progress in artificially engineered strong uniaxial anisotropy in intermetallic heterostructures of rare earth and transition metals. By replacing the FM layer of the spintronic emitter with a carefully designed FeCo/TbCo<sub>2</sub>/FeCo heterostructure, we experimentally demonstrated Stoner-Wolfarth-like coherent rotation of the THz polarization only by a unipolar variation of the strength of the hard axis magnetic field. These results improve greatly the feasibility of fast polarization switchable integrated THz sources impacting practical applications such as ultrabroadband THz spectroscopic ellipsometry without rotating elements, or polarization modulated high speed wireless data communications, but also fundamental physical studies into ultrafast terahertz optospintronics. This work also opens paths toward new THz high speed modulation schemes via the control of magnetization, but also new methods in interfacial magnetometry.

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