Spintronic nano-oscillators: towards nanoscale and tunable frequency devices

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Spin transfer nano-oscillators are microwave devices based on two major spintronic physical phenomena: spin transfer effect and magnetoresistive effect. These spintronic oscillators are possibly new type of integrated devices for applications such as microwave emission, frequency modulation, frequency mixing and frequency detection. In order to reach telecommunication applications required specifications, several issues must be tackled such as operating conditions without a magnetic field and phase noise reduction. Here we investigate experimentally how two different types of spin transfer oscillators based on magnetic vortex core dynamics might be a solution to address these issues.

Keywords—nanodevices, spintronic devices, rf oscillators

I. INTRODUCTION

The prediction of the spin transfer effect in the late 90's is a new paradigm in spintronics as it provides a novel mean to act on the magnetic configuration of a nano-magnet through the injection of a spin polarized current without the need to apply an external magnetic field [1], [2]. This discovery has generated a huge research effort in the last decade and todays has the power to impact Information and Communications Technologies (ICT) in the same way as the discovery of Giant Magneto-resistance (GMR) did in the 1990's for data storage [3], [4]. This fundamental prediction, first evidenced in 2003 [5], [6], is a very efficient mechanism for driving large amplitude magnetization dynamics of magnetic layers, leading to the generation of high emission power [7], [8] and high frequency voltage signals in the frequency range from low frequency range (0.1 – 2 GHz) up to large 65 GHz [9][10], depending on the magnetic modes that is amplified by spin transfer.

Besides the alluring potentialities of these spintronic rf devices in terms of frequency tuning (related, as we will see later, to the non linearities associated to the magnetization dynamics), range of modulation bandwidth and frequency agility, their extremely small volume allowing unprecedented integration level and their insensitivity to radiations compared to existing integrated rf technologies (LC circuit, ring oscillator etc...), new original functionalities for signal transmission/reception and for frequency detection are foreseen. While many crucial advances have been made in the fabrication and understanding of such Spin Transfer Nano-Oscillators (STNO), there remain several critical problems yet to be resolved, in particular, the low microwave power and quality factor of single STNOs. So far these devices, often associated to magnetic excitations of a uniform mode in a nanomagnet, are limited by their emission properties in terms of emission power, phase noise and the need of an external applied field. The main objectives of this letter is to address these issues by following an alternative approach in which current driven oscillations of a magnetic vortex are used as the source of microwave power.

II. STNO : A DEVICE BASED ON THE DYNAMICS OF MAGNETIZATION INDUCED BY A SPIN POLARIZED DC CURRENT AND CONVERTED INTO RESISTANCE OSCILLATION

The principle of a Spin Transfer Nano-Oscillator (STNO) is based on the spin transfer torque (STT) effect where the magnetization dynamics can be excited when a spin polarized current is injected in a ferromagnetic material, as a consequence of the interaction between the spin angular momentum of the conduction electrons and the magnetization of the magnetic layer. This STT effect allow the compensation of the natural magnetic relaxation of the system (intrinsic damping due to magnetic properties) and the generation of sustain magnetization oscillations under some particular conditions of injected current and magnetic field [5], [11]. Such features can be observed in devices made of a layered stack of a magnetic (M1) /nonmagnetic (NM) /magnetic (M2) materials called spin valve, respectively magnetic tunnel junction (MTJ), when the NM layer is metallic, resp. an insulating barrier. Another basic property of spintronic structures is that they display large magnetoresistance (MR)

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effect i.e. the whole stack resistance level depends on the relative orientation in between the M1 and M2 magnetizations. This effect is called Giant MagnetoResistance (GMR) in case of a spin valve [3], [4] or Tunnel MagnetoResistance (TMR) in case of a MTJ [12], [13]. The MR ratio is defined as the highest relative resistance change [14].

STNOs combine STT and GMR or TMR effects in a M1/NM/M2 stack (see schematic in Fig. 1): injecting a dc current through the stack, the current becomes spin polarized by flowing through the M2 layer, which magnetization is assumed to be fixed. Then, the spin polarized current generates the excitation of modes of the magnetization of M1 due to STT. This magnetization dynamics is converted into voltage oscillations due to magnetoresistive effect. Thus an electrical signal is emitted. Their properties are directly linked to the dynamics of the magnetization of the layer M1 and to the properties of the magnetic layers in the spintronic devices: the carrier frequency is the frequency of the free layer M1 excited mode, the power is proportional to the amplitude of the magnetic oscillations and to the square of MR ratio and the coherence of the electrical signal is proportional to the dynamical noise of the magnetization.

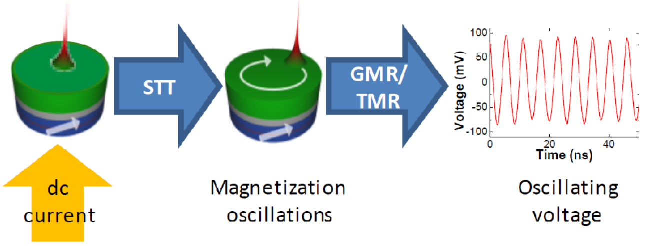

Fig.1: Schematic of STNO working principle : from the injection of a dc current to the generation of voltage oscillations

STNOs are nanosized devices working in a large range of temperature (from cryogenic temperature up to room temperature) [15], [16]. One of the crucial advantages of STNOs is that they are tunable (with a rate depending on the magnetic mode considered from 10MHz/mA up to 1GHz/mA) and agile (from 1 ms down to 1 ns relaxation time). Moreover STNO devices are CMOS compatible and radiation hard. These specificities make them good candidates for integration in future rf systems. Finally, the fabrication process for STNO technologies is identical to the one used by the boosting market of new generation of magnetic data storage devices e.g. STT-MRAM [17].

In today’s spintronic rf devices, two issues that are detrimental for rf applications are still under investigation: the need of an external applied field to obtain sustained magnetic oscillations [18] and the large phase noise level due to the nanometric size of the STNO devices and of their nonlinear nature [19], [20].

III. VORTEX BASED STNOS

Here, we address two emission features of the STNOs that are not yet completely mastered and that limit their use for applications: the study of the high level of phase noise that limits the coherence of the emission power and the difficulty to obtain large amplitude oscillations when no external field is applied. One of the specificities of our system is that we consider a particular circularly confined system where the magnetization of the free layer M1 has a vortex distribution at remanence which is stable due to geometrical and energy consideration [21]. Vortex magnetization corresponds to an in-plane curling magnetization except in the center of the disk where the magnetization points out-of-the-plane (see Fig 2). This central out-of-plane magnetization region is named the vortex core and has a radius of the order of 10 nm. The vortex magnetization presents a fundamental mode called the gyrotropic mode, well separated from other higher energy modes [22] , which can be excited with low current density and presents the best coherence among nowadays spintronic devices. These advantages, specific to vortex based STNOs, are strategic when applications in telecommunication are envisaged. One requirement for the STT induced gyrotropic mode is the need to spin polarize the current with an out-of-the-magnetic-layer-plane component spin [23]. For STT sustained oscillations, the vortex dynamics exhibits large amplitude oscillations that correspond to the vortex core oscillation around the center of the dot along a circular trajectory. The gyrotropic frequency can be expressed in first approximation as:

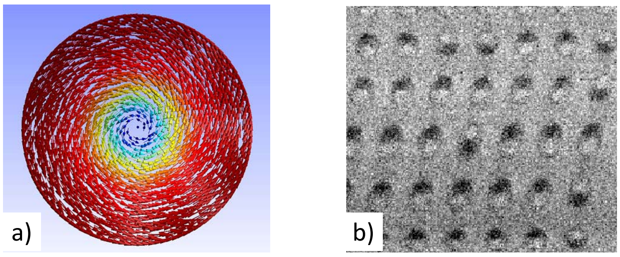

Fig. 2 a) Micromagnetic simulations of a vortex magnetization distribution in a nano-disk. The arrows represent the local magnetization while the color scale represents the out-of-plane component of the local magnetization. b) SEMPA imaging of an array of dots with vortices (in-plane magnetic contrast is detected).

$$f \sim f_0 + f_j I \qquad (1)$$

where: $$f_0 = \frac{5}{18\pi^2}\gamma\mu_0 M_s \frac{L}{R}$$

with the gyromagnetic ratio γ, the vacuum permeability μ_0, the saturation magnetization of the free layer M_s, the dc current I, the free layer thickness L and radius R. Thus the average gyrotropic frequency range depends on the ratio of the free layer thickness L and radius R as f_0. As a consequence of (1), the vortex dynamics frequency ranges from 100 MHz up to few GHz, and can be chosen during the fabrication process. Equation (1) highlights another specificity of vortex based STNO which is their frequency tunability. The $f_j I$ term in (1) that is linked to both the direct dependence of the intrinsic energy of the system with current and the nonlinear nature of vortex based STNOs [24] where the amplitude and phase are coupled similarly to other types of spintronic oscillators. The resulting tunability is around 10 MHz/mA.

IV. MEASUREMENTS OF TWO TYPES OF VORTEX BASED STNO DEVICES

Here we present the study of two types of STNOs containing magnetic vortices:

- Standard MTJ STNO are classical circular MTJ made of a layered stack of //PtMn(15)/CoFe(2.5)/Ru(0.85)/CoFeB (3)/MgO(1.075)/NiFe(5) (thickness in nm) with 500 nm diameter (see schematic in Fig. 3-a). Due to the size of the NiFe layer, it has a stable vortex distribution at remanance. The PtMn/CoFe/Ru/CoFeB stack (SAF layer) acts both as a reference layer for the magnetoresistance conversion and as an out-of-plane spin polarizer when its magnetization is tilted out of the plane by anapplied out-of-plane magnetic field. The tunnel barrier is made of MgO and gives TMR ratio of 15%.
- Hybrid circular spin valve-MTJ stacks made of //IrMn(9) /CoFe(2.5)/Ru(0.85)/CoFeB(3)/CoFe(0.5)/MgO(1.1)/ CoFe(0.5)/CoFeB(1.3)/NiFe(10)/Co(0.6)/Cu(5)/[Co (0.2) / Ni (0.5)]$_{10}$ (thickness in nm) of 100 nm diameter (see schematic in Fig. 3-b). The vortex is at remanance in the CoFe/CoFeB/NiFe/Co stack. The $[Co/Ni]_{10}$ stack is the out-of-plane spin polarizer that gives the out-of-plane spin component to the current when no external field is applied. The IrMn / CoFe / Ru / CoFeB / CoFe layer is the reference layer for the magnetoresistance conversion where the MR ratio is around 60%.

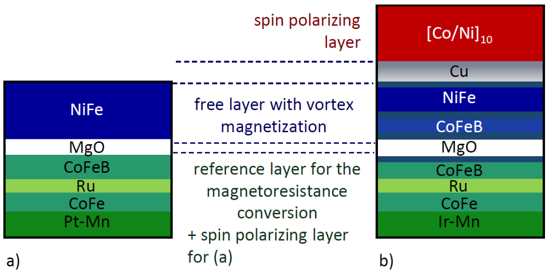

Fig.3: Examples of the two studied structures: (a) standard MTJ vortex based STNO structure and (b) hybrid MTJ/GMR vortex based STNO structure. The vortex magnetization dynamics take place in the NiFe free layer (blue layers). The synthetic antiferromagnetic layer (SAF : green layers), is common to both structure and permits to convert the magnetization dynamics into rf-oscillations. In (a) the SAF also acts as polarizer for the spin current, which indeed implies the presence of an out-of plane field. In (b), the use of a perpendicular polarizer (red layer) permits to induce magnetization dynamics with no out-of-plane field.

V. CONDITIONS FOR THE DETECTION OF A RF SIGNAL: FREQUENCY DOMAIN MEASUREMENTS

From the measurements in frequency domain with a spectrum analyszer, we compare the emission spectrum of the two types of STNO devices for different condition of applied external magnetic field and dc current. In Fig. 4 we plot the power spectral density (PSD) in color scale as a function of the applied external field and frequency for a fixed dc current. For both STNO devices, the emission power has a frequency evolution quasilinear with field as described in [25], from 300 to 500 mT for the standard MTJ STNO and from -20 up to 120 mT for the hybrid GMR/TMR STNO. As predicted, Hybrid GMR/TMR STNO with the perpendicular spin polarizer emits a large power signal when no magnetic field is applied unlike standard MTJ STNO for which no signal is measured at zero magnetic field. Indeed, for standard MTJ STNO, an external magnetic field higher than 300 mT is needed to tilt out-of-plane the magnetization of the polarizing layer in order to get the needed out-of-plane spin polarized dc current. This generation of spin transfer induced emission is a real breakthrough for spintronic devices.

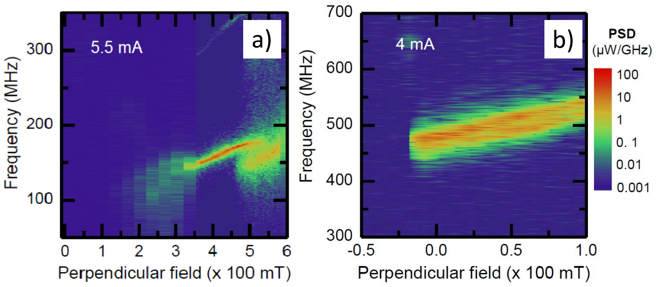

Fig.4 Color scale of the PSD of the standard MTJ STNO (a) and of the hybrid GMR/TMR STNO (b) vs perpendicular magnetic field at a fixed dc current 5.5 mA for (a) and 4.0 mA for (b).

At a given field, the emission features can be extracted from the PSD that has a lorentzian distribution. One can extract the power and the full-width-at-half-maximum (FWHM). For the standard MTJ STNO, the largest measured power is of the order of 50 nW and is obtained around 400 mT, whereas for the hybrid GMR/TMR STNO the largest power is obtained at 0 mT and is of the order of 200 nW. It should be noted that this value is at the state of the art compared to other spintronic oscillators having similar tunability and quality factor. The large difference in power amplitude is due to the difference in the MR ratio of standard MTJ STNO and hybrid GMR/TMR STNO. Concerning the spectral coherence, the spectral linewidth (FWHM) is much lower for standard MTJ STNO with FWHM of the order of 0.1-1 MHz whereas in the results presented her for hybrid GMR/TMR STNO, the FWHM is of the order of 1-10 MHz. Such high values of the FWHM are link to the size of the device and to the operation point in terms of current and field. Recently we measured much lower FWHM on these hybrid GMR/TMR devices of the order of few 100 of kHz when no external magnetic field is applied [26].

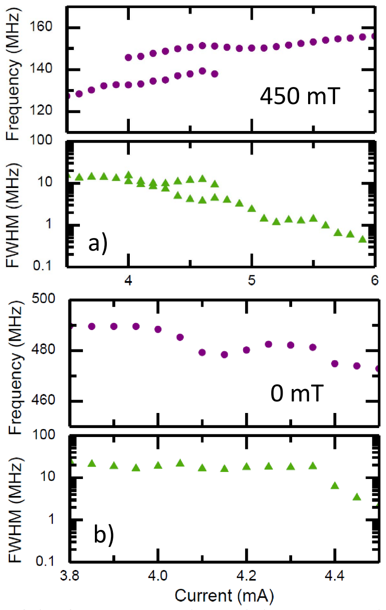

Fig. 5 Evolution of the frequency carrier and the FWHM with current for the standard MTJ STNO at 450 mT (a) and for the hybrid GMR/TMR STNO at 0 mT (b).

In Fig. 5 we plot the evolution of carrier frequency and of FWHM as a function of the dc injected current at a given field. For the standard MTJ STNO, the frequency evolves quasi linearly with current as expected from analytical predictions. On the other hand, the frequency evolution is more complex for the hybrid GMR/TMR STNO: the frequency mainly decreases with current but at some particular current locally increases. This local increase of the frequency is often linked to the existence of several modes excited by STT [27]. On the contrary, the FWHM evolution with current is qualitatively similar for both type of STNO: as increasing the current, the FWHM decreases. This decrease is the signature of an operation point above threshold current for spin transfer sustained oscillations. In the case of hybrid GMR/TMR STNO, the decrease of FWMH appears for current above 4.1 mA, close to the maximum dc current that can be applied before damaging the tunnel barrier (for those samples, the MTJ breakdown is about 500 mV). Thus, a complete understanding of the rf signal is not yet achieved for hybrid GMR/TMR STNO.

VI. CHARACTERIZATION OF STNO PHASE NOISE.

In order to improve the spectral coherence of the vortex based STNOs, the understanding of the main source of noise in these devices is crucial. Thus we focus on the study of the phase noise of vortex based STNOs. From time domain measurements, we use the Hilbert Transform Method [19], [20], [28] to separate and extract the phase and amplitude from the voltage time traces measured at the output of the STNO after a 30 dB amplifier (1.8 dB noise figure). By suppressing the main component, we extract the amplitude and phase noise. In Fig. 6 we plot characteristic measured phase and amplitude noise PSDs (see markers) as a function of the offset frequency. For the standard MTJ STNO, we measure 16.4 ms long time trace with a sampling rate is of 2.5 GSa/s and for the hybrid GMR/MTJ STNO we measure a 8.2 ms long time trace with a 5 GSa/s sampling rate. For both types of STNOs, the distributions are similar. The amplitude noise is much lower than the phase noise but still higher than the Johnson Nyquist noise floor which is around -120 dBc/Hz. The amplitude noise has a Lorentzian distribution with a roll-off frequency around 1 MHz, while the phase noise presents a $1/f^2$ evolution for small offset frequencies, and a $1/f^n$ with $2<n<4$ for offset frequencies higher than the amplitude noise roll-off frequency.

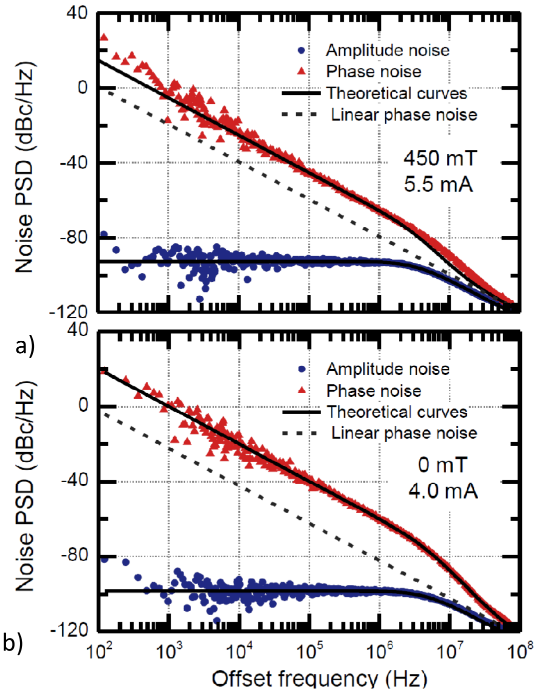

Fig. 6 Phase noise and amplitude noise PSD of (a) standard MTJ STNO for 450 mT and 5.5 mA corresponding to a STNO emitted power of 18 nW and of (b) hybrid GMR/TMR STNO for 0 mT and 4.0 mA corresponding to a power of 70 nW. The markers correspond to measurements and the solid lines correspond to fits to (2-3). The black dotted line is the theoretical intrinsic phase noise.

In Ref. [29] we have recently shown that a simple analytical description of the vortex core dynamics [24] allows to describe the voltage response of the STNO in the case of energy exchange with a thermal bath [30]–[32] and thus the PSD of amplitude and phase. The response to noise of the vortex based STNO can be described with three key parameters: the generation FWHM in the linear regime $2\Delta f_0$ (which is proportional to the ratio between the energy of the system and the thermal energy), the relaxation rate of the system for a given stable equilibrium πf_p, and the normalized dimensionless nonlinear frequency shift ν which quantify the coupling between phase and amplitude. We highlight that these key parameters depend on the quality of the STNO in terms of intrinsic damping and spin polarization. We can express the amplitude noise PSD $S_{\delta\varepsilon}$ and the phase noise PSD $S_{\delta\theta}$ as:

$$S_{\delta\varepsilon} = \frac{\Delta f_0}{2\pi}\frac{1}{{f_p}^2+f^2} \qquad (2)$$

$$S_{\delta\theta} = \frac{\Delta f_0}{\pi f^2} + \nu^2 2 \frac{{f_p}^2}{f^2} S_{\delta\varepsilon} \qquad (3)$$

These two equations clearly highlight the large impact of the amplitude-phase coupling ν on the measured phase noise: if the STNO would be linear, the phase noise would be equal to its linear part proportional to $2\Delta f_0$ (first term of the right hand side of (3)) but because the amplitude is coupled to the phase, an additional term due to the amplitude noise and proportional to ν^2 increases the phase noise (second term in the right hand side of (3)). Moreover it predicts a Lorentzian distribution for the amplitude noise PSD with the roll-off frequency proportional to the relaxation rate πf_p. In Fig.6, we plot the fits to (2-3) with black solid lines: experiments and analytical predictions are in good agreement. We extract the value for the response to noise parameters. For the standard MTJ STNO, Δf_0 = 36 kHz, f_p = 3.2 MHz and ν = 5. Whereas for the hybrid GMR/TMR STNO Δf_0 = 19 kHz, f_p = 4.5 MHz and ν = 13. The intrinsic linewidth in the linear regime $2\Delta f_0$ and the relaxation rate πf_p are of the same order of magnitude for the two types of STNO, but differ due to the different size and magnetic properties of the material, and due to the different conditions of field and current. Indeed, the smaller the intrinsic linewidth $2\Delta f_0$, the smaller the intrinsic phase noise and the smaller the ratio $\Delta f_0/ f_p$, the lower the amplitude noise achieved. As a consequence, the intrinsic phase noise level and the amplitude noise level of the hybrid GMR/TMR STNO are slightly below the ones of the standard MTJ STNO. Indeed considering the high coupling coefficient value ν of the hybrid GMR/TMR STNO, the phase noise is strongly degraded due to the amplitude-to-phase noise conversion. Such a high value of the coupling coefficient value may be due to the coexistence with other modes [21], and link to the dimensions and operating point of the measured hybrid GMR/TMR STNO.

VII. CONCLUSIONS

To conclude, we investigate two main issues of vortex based STNOs i.e. the emission without applied external magnetic field and the high level phase noise. We study two types of spintronic devices containing a vortex, one of them designed for working with no applied external field. We measure the emitted signal of these two types of STNO in frequency and time domain for different conditions of magnetic field and dc current, and compare their emission properties. Experimentally, we demonstrate that large amplitude oscillation due to spin transfer induce vortex oscillation are generated, allowing large power emission compare to other spintronic devices and tunability. For specifically designed STNO with perpendicular spin polarizer, we measure the best rf feature when no external magnetic field is applied. In terms of phase noise, these two types of STNO present qualitatively similar amplitude and phase noise PSD, with non classical distribution due to the strong amplitude-phase coupling. These properties can be furthermore improved at fabrication process as the higher the ratio between intrinsic spin polarization over natural damping, the better in term of noise. Finally, the coupling between several vortices [33] would to correct the phase noise, and as these systems are sensitive to injection locking [34], [35], they can be included in a phase lock loop or with parametric excitation to favor only one mode [36], [37].

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