Recent advances in nano-contact spin torque oscillators

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We present a comprehensive review of the most recent advances in nano-contact spin torque oscillators (NC-STOs). NC-STOs are highly tunable, with both applied magnetic field and dc current, broadband microwave signal generators. As opposed to the nano-pillar geometry, where the lateral cross section of the entire device has been confined to a typically <100 nm diameter, in NC-STOs it is only the current injection site that has been laterally confined on top of an extended magnetic film stack. Three distinct material combinations will be discussed: (i) a Co/Cu/NiFe pseudo spin valve (PSV) where both the Co and NiFe have a dominant in-plane anisotropy, (ii) a Co/Cu/[Co/Ni]$_4$ orthogonal-PSV where the Co/Ni multilayer has a strong perpendicular anisotropy, and (iii) a single NiFe layer with asymmetric non-magnetic Cu leads. We explore the rich and diverse magnetodynamic modes that can be generated in these three distinct sample geometries.

***Index Terms*— Magnetodynamics, Spin torque oscillator, Spin transfer torque, Spin waves**

I. Introduction

NANO-CONTACT SPIN TORQUE OSCILLATORS (NC-STOs) are broadband microwave signal generators where a dc current enters an extended ferromagnetic layer through a constriction [1] with dimensions on the order of 100 nm and generates a microwave response via the spin transfer torque (STT) [2-4] effect. Typically, the magnetically active portion of the extended layer consists of a ferromagnet/spacer/ferromagnet (FM/S/FM) trilayer pseudo spin valve (PSV) structure. One of the FM layers is considered "free" and easily susceptible to the influence of STT. For this reason it is advantageous for the free layer to be relatively thin and have a low intrinsic Gilbert damping; a typical material choice for the free layer is Permalloy ($Ni_{81}Fe_{19}$, and simply referred to as NiFe). In contrast the other FM layer is considered "fixed", either by pinning to an adjacent magnetic layer, an intrinsically high anisotropy, or simply by virtue of being thicker. The primary role of the fixed layer is to spin polarize the initially unpolarized electron current. STT can either increase or decrease the local damping depending on its sign and the local magnetic configuration. When the negative damping induced by the STT is balanced by the additional non-linear positive damping present, steady state, high amplitude spin wave (SW) excitations can be indefinitely sustained, which forms the basis of a STO [5-8]. Owing to their strongly nonlinear magnetodynamics and variety of SW modes, STOs are not only of fundamental interest but also offer many potential applications. In particular STOs offer the opportunity to achieve nanoscale wideband frequency-tunable [9, 10] and rapidly modulated [11-19] microwave oscillators for telecommunication, vehicle radar, and microwave spectroscopy applications [20, 21]. Additionally, unlike in nano-pillar [22] STOs, the induced magnetodynamics are not bounded by the physical dimensions of the device allowing for potentially unfettered SW propagation, and are therefore potentially useful in magnonics [23-25] applications.

This paper is organized as follows. In Section II the fabrication of NC-STOs, from film deposition through to nanolithography, will be discussed. The following three sections are then devoted each to a particular magnetic film stack. Section III is devoted to STOs based on PSVs where the constituent magnetic layers have in-plane anisotropy. Section IV discusses an orthogonal-PSV structure with a [Co/Ni]$_4$ free layer that exhibits a strong perpendicular magnetic anisotropy (PMA). Section V then focuses on a STO with a single NiFe layer with asymmetrical Cu leads. Finally, Section VI concludes the manuscript and discusses several open questions and the prospects for the future.

II. Fabrication

The first step in device fabrication lies in the creation of a spin valve mesa, typically 8 μm x 16 μm in lateral dimension, Fig. 1(a), and defined either by standard liftoff or etching techniques. The initial layer stack in each mesa is deposited by magnetron sputtering in a chamber with a base pressure better than 5×10^{-8} Torr. Three distinct material stacks will be discussed, as schematically shown in Fig. 1(b, i-iii). The in-plane film stack, Fig. 1(b, i) is based on a PSV structure composed of a Co(8 nm)/Cu(8 nm)/NiFe(4.5 nm) trilayer structure where the Co and NiFe play the role of the aforementioned fixed and free layers, respectively. Note the thick Cu bottom layer is used to promote a more vertical electron transport through the trilayer structure and reduce unwanted lateral current spreading [26, 27]. The orthogonal-PSV structure is shown in Fig. 1(b, ii) and utilizes a [Co/Ni]$_4$ multilayer (ML) with strong PMA as a free layer separated from a Co(6 nm) fixed layer by a 6 nm thick Cu spacer. An additional (111)-textured Ta(4 nm)/Cu(10 nm)/Ta(4 nm) seed layer is used to both promote PMA in the Co/Ni multilayer as well as minimize lateral current spreading. Great care must be taken to fully optimize the Co/Ni ML stack, e.g. number of ML repeats, individual layer thicknesses, deposition rate and pressure [28]. Finally, the only magnetic component to the single layer stack, Fig. 1(b, iii), is based on a standalone NiFe (7 nm) film surrounded by Cu layers of different thicknesses. The film stacks are capped with either Cu(2 nm)/Pd(2 nm) or Pd(2 nm) to prevent oxidation. The topmost SiO_2(30 nm) layer acts as an insulation layer for the subsequent NC electrode fabrication.

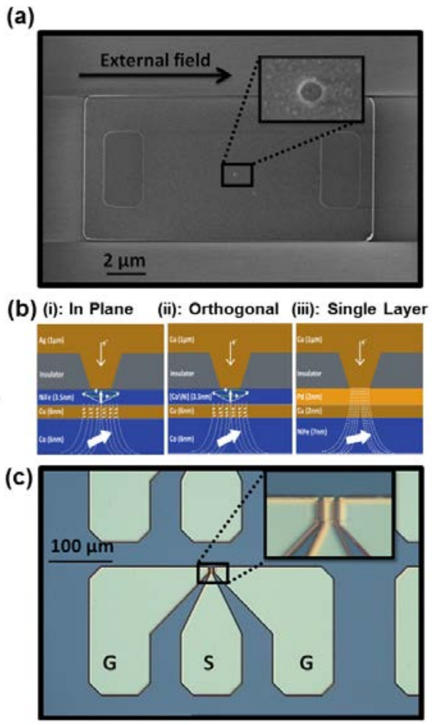

Fig. 1. (a) Scanning electron microscopy image of a patterned mesa and a 100 nm diameter NC. (b) Side view schematic of the (i) in-plane PSV, (ii) orthogonal-PSV, and (iii) single layer material stacks. (c) Optical microscopy image of the coplanar ground-signal-ground (G-S-G) waveguide used to provide low-loss electrical contact to the mesa, shown in the inset.

The NC itself has been most commonly defined by electron beam lithography (EBL) as this allows for the most precise control of the NC geometry. However, very recently a new technique based on hole-mask colloidal lithography (HCL) has proven to be a simple and cost effective bottom-up method to realize both single NCs and mutually synchronized NC arrays [29]. After the definition of the NC a Cu(1.1 µm)/Au(100 nm) top contact is formed into a coplanar waveguide structure, Fig. 1(c), using standard optical lithography and lift-off processes.

Measurements are then performed in a custom probe station allowing for characterization under variable current and magnetic (angle and magnitude) fields. The induced magnetodynamics result in a time varying voltage across the devices via the giant magnetoresistance (GMR) or anisotropic magnetoresistance (AMR) effects in the PSV and single layer devices, respectively. This voltage is then amplified using low noise broadband microwave amplifiers and analyzed in the frequency domain using a spectrum analyzer or time domain using an oscilloscope.

III. In-plane Spin Valve NC-STOs

Both the earliest experiments [1] utilizing point contacts and the first experiments [10, 30] on true NC-STOs were performed on material stacks where the constituent FM layers exhibited a dominant in-plane shape anisotropy. As we discuss below, this particular magnetic configuration yields a very strong angular dependence of the generated SW modes.

A. Fundamental spin wave modes

Slonczewski [8] predicted exchange dominated propagating SWs with a wave vector inversely proportional to the NC radius when the free layer is magnetized perpendicularly to the film plane. The propagating character of these SWs was experimentally proven by Brillouin light scattering experiments [24]. Conversely, when the free layer is magnetized in-plane a strongly non-linear, self-localized solitonic "bullet" mode can also be established [30-36]. For intermediate oblique angles the behavior becomes much more complicated and both simulations [32] and experiments [36] provided evidence of mode hopping [31, 32, 36-39] between the propagating and localized bullet modes.

B. Role of the Oersted field

The role of the current induced Oersted field had been often ignored in prior studies of NC-STOs. However, as will be discussed below, it plays a critical role in the character of the generated SWs and can promote true mode-coexistence [40]. As an example, for a NC diameter of 70 nm at a typical drive current of 18 mA the Oersted field at the edge of the NC is calculated to be approximately 0.1 T. Given the typical externally applied fields in such experiments are ~1.0 T, the Oersted field should not be considered an insignificant contribution.

The angular dependence of the generated SW mode frequencies is shown in Fig. 2(a). For $\theta > 60^{\circ}$ only one frequency, significantly above the ferromagnetic resonance (FMR) frequency of the extended NiFe film, is found in the spectrum, corresponding to the propagating SW mode. However, for $\theta < 60^{\circ}$ a second, much weaker, signal begins to appear and lies well below the FMR frequency. This low frequency mode corresponds to the solitonic bullet mode which is stable only for angles less than the critical angle [41], namely 60º for these experimental conditions. Interestingly, a very broad, signal ($f < 3$ GHz) accompanies the critical angle and is associated with the much slower mode-hopping dynamics that are dominant for this range of angles. For $\theta < 45^{\circ}$ this low frequency mode hopping feature disappears, signaling the beginning of mode-coexistence. It is especially interesting to note that the angle at which the low frequency mode-hopping frequency disappears coincides with the angle at which the propagating mode frequency becomes less than the FMR frequency and therefore becomes localized. This localization of both modes at low angles is one of the key factors promoting mode-coexistence.

The Oersted field plays an important role in the spatial characteristics of the modes. For externally applied field angles not exactly at 90º the cylindrically symmetric Oersted field locally modifies the FMR frequency in the vicinity of the NC, Fig. 2(b). Towards the bottom half of the NC the net (Oersted plus external) fields are higher and therefore the FMR frequency can be larger than the propagating SWs, which then act as a fence, or a corral [42], blocking propagation towards the lower half-plane, Fig. 2(b).

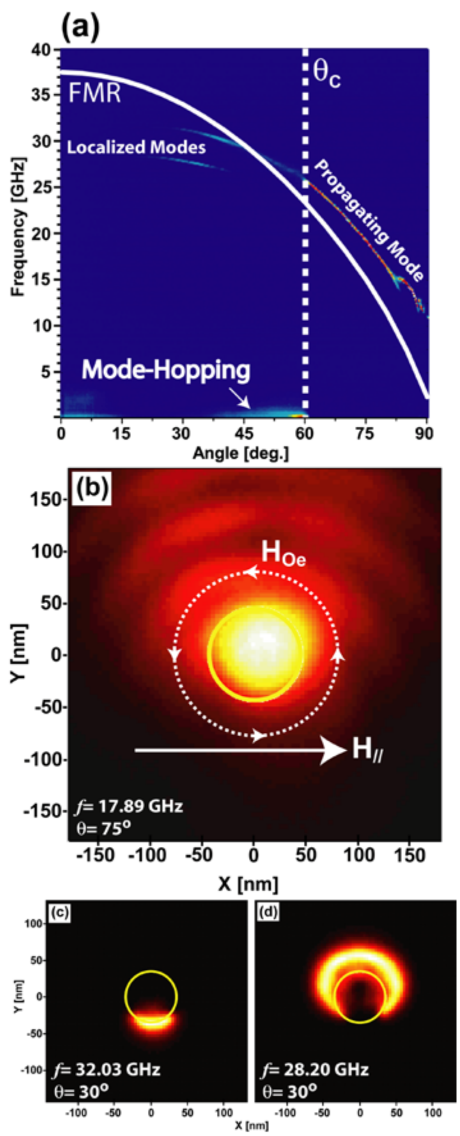

Fig. 2. Experimentally measured frequency response of an in-plane PSV STO with a NC diameter of 90 nm as a function of the applied field angle. The simulated spatial profiles of the (b) propagating mode (applied field angle of 75º), and (c, d) localized modes (applied field angle of 30º) highlight the critical role played by the Oersted field.

Another key factor is the physical separation [43] of the modes at reduced field angles on opposite sides of the NC. This physical mode separation is a direct consequence of the current induced Oersted field in the vicinity of the NC, as shown using simulations in Fig. 2(c, d). The power of the localized bullet mode is primarily located to an arc around the upper half of the NC diameter, whereas the now localized propagating mode is centered at a point where the in-plane component of the external field, $H_{//}$, and Oersted field produce a local field maximum at the bottom of the NC. In simulations that neglect the Oersted field no such mode separation occurs.

C. Synchronization

One of the significant drawbacks that limits the potential applicability of STOs is their low signal-to-noise ratio (SNR), stemming from their intrinsically low output power and high phase noise. One potential solution to this issue is to synchronize, or phase–lock, several oscillators. Synchronization is relatively easily achieved in NC-STOs [44, 45] as the individual oscillators all share a common free layer allowing for spin wave mediated [46-48] phase-locking. Since the first observation of synchronization STOs in 2005 the record number of NCs to be synchronized has been two high frequency NC-STOs [15, 44, 45] and four low-frequency vortex-STOs [49]. However, very recently mutual synchronization of three high-frequency NC-STOs and pair-wise synchronization in four and five NCs has been observed in devices fabricated using the aforementioned HCL technique [29].

D. Modulation of the propagating mode

Modulation can be achieved when an additional radio/microwave frequency current (or field) is applied to the STO. High modulation speed is a prerequisite for high speed data transmission using STOs, for example in potential hard disk drive read head applications [50, 51]. The first experimental observation of frequency modulation of a STO was reported in 2005 for a single modulation frequency of 40 MHz [17]. Recently a more thorough analysis provided the first experimental evidence [12] of amplitude modulation. It also showed excellent quantitative agreement with a non-linear frequency and amplitude modulation (NFAM) theory [11] as well as modulation up to 3.2 GHz [13, 14, 52]. It has also been shown that modulation has a general averaging effect on the non-linearity of the STO signal where modulation over regions of high frequency non-linearity results in a significant reduction (up to 90%) of the signal linewidth [16]. Fig. 3(a) shows an example of modulation with a frequency of f_W=500 MHz, clearly showing a decrease in the linewidth, Δf. as the modulation strength increases. Additionally, by performing modulation using two simultaneous signals [19] it is possible to further improve the linewidth and significantly improve the usable operating frequency bandwidth for communications applications. For example in Fig. 3(b, c) such a method is implemented with a narrow modulation frequency of f_N=40 MHz and a wide modulation of f_W=500 MHz. Clearly when the wide modulation signal is applied, Fig. 3(c), the modulation sidebands due to f_N become significantly sharper.

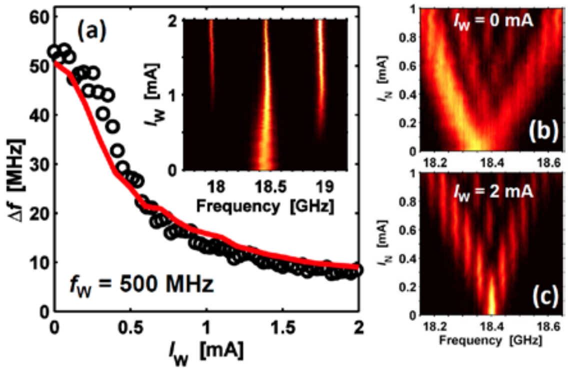

Fig 3. (a) Decrease of Δf as a function of modulation current, I_W. (b) and (c) highlight a double modulation experiment with f_N=40 MHz and f_W=500 MHz with modulation currents of I_W= 0 mA and 2 mA, respectively.

In order to ensure the possibility to use synchronized STOs in future communication and information applications it is important to demonstrate that the signal from several synchronized STOs can be modulated without deterioration of the synchronized state. Experimental studies on a pair of NC-STOs showed that the synchronized state can be well modulated and remains stable even under strong modulation [15]. The overall behavior of the modulation sidebands in the synchronized state can be quantitatively described by the aforementioned NFAM theory[11], assuming that the synchronized pair behaves as a single oscillator.

E. Temperature dependence

Temperature dependent studies on NC-STOs are limited. The work by Schneider *et al.* [53] distinctly showed two different behaviors of temperature dependent linewidth. At high temperatures, in the absence of observable low-frequency noise, the linewidth is found to decrease roughly linearly with temperature. However, extrapolation of the quasi-linear response to zero temperature can yield either a positive or negative value and when 1/f noise is present in the device the linewidth is found to vary quasi-exponentially, both of which are in direct disagreement with the predictions of single mode oscillator theory [7, 54, 55]. Recent studies [56] also show a disagreement with single mode oscillator theory of STOs, showing a highly non-linear increase or decrease of the linewidth depending on the exact experimental conditions. Systematic investigations reveal that this anomalous behavior strongly depends on the operating current, especially in regards to the proximity of mode transitions present in the sample. Here, the temperature dependence was attributed to the presence of multiple modes and mode coupling that enhances the non-linear amplification behavior, which carries its own additional temperature dependence, in standard single mode theory.

IV. Orthogonal spin valve NC-STOs

Dramatic changes in the magnetodynamical processes are found when the free layer is changed to a Co/Ni ML with PMA. In what follows the external field angle is fixed to be perpendicular to the film plane and the response in low, moderate, and high fields will be presented.

A. Low-field operation

The measured microwave response of an orthogonal NC-STO with a NC diameter of 105 nm in a perpendicularly applied field of 0.2 T is shown in Fig. 4(a). The observed behavior is consistent with a small precession FMR-like mode [57]. As the current increases there is a gradual increase (decrease) in mode power (frequency), consistent with an increasing precession angle at larger drive currents.

B. Moderate field operation – droplet nucleation

In a moderate field of 0.8 T, Fig. 4(b), the oscillator behavior changes dramatically. As similarly shown in low fields the FMR-like mode is present at small drive currents. However, at a critical current of approximately -12.4 mA there is a dramatic drop in frequency and increase in oscillator power, both of which are consistent with the formation of a magnetic droplet soliton [58].

The theoretical basis for a droplet soliton was initiated in the late 1970's in the analytical work of Ivanov and Kosevich [59, 60] which showed that the Landau-Lifshitz equation can sustain a family of conservative magnon drop solitons provided there is no SW damping. In short, magnons in materials with PMA were found to attract each other, forming a condensate (magnon drop) at a critical density of magnons, which is then stabilized by a balance between the anisotropy and the exchange energy. While ordinarily the condition of zero SW damping is not realistic, especially in metal based magnets, it was recently shown by Hoefer, Keller and Silva [61, 62] that the balance between STT and damping underneath a NC could provide the needed zero net damping necessary to locally emulate a zero damping material. Their analytical and numerical results showed that magnon-drop-like excitations were indeed possible. However, in contrast to the aforementioned magnon drops, these excitations were strongly dissipative as they not only relied on a balance between the exchange and anisotropy energy contributions, but also on a far from equilibrium balance between the STT and the non-linear damping, singling out a specific magnetic droplet with a well-defined frequency.

The inset of Fig. 4(b) shows a frequency spectrum at the critical current density of -12.4 mA. Clearly both a high and low frequency signal is seen in the frequency domain indicating that the transition to the droplet mode is not perfectly sharp and mode-hopping between the FMR-like and droplet modes is likely taking place [63].

C. High-field operation – droplet collapse

The field dependence of the MR of an orthogonal NC-STO with a NC diameter of 80 nm is shown in Fig. 4(c) for two drive currents, both below (I=-8 mA) and above (I=-10 mA) the current necessary to nucleation a droplet. For a drive current of -8 mA (black squares) the MR shows a simple monotonic decrease as the magnetization of the fixed Co layer is slowly pulled out of plane, therefore becoming more parallel to the Co/Ni ML free layer. However, at a drive

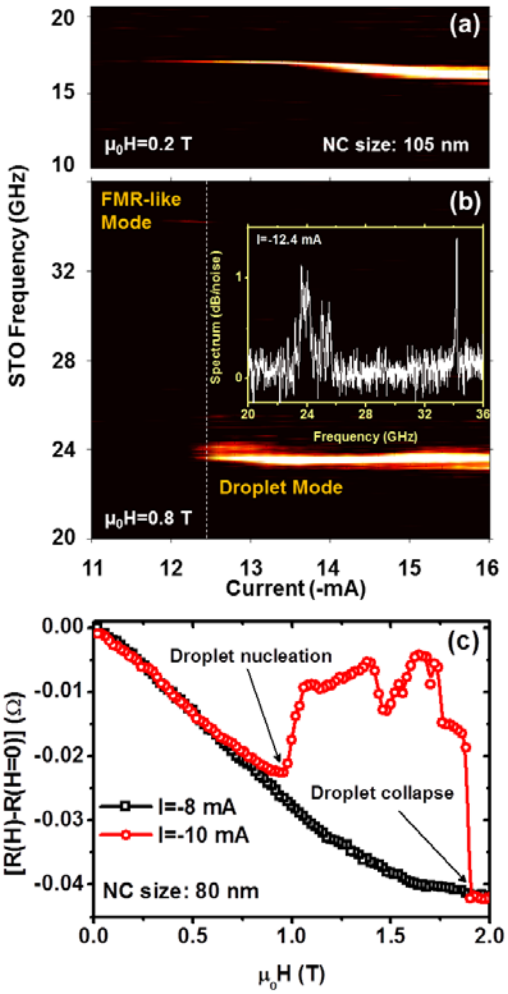

Fig 4. The frequency response of an orthogonal-PSV with a NC diameter of 105 nm in perpendicularly applied fields of (a) 0.2 T and (b) 0.8 T is shown as a function of drive current. At low fields (a) only the FMR-like mode is found while droplet nucleation can occur at higher fields (b) at a critical current of approximately -12.4 mA. The MR of a device with a NC diameter of 80 nm is shown in (c) as a function of applied field at I_{dc}=-8 mA (black squares) and I_{dc}=-10 mA (red circles). For I_{dc}=-10 mA both droplet nucleation and subsequent collapse is found as the applied field is increased.

current of -10 mA (red circles) a different MR profile is found. At a field of approximately 1.0 T there is a sharp increase in the MR indicating a portion of the free layer magnetization has reversed, increasing the relative angle between the fixed and free layers, providing a clear signature of droplet nucleation. Such out-of-plane fields are necessary for droplet formation as a sufficient perpendicular component of the spin polarized current density is needed, and can only occur if the fixed layer magnetization is pulled out-of-plane by this perpendicular field. Just after the droplet nucleation the sign of the MR signal has now changed as the relative orientation of the fixed and free magnetizations now becomes progressively more anti-parallel as the field is increased. Finally, for very large fields the role of the Zeeman energy begins to dominate. A droplet, with its highly reversed core, comes at the expense of Zeeman energy which increases linearly with applied field. Once the fixed layer becomes more or less saturated out-of-plane the Zeeman energy will dominate and the droplet will collapse. A signature of the droplet collapse can be seen as the rapid drop in MR at an applied field of approximately 1.8 T as the relative orientation of the fixed and free layer magnetizations returns to a nearly parallel configuration.

V. Single-layer NC-STOs

A. *Theory behind STT in single layers*

To this point all of the NC-STO samples discussed in this paper were based on utilizing a PSV stack where the fixed layer not only provides the necessary spin polarization, but also provides a stationary reference magnetization for the GMR effect. Experiments on nano-pillars with a single Co layer showed through resistive measurements that STT could still be generated and both produce SW excitations [64] in, and switch [65], the Co magnetization. The key to generating STT in single layer devices is the presence of asymmetric interfaces on either side of the FM layer. Theory [66, 67] predicts that spin filtering by the single FM layer generates a sizeable spin accumulation at each interface. Only when these interfaces are asymmetric will an imbalance of spin accumulation, and therefore STT, be present. Similarly to GMR based PSV devices, only one current polarity will result in negative damping necessary for steady state oscillations.

B. *Results*

The frequency response of a single layer STO is shown in Fig. 5. The threshold current for signal generation is found to be strongly hysteretic in that a large negative onset current must first be applied before oscillations begin. As the applied current is then increased back towards zero the oscillations persist up to a cutoff current of approximately -12 mA. The observed response exhibits a large number of harmonics and the frequency response increases highly linearly with current. While the output power is much lower than standard PSV-GMR based STOs, as the generated voltages are due to the much smaller AMR effect in the single NiFe layer, the linewidth is of the same order. At a first glance the observed behavior is consistent with the gyrotropic motion of a vortex underneath or around the NC. However, the observed frequency range (nearly up to 4 GHz) is much wider than that typically observed in vortex NC-STOs. Furthermore, only excitations with a non-zero vorticity (e.g. a vortex/antivortex pair [68-70]) should be allowed in an extended film with a highly homogeneous magnetization. Therefore the presumed oscillation mode is believed to be via a periodic vortex/antivortex creation/annihilation mechanism [71].

VI. Conclusion

In conclusion, we have presented a review of the most recent developments in state-of-the-art NC-STOs based on in-plane PSVs, orthogonal PSVs, and single ferromagnetic layers. Among the many recent emergent phenomena in NC-STOs, we have given particular attention to the critical role of the Oersted field, to the detailed properties of current modulated NC-STOs, and to the demonstration of single-layer NC-STOs with greatly reduced material complexity. The

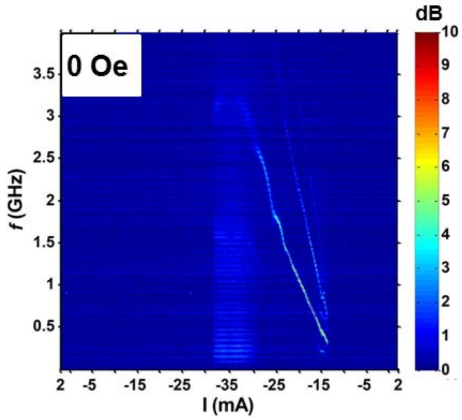

Fig. 5. Hysteresis current scan, starting from +2 mA up to -35mA and back to +2mA in zero applied field.

recent discovery of the highly non-linear magnetic droplet soliton was also discussed. While the first SW excitations in magnetic point contacts were reported almost 15 years ago, we are only now beginning to grasp the complexity and versatility of the highly non-linear SW modes available in these devices. Based on this newly developed understanding, we can now better tailor the NC design and underlying materials for microwave generators, modulators, and detectors, as well as magnonic integrated circuits, where the wide range of available nano-scale SW modes may lead to a truly miniaturized and ultra-broadband microwave technology platform.

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