# Frequency Domain Measurements of Arrays of Constriction-Based Spin-Hall Nano-Oscillators in Weak In-Plane Fields

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*Primary CNF Tools Used: JEOL 9500, MA6 contact aligner*

## Abstract:

**Spin-Hall nano-oscillators (SHNOs) convert D.C. charge current to microwave frequency magnetic oscillations — enabling applications as highly agile microwave sources. The use of SHNOs for applications is still limited by low output microwave power and large linewidth. Mutual synchronization of arrays of constriction-based SHNOs under out-of-plane magnetic fields close to 1 T [1] have been studied as a route to improve these characteristics. However, such high magnetic fields are impractical for device applications. Therefore, we study mutual synchronization in devices under in-plane magnetic fields of tens of mT. We fabricated arrays of four constriction-based SHNOs with different geometries, and performed frequency domain measurements under varied bias current and magnitude of magnetic field.**

## Summary of Research:

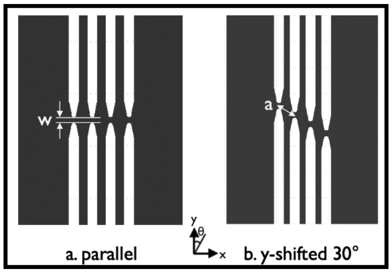


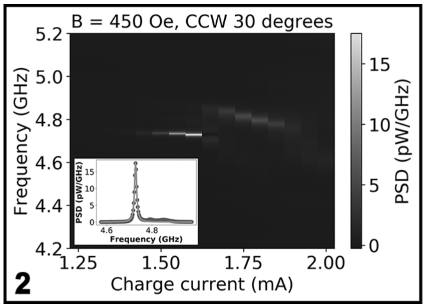
*Figure 1: Central areas of SHNOs studied: (a) in-line constrictions (b) constrictions with a lateral shift.*

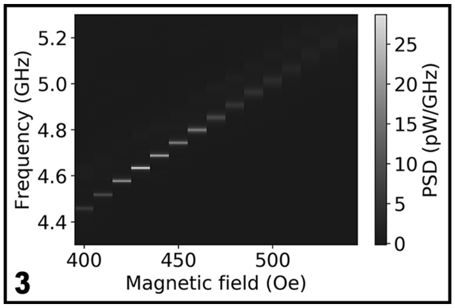
The spin Hall effect (SHE) is the generation of transverse spin currents by electric currents; in a non- magnetic material (NM), this leads to the accumulation of spins with opposite polarization at opposite edges of the NM [2,3]. By placing a nonmagnetic film on top of a ferromagnetic film, the spin current generated in the NM can diffuse into the ferromagnet (FM), providing spin transfer torque (STT) to the FM [2]. Under suitable conditions, the STT is able to compensate the damping of magnetic precession, leading to steady precession of magnetization [4]. With this principle, spin-Hall nano-oscillators (SHNOs) are developed as a bilayer system consisting of NM and FM, patterned as nanowires or nanoconstrictions.

In our study, we fabricated arrays of four $Ni_{81}Fe_{19}$ (5 nm)/$Au_{0.25}Pt_{0.75}$ (5 nm) constriction-based SHNOs on 20.5 µm × 4 µm wires, with different constriction width, separation and lateral shift. We used JEOL 9500 for the e-beam patterning of the SHNOs, and MA6 contact aligner and evaporator for depositing contact pads for electrical measurements. We measured the auto-oscillations of two devices. Each has a constriction width $w$ = 100 nm, constriction separation $a$ = 550 nm, however, one has in-line constrictions (Figure 1a), and the other with a lateral shift of the constrictions corresponding to a 30° angle (Figure 1b).

To measure the auto-oscillations, we apply a D.C. charge current to the device under a static in-plane magnetic field. Magnetic precession is induced in the FM ($Ni_{81}Fe_{19}$) due to SHE, leading to the oscillation of the FM layer's resistance due to anisotropic magnetoresistance. The oscillation signals are then measured using a spectrum analyzer with a pre-amplifier.

For the device with a lateral shift, we observed a single dominant peak over a range of currents at external





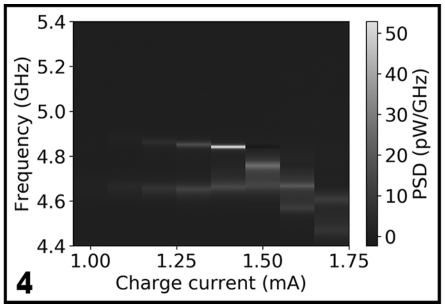


***Figure 2, left:*** *Power spectral density (PSD) of device with lateral shift under* H *= 450 Oe with* θ *= 30°. Inset: the peak profile at 1.6 mA (dots) with Lorentzian fit (line).* ***Figure 3, middle:*** *PSD of device with lateral shift under a magnetic field with* θ *= 30° and charge currents of 1.6 mA.* ***Figure 4, right:*** *PSD of device with in-line constrictions under* H *= 450 Oe with* θ *= 30°. (See pages vi-vii for full color versions.)*

magnetic field $H$ = 450 Oe applied $\theta$ = 30° with respect to the $y$ axis (Figure 2). The angle of magnetic field accounts for the directionality of the spin wave emission perpendicular to the magnetic field [5]. By fitting the peak with a Lorentzian (Figure 2 inset), we extrapolate the linewidth of the optimal peak to be 10.8 MHz and the total power to be 0.2 pW, which is comparable to a prior report [6] in devices with similar resistance. We also observe a jump in the oscillation frequency, which is possibly due to the switching of dynamic modes [7]. At 1.6 mA bias current, the auto-oscillation frequency increases linearly with $H$; only one dominant peak occurs (Figure 3), suggesting that there may be some synchronization [1]. However, to verify whether the SHNOs are actually mutually synchronized, a study of the phase difference between them is required.

We also measured the auto-oscillation on the device with in-line constrictions under the same external magnetic field (Figure 4). In this case, two modes are observed at the same bias current, suggesting that the SHNOs are not synchronized.

## Conclusions and Future Steps:

We performed frequency domain measurements on two of the fabricated devices, however, we have not yet experimentally confirmed mutual synchronization. Future studies using optical imaging techniques may reveal the phase information of the individual SHNOs. We also plan to study devices with smaller separation between constrictions, which we expect to synchronize robustly.

## References:

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