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Power and Phase Profiles in Nano-constriction Based Synchronized Spin Hall Nano-oscillators near Threshold Current

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Spin Hall nano-oscillators (SHNOs) demonstrate self-sustained magnetization auto-oscillations, that have recently received much attention due to their potential for cutting-edge applications. In this work, the power and phase profiles, i.e., the complex quantized propagation dynamics of nano-constriction-based spin hall nano-oscillators (SHNOs) near the threshold current have been investigated. The SHNO generates a 12 GHz microwave frequency upon application of 2 mA direct current in presence of a 0.6 T external bias magnetic field. Power profile reveals that spin wave (SW) modes are quantized along x-axis. The phase profile reveals a complex nature of the SW modes at the dominant frequency (mostly localised at the nano-constriction region and additionally propagates from centre to the edges). Whereas SW mode of other frequencies mostly propagate towards the edge from the central nano-constriction region having a complex spiral nature. The SHNO devices, which are operational at high-frequencies, can be useful in energy-efficient tuneable microwave oscillators and neuromorphic computing.

***Index Terms*—Ferromagnetic (FM)/non-magnetic heavy metal (HM) bilayer heterostructures, Micromagnetic Simulation, Neuromorphic Computing, Spin-Orbit Coupling (SOC), Spin Hall Nano-Oscillator (SHNO), Spin wave (SW), Synchronization**

I. Introduction

MICROWAVE BASED technologies generating stable mutually synchronized oscillation of microwave frequencies [1] are of great interest in applications such as efficient radars, antennae, neuromorphic computing etc. Several high-end features, e.g., a relatively lower power consumption, strong signal amplitude, and good frequency stability with mutual synchronization, become the prerequisite of such advanced systems to perform necessary operations smoothly. However, conventional voltage controlled oscillators typically consume a large amount of power to perform such operations [2]. Recently, phonon-magnon coupling based MHz-GHz level microwave-generation/transmission in piezoelectric-magnetostrictive nano heterostructures have been investigated for antenna applications [1], [3], however, they are not suitable for spintronic-based neuromorphic computing [4], [5] due to the absence of spin currents.

On the contrary, mutually synchronized spin hall nano-oscillators (SHNOs) [4]–[6], usually driven by spin currents, are Spin-Orbit Torque (SOT) devices, which could be utilized as the source of tuneable microwaves for neuromorphic computing [4]. In ferromagnetic/non-magnetic heavy metal (HM) bilayer heterostructures, the pure spin currents are usually generated by the HMs with strong spin-orbit coupling (SOC) that flow perpendicularly to the in-plane currents due to the Spin Hall Effect (SHE), which give rise to a steady magnetization precession around the effective magnetic field.

Here, we investigate the power and phase profiles of a Permalloy (Py)/Platinum (Pt) bilayer based SHNO device near threshold current. Previously, SHNO devices have been studied experimentally and also through micromagnetic simulations [7], [8]. The fabrication of such SHNO devices is well established and the mutual synchronization property has also been demonstrated for potential applications such as neuromorphic computing [4], [5]. The power profile has been studied earlier at the threshold current. However, the power-phase relations are often less characterized near the threshold current, which is required to properly explain the prevalent spin wave (SW) oscillation mechanism.

II. Micromagnetic Simulation

Here, $1\ \mu m \times 1\ \mu m$ SHNO consisting of a bottom conducting non-magnetic Pt (6 nm) and a top magnetic Py (5 nm) layers, with a 100 nm nano-constriction patterned in the centre have been considered. The current distribution and the corresponding Oersted field are obtained by simulating the Pt layer in COMSOL® [9]. The Py layer is then simulated using MuMax^3 [10] by solving the Landau Lifshitz Gilbert Slonczewski (LLGS) equation. The SHE torque has been designed with the Slonczewski Spin Transfer Torque functionality in MuMax^3 by setting the Slonczewski Λ parameter $= 1$ (to eliminate the effect from spacer layer), the secondary spin-torque parameter, $\epsilon' = 0$ and equating the spin polarisation efficiency P with the spin hall angle θ_{SH}. The outputs obtained from COMSOL are used as input in MuMax^3, as explained elsewhere [1]. The Py block is discretised into $256 \times 256 \times 1$ cells, which corresponds to a cell size of $3.9 \times 3.9 \times 6\ nm^3$. Thus, the dynamics will remain constant along the thickness of the film. We have used the following material parameters: conductivity of platinum, $\sigma_{Pt} = 8.9 \times 10^6\ \mathrm{S/m}$, saturation magnetisation, $M_S = 8 \times 10^5\ \mathrm{A/m}$, exchange stiffness constant, $A_{ex} = 10 \times 10^{-12}\ \mathrm{J/m}$, exchange anisotropy constant,

K = 0, Gilbert damping, $\alpha = 0.02$ and spin hall angle $\theta_{SH} = 0.08$. The external magnetic field B was fixed throughout the simulations at a magnitude of 0.6 T, an in-plane angle of 24°, and an out-of-plane angle of 70°.

III. Results and Discussion

The magnetization component, M_Z, as a function of time has been shown in Fig. 1(a), M_Z represents the magnetization component normal to the plane. The oscillator remains in transient mode [7] upto 10 ns, hence, that has been discarded from analysis. The stable oscillation suffering from a small beating period has been shown in Fig. 1(b). Fast Fourier Transformation (FFT) of the oscillation, obtained with a hamming window, in Fig. 1(c) shows that the dominant peak (f_1) is at 12 GHz frequency. However, it has satellite peaks at higher frequencies, i.e., $f_2 = 24$ GHz and $f_3 = 36$ GHz frequencies, respectively. Lorentzian fitting of the dominant frequency, $f_1 = 12$ GHz (Fig. 1(d)) yields linewidth, $\Delta f = 0.13$ MHz.

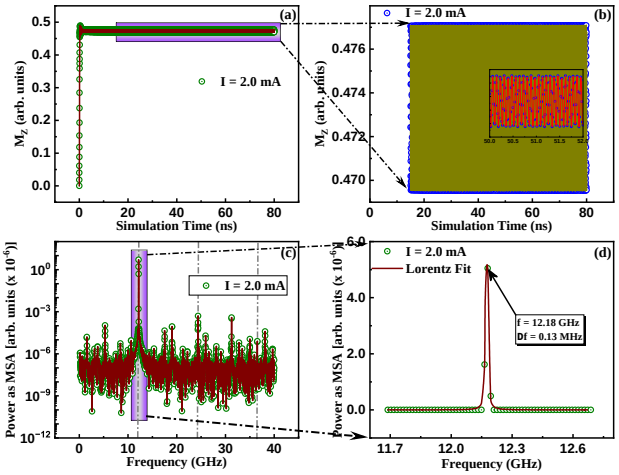


Fig. 1. (a) M_z component as a function of simulation time. (b) Magnified stable oscillation (M_z) after 15 ns transient. Inset: sinusoidal nature at 50−52 ns time span, (c) FFT Spectra in logarithmic scale of M_Z as in (b). Here, $f_1 = 12$ GHz, $f_2 = 24$ GHz, and $f_3 = 36$ GHz. (d) Lorentzian fitting of $f_1 = 12$ GHz yields the linewidth, $\Delta f = 0.13$ MHz.

The propagation modes, i.e., the power and phase profiles at f_1, f_2, f_3 are shown in Fig. 2(a)-(c) and (d)-(f), respectively. Power profiles in Fig. 2(a)-(c) reveal that SW modes at f_1, f_2, f_3 are quantized along x-axis with $n = 2, 5$ and 2, respectively. The phase profile [Fig. 2(d)] reveals a complex nature of the SW mode at dominant frequency, i.e., at f_1, it is mostly localised at the nano-constriction region (low intensity) and additionally propagates from centre (low intensity) to the edges (high intensity) of the oscillator (particularly along the diagonal). Whereas the SW modes of f_2 and f_3 [Fig. 2(e)-(f)] mostly propagate towards the edge from the nano-constriction region having a complex spiral nature in the central nano-constriction region, which also gets quantized after few orbits.

Figure 1(c)/(d) shows a dominant mutually synchronized peak, nevertheless the corresponding power spectra at Fig. 2(a) confirms that left/right half of the SHNO is not synchronized to each other. Therefore, the two halves in the array could serve as neurons, which interacts in a predominantly nearest neighbour fashion [4]. However, further analysis of the power-phase spectrum will be elucidated in the full paper.

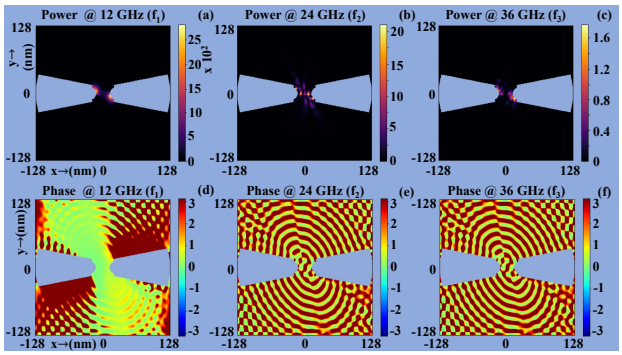


Fig. 2. (a)-(c) Power and (d)-(f) Phase profiles at 12 GHz, 24 GHz and 36 GHz, respectively, showing different complex quantised propagation modes.

IV. Conclusion

In summary, we have investigated nano-constriction based SHNO devices, demonstrated the mutual SW synchronization and obtained a high frequency 12 GHz microwave at 2 mA in presence of an external bias magnetic field of 0.6 T. Lorentzian fittings estimates the 0.13 MHz linewidth. Power and phase profiles show localised and complex quantized propagation modes at different frequencies. Such SHNO devices could be useful for neuromorphic computing.

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