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THz generation and frequency manipulation in AFM/HM interfaces

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Abstract. In this paper, we propose an approximate nonlinear theory of a spintronic terahertz-frequency oscillator based on antiferromagnet-heavy metal interfaces. We present a model of excitation of nonlinear oscillations of Neel vector in an antiferromagnet under the action of terahertz pulses of an electromagnetic field. We determine that, with increasing pumping pulse amplitude, the spin system response increases nonlinearly in the fundamental quasi-antiferromagnetic mode. Our results theoretically show that a spin-current flowing from a heavy metal due to the spin-Hall effect vary the frequencies of the output EM oscillations in a wide range, which could be detected by a standard pump-and-probe spectroscopy. Our study paves the way to laser-induced, electrically tunable, low-power, ultrafast AFM-based oscillator that operates without external magnetic fields at room temperature for telecommunication systems, bio-inspired networks and optical networks on chip. The nonlinear dynamics of the antiferromagnet-based emitters discussed here is of importance in terahertz-frequency spintronic technologies.

1. Introduction

Antiferromagnets (AFMs) have great potential to accelerate spintronics to the THz frequency range [1] using numerous intrinsic physical effects: they display ultrafast dynamics governed by exchange interaction, produce no stray fields, and are capable of generating large magneto-transport effects. In a pure spintronics scheme, usually high-frequency magnetic signals originate from the dynamics of spin-polarized electric currents in thin multilayered magnetic structures resulted in so-called spin-torque nano-oscillators (STNOs) and spin-Hall nano-oscillators (SHNOs) [2]. The key goal of spintronics is the demonstration of devices, allowing for information processing and storage up to the THz speed range. The latest advances in antiferromagnetic spintronics have made it possible to observe and control low-energy excitations on picosecond and femtosecond timescales [3]. As compared to ferromagnets, spin dynamics in



AFMs is governed by the exchange interaction, leading to much faster operations, up into the THz range of frequencies, enabling ultrafast information processing and communication [4]. Spin transfer torque (STT) and spin pumping are reciprocal processes, intrinsically connected and derivable from each other [5].

2. Motivation

Recently [6], it was reported that THz-frequency emission can be realized in nanosized structures composed of heavy metal (HM) and ferromagnetic (FM) thin films upon excitation by picoseconds and femtosecond laser pulses, where the ISHE plays the crucial role. The FM material in such experiments is magnetized by an applied magnetic field. One of the possible ways to develop magnetic-based THz emitters without applied magnetic fields is to use AFM materials with strong internal magnetic fields. The THz-driven nonlinear spin response of a thin AFM film was discovered in [7].

The theoretical investigations of AFM oscillators based on the concept of spin-Hall effect have been published in [8]. Earlier [9] was shown that radiation power of the single AFM-based SHNO increases with the increase of working frequency. In [10], coherent THz control of spin waves in an AFM/HM type structure was demonstrated, The result implies a possibility of ultra-high speed operation of AFMR spintronic devices. However, the output power of SHNO-based devices will still have to be improved.

In this work, we propose and theoretically analyze a THz-frequency SHNO based on the bilayer of canted AFM and HM. The article is organized as follows. First, we consider a physical structure of the AFM-based THz-frequency nonlinear emitter. Second, we present a model of excitation of nonlinear spin oscillations of Neel vector in an antiferromagnet under the action of terahertz pulses of an electromagnetic field. We demonstrate theoretically that a structure consisting of a HM layer with a strong spin-orbit interaction and a layer of an AFM dielectric can be a base of a tunable THz-frequency signal oscillator.

3. Method

Fig.1 schematically shows a bilayered AFM-based THz oscillator consisting of a NiO/Pt under photoexcitation. Applying THz pump pulse to the structure causes small displacement of magnetic moments from their equilibrium state. The displacement causes oscillated relaxation of the sample, in other words, magnetic moments return to their initial state through oscillations. A DC electric current passing through the Pt layer creates, via the spin-Hall effect, a perpendicularly polarized spin current flowing into the NiO layer. We consider the spin dynamics in an AFM under the action of THz pulses using the sigma-model widely used in the theory of antiferromagnetism [11]. For this purpose, using the Landau-Lifshitz-Gilbert (LLG) equations of motion for the magnetizations of sublattices M_1 and M_2 , one resorts to the dynamic variable $\mathbf{l} = (\mathbf{M}_1 - \mathbf{M}_2)/2M_s$, where M_s is the saturation magnetization. We perform parametrization of the Neel vector $l(t)$ through polar $\theta(t)$ and azimuth $\varphi(t)$ angles in the spherical coordinate system: $l_z = \cos(\theta)$ $l_x = \sin(\theta)\cos(\varphi)$ $l_y = \sin(\theta)\sin(\varphi)$. From the experimental data [12] it is known that the dynamics can be described only by the azimuth angle of inclination $\varphi(t)$ of the Neel vector. After some transformations the following differential

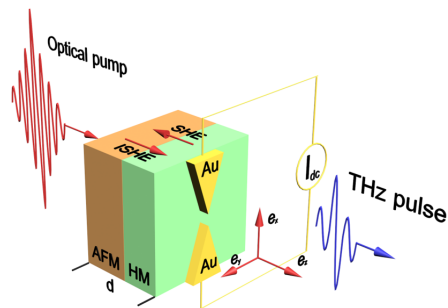


Figure 1. Proposed experimental geometry. Here NiO is supposed to be used as AFM, Pt as HM and Au as DC contacts.

equation can be obtained:

$$\frac{d^2\varphi}{dt^2} + \alpha\omega_{ex}\frac{d\varphi}{dt} + \frac{\omega_{AFMR}^2}{2}\sin(2\varphi) + \omega(t)\omega_D\cos(\varphi) = \omega_{ex}\sigma j + \frac{d\omega(t)}{dt}$$

(1)

Here α is the Hilbert damping constant in AFM, $\omega_{ex} = \gamma H_{ex}$ and H_{ex} is the exchange field between sublattices in AFM, γ is the gyromagnetic ratio, ω_{AFMR} is the resonant frequency of the quasi-ferromagnetic mode, $\omega_D = \gamma H_D$ and H_D is the Dzyaloshinsky-Moriya field in AFM, j is the spin polarization constant [13], σ is the constant electric current density through heavy metal layer and

$$\omega(t) = \gamma H_{peak} \exp\left[-\left(\frac{t-t_0}{\sigma_t}\right)\right] \cos(\Omega(t-t_0))$$

(2)

where t_0 is the delay time of the terahertz pumping envelope, σ_t is the pulse width for which when $t = t_0 + \sigma_t$ the envelope value $\omega(t)$ decreases by a factor of e , Ω is the pump frequency, and H_{peak} is the pulse amplitude at $t = t_0$.

Equation (1) is an equation of a nonlinear pendulum with a driving force and can be investigated using standard methods of the theory of oscillations and waves, for example, the envelope method.

To do that, we search for a solution $\varphi(t)$ in the form of a response at a frequency of forcing oscillations

$$\varphi(t) = \omega_{gen}t + \beta_0 + \beta_1 \sin(\omega_{gen}t)$$

(3)

where ω_{gen} is the oscillation frequency of the AFM under the action of current, β_0 is the constant to be determined, and $\beta_1(t)$ is a slowly varying function of time, which is found by substituting (3) into (1) and averaging the frequency of the forcing oscillations over a period. A detailed derivation of expressions for β_0 and $\beta_1(t)$ is given in [30].

4. Results

To obtain information about the system's dynamics equation (1) was solved in a range of current densities from $j = 0 \frac{A}{cm^2}$ to $j = 4.5 \cdot 10^9 \frac{A}{cm^2}$. During simulation the following parameter values were considered: $\alpha = 3.5 \cdot 10^{-3}$, $\omega_{ex} = 2\pi \cdot 27.4$ THz, $\omega_{AFMR} = 2\pi \cdot 1.1$ THz, $\omega_D = 2\pi \cdot 250$ GHz, $\sigma = 2\pi \cdot 4.32 \frac{Hz \cdot cm^2}{A}$, $H_{peak} = 0.4$ T, $t_0 = 0.1$ ps, $\sigma_t = 10$ fs, $\Omega = 400$ THz. All sample-dependent parameters are calculated taking in account the following sample configuration: NiO layer is 5 nm, Pt layer is 10 nm. Layer thicknesses

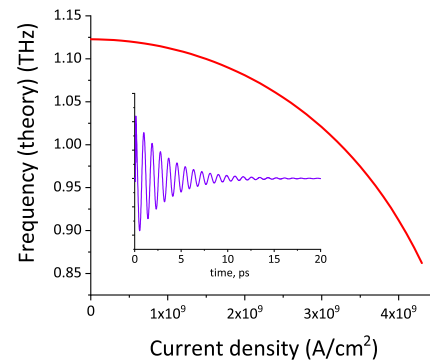


Figure 2. Oscillation frequency of equilibrium state as a function of applied DC density

mentioned above play a crucial role in THz pulse characteristics because they directly affect the efficiency of spin-pumping and signal damping effects [14, 15]. All physical parameters chosen for the modeling can be implemented in a pump-probe experiment.

The simulation showed that two kinds of motions are possible: damped oscillations with the AFMR frequency (equilibrium state) and stable oscillations caused by the action of current (Neel vector rotation). Both modes of oscillations depend on the magnitude of the direct current. However, for now, we only speak about equilibrium state AFMR mode evolution, because stable oscillation mode's dynamic is a subject of separate research. The example of evolution of the mode in time domain for current density $j = 0 \frac{A}{cm^2}$ is shown at the insert for Fig. 2. The dependence of oscillation frequency of equilibrium state mode on applied DC current is demonstrated at Fig. 2. By the shift of AFMR frequency oscillation and the presence of bistability, one can identify the effect of current on an antiferromagnet and find the critical current for oscillations.

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