Emission of coherent THz magnons in an antiferromagnetic insulator triggered by ultrafast spin–phonon interactions

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Abstract—Antiferromagnetic (AFM) materials have been proposed for new types of narrowband THz spintronic devices owing to their ultrafast spin dynamics. Although manipulating coherently their spin dynamics remains a key challenge, this can be potentially accomplished by spin-orbit torques or direct optical excitations. Here, we demonstrate the combined generation of broadband THz (incoherent) magnons and narrowband (coherent) magnons at 1 THz in ultra-thin films of AFM – heavy metal (NiO/Pt). We show, experimentally and through modeling, two excitation processes of the spin dynamics in NiO, an off-resonant instantaneous optical spin torque in (111) oriented films and a strain-wave induced THz torque induced by ultrafast Pt excitation in (001) oriented films. Both phenomena lead to THz emission through the inverse spin Hall effect in the adjacent heavy metal layer, opening new routes towards the development of fast opto-spintronic devices based on AFM materials.

I. INTRODUCTION

ANTIFERROMAGNETIC (AFM) spintronics has recently become an important research field from both a fundamental viewpoint and its strong applicative potential [1,2]. Compared to ferromagnets (FM), AFMs have key advantages linked to their magnetic ordering: they are insensitive to perturbative external magnetic fields, stray fields are absent, and magnon modal frequencies reach very high frequencies – the terahertz (THz) regime [1–3]. This renders AFMs prime candidates for ultrafast spintronic devices compared to their FM counterparts.

An important spintronic application is spintronic-based broadband THz emission that currently relies on FM/heavy metal heterostructures [4,5] and harnesses spin-to-charge-current conversion through the inverse spin Hall effect (ISHE). In this regard, AFM materials with their characteristic THz resonant magnon modes have been predicted to enable the development of narrowband THz spintronic emitters, i.e., THz nano-oscillators, which can be driven by spin-orbit torques [6]. A recent work observed broadband THz emission in AFM thin films, triggered by an off-resonant optical torque [7]. However, the targeted narrowband emission of coherent THz magnons, which is highly desirable to fully functionalize spintronic THz emission, remains to be shown.

II. RESULTS

In this work [8], we report the combined generation of narrowband coherent THz emission centered at 1 THz and incoherent broadband THz magnons in thin NiO/Pt bilayers. For this purpose, we use femtosecond near-infrared laser pulses to either trigger direct and off-resonant light spin interactions in (111) oriented films, or phonon–spin interactions in (001)
oriented films through an ultrafast strain pulse that is generated upon heating of the metal layer (figure 1a). We demonstrate that their respective efficiencies in generating THz spin-currents depend on the orientation and thickness of the AFM films. We identify the processes via the anisotropic or isotropic dependence on the pump polarization and show that the THz emission process arises in both cases from the ultrafast ISHE.

Figure 1b shows the typical coherent emission of THz magnons from 10 nm thick NiO (001) thin films capped with 2 nm Pt layer, detected using THz-TDS spectroscopy. The generated THz signal from the bilayer has two main components as shown in the inset of Fig. 1b: i) a broadband contribution (up to 3 THz – cut-off frequency of the detector) alongside ii) a narrowband contribution centred at 1.1 THz (periodic oscillations of period around 1 ps). NiO possesses two magnon modes (i.e. precession of the Néel vector components \( \mathbf{n} = \mathbf{M}_1 - \mathbf{M}_2 \)): one low-frequency mode around 180 GHz and one high-frequency mode around 1.1 THz. The latter can be associated with the measured narrowband 1.1 THz contribution of the THz radiation from NiO/Pt bilayers. The THz signal originates from the spin-to-charge conversion of the magnonic current flowing from the NiO layer to the Pt layer via the ISHE. This is modelled through the strain induced THz torque, showing an excellent fit with the temporal experimental data. We show that this narrowband emission is absent in (111) films owing to the different spin interactions. We further evidence the different physics in (111) and (001) oriented films by measuring the decay times of the emitted THz spin currents, which vary by one order of magnitude between the direct light spin coupling (< 50 fs) and spin-phonon (> 300 fs) excitation processes.

III. SUMMARY

We show THz emission and two ultrafast mechanisms of magnonic excitations in the AFM NiO interfaced with a metallic Pt layer with largely different timescales. The THz emission appears via ultrafast off-resonant optical spin torque in (111)-oriented NiO samples, whilst it comes from spin-phonon interactions exciting the high frequency magnon branch of NiO for (001) orientation. We also demonstrate by angular crystallographic THz emission mapping that the magnon generation mechanism is directly linked to the Néel vector orientation of NiO. As well as showing the complexity of the the THz properties of AFM materials, this work opens routes towards AFM spintronic devices for the THz range.

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