Computing with spin waves

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(Dated: June 11, 2019)

Abstract: When enough spin-polarised current crosses a thin ferromagnetic film through a nanoscale contact, the local magnetisation might describe high-frequency oscillations in the microwave spectrum band that can then propagate through the film in form of spin waves. Devices that transform direct current into spin-wave excitations, so called spin torque nano-oscillators (STNO), are promising candidates into a new era of nanotechnology, with possible applications in mobile communications or in computation. Combining STNO with different currents in the same film can lead to the synchronisation of their frequencies, describing static and dynamic interference patterns. In this paper we simulate systems with one and two STNO and characterise their oscillations and synchronisation conditions.

I. INTRODUCTION

Traditionally, magnetic fields have been used to work with the magnetisation of a material. For instance, changing the orientation on magnetic moment of a piece of material would eventually require a device creating a magnetic field that could be an inconvenient. However, recent experiments [1, 2], have proven that, when a spin-polarised current crosses a ferromagnetic film with a thickness in the nanometric scale, a torque is exerted on the local magnetic momenta, creating a precession movement. Given enough current density, this torque can overcome the magnetic damping of the region and, in consequence, the precession movement describes self-sustained oscillations of the magnetisation of high frequency (1 GHz - 1THz) [3]. Given the right conditions, these oscillations then can propagate through the thin ferromagnetic film in form of 2D spin waves.

Devices that fulfill these characteristics, transforming direct current into spin-wave excitations, are called spin torque nano-oscillators (STNO) and they are promising candidates into a new era of nanotechnology since they were first predicted [4]. One of its most valuable characteristics is how highly tunable its frequency is: adjusting the current that goes through the STNO changes the frequency of the oscillator nonlinearly in the microwave spectrum band. Given its nanoscale dimensions, such tunability could be used, for example, in mobile telecommunications [5].

Moreover, STNO can interact strongly enough with other oscillations coming from an external source or from other STNO that they lock their phase and frequency when frequencies of both oscillations are close in magnitude. Two or more STNO are synchronised when they are mutually phase-locked creating patterns of spin waves. The range of frequencies in which they synchronise depend on the strength and range of interaction. Studying when STNO synchronise and what patterns they describe could lead to applications in computation and telecommunications as they could be used as detectors [6], for signal modulation [6], to reduce noise [3], or, for example, as a neuronal network trained to detect patterns [7].

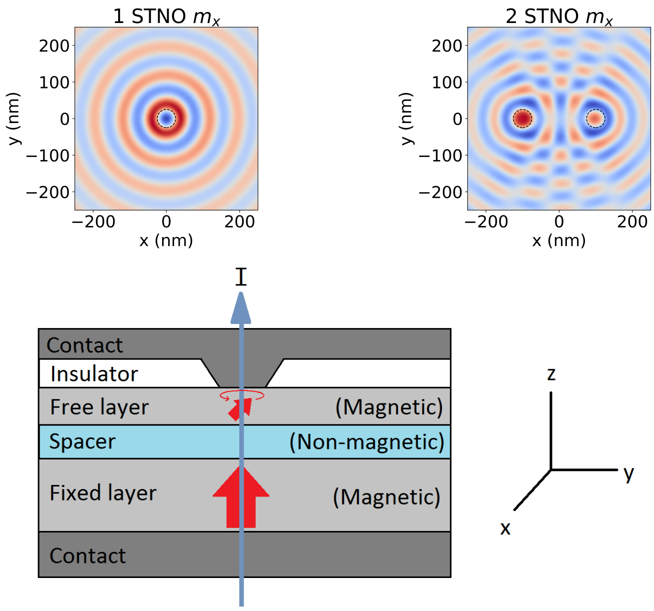

FIG. 1: Spin-wave pattern created by 1 STNO (*top left*) and by 2 synchonised STNO (*top right*) and a schematic description of the STNO nanocontact (*bottom*). The fixed layer and the free layer are separated by a non-magnetic spacer.

However, experimentally, these devices have shown two major flaws [5]. First, the coherence of STNO is usually poor at room temperature, lowering the quality factor ($Q = f_0/\Delta f$) up to 4 orders of magnitude in comparison to other commonly used oscillators in microelectronics (such as quartz oscillators). Secondly, the output power of STNO is weak for applications, emitting less than 1nW [8].

In this paper, we simulate a 2D ferromagnetic film and study the oscillations behind the STNO, describing their dependence on the current applied. Afterwards, we simulate the two STNO system, studying how interactions affect each other and when the system is synchronised.

II. MECHANISMS BEHIND STNOS

In order to describe how STNOs work it is necessary to explain what the spin-transfer torque (STT) effect is. When an electron with a certain spin crosses a ferromagnetic film, it can exchange angular momentum with the closer magnetic moments. This process becomes more relevant for the ferromagnetic film when the flow of electrons has a distribution of spins favoured to one direction, that is to say, the current of electrons is spin-polarised. This transfer occurs in transition metals where the electron transport naturally spin-polarises [5]. The spin-polarised current is obtained by making current flow through a ferromagnetic layer thicker enough so that the layer is not affected by the spin-transfer effects. This layer, known as reference layer or fixed layer, acts as a polariser as the electron flux becomes collinear with its magnetisation [5].

After the current has been spin-polarised, it crosses the thin ferromagnetic layer, also known as the free layer, where the excitation of spin waves happens. From the point of view of the electrical current, when a spin-polarised current crosses a magnetic material a resistance, known as giant magnetoresistance (GMR) [9], is detected, depending on the relative orientation of the magnetisation of the free layer and the spin of the electron flux or, in other words, depending on the relative orientation of the magnetisation of both layers since we used the fixed layer to spin-polarise the current. Therefore, in order to cause spin-wave excitations in the free layer, both layers have to be magnetically decoupled because, if not, the current would not exert a torque on the magnetic moments of the free layers and there would not be oscillations. To do this we introduce a non-magnetic layer in between as seen in Figure 1.

Accordingly, applying enough current density to the STNO will make it radiate spin-waves through the free layer in two dimensions as shown in [10], where cutting the material between two synchronised STNO would prevent them from coupling through spin waves.

III. MATHEMATICAL DESCRIPTION OF MAGNETISATION DYNAMICS

The magnetisation dynamics of the free layer can be described by the Landau-Lifshitz-Gilbert-Slonczweski differential equation (LLGS), that expresses the time evolution of the magnetisation as a function of three separated terms [3, 5].

$$\begin{aligned}\frac{\partial \boldsymbol{M}}{\partial t} =& -|\gamma|\mu_0 \boldsymbol{M}\times\boldsymbol{H}_{\text{eff}} \\ &- \alpha\frac{|\gamma|\mu_0}{M_{\text{s}}}\boldsymbol{M}\times\boldsymbol{M}\times\boldsymbol{H}_{\text{eff}} \\ &+ \beta(\boldsymbol{r})\boldsymbol{M}\times\boldsymbol{M}\times\boldsymbol{m}_{\text{p}}.\end{aligned} \tag{1}$$

The first term of the equation describes the precession of the magnetisation around the effective magnetic field whenever both vectors are not aligned. It depends on the gyromagnetic constant $|\gamma|\mu_0$. On the other hand, the term in the middle describes the damping that would eventually stop any of the previous precession, aligning the magnetisation with the effective field. This term also depends on the gyromagnetic constant and also on the Landau-Lifshitz damping constant α and the saturation magnetisation M_{s}. The last term of equation 1 introduces the effect of the spin-polarised current flowing through the STNO that depends on the direction the current is spin-polarised (m_{p}). The $\beta(r)$ defines the STNO dimensions and the applied current.

The effective magnetic field vector $\boldsymbol{H}_{\text{eff}}$ that contributes to the two first terms can be described as the sum of the external magnetic field, the demagnetising field and the exchange field [3, 11]:

$$\begin{aligned}\boldsymbol{H}_{\text{eff}} =& \boldsymbol{H}_0 - \frac{1}{4\pi}\int_V \nabla\nabla\frac{1}{|\boldsymbol{r}-\boldsymbol{r'}|}\boldsymbol{M}(\boldsymbol{r'})\,d\boldsymbol{r'} \\ &+ \frac{D}{|\gamma|\mu_0 M_{\text{s}}\hbar}\nabla^2\boldsymbol{M},\end{aligned} \tag{2}$$

where D is the exchange parameter. The exchange field contributes to keep spins oriented locally whereas the demagnetising field competes with it trying to keep spins disordered across the film. The demagnetising field has a non-local expression, that is, for every spin, we need to calculate the contribution of every other spin. Therefore, solving the equations with linear programming is inefficient. To solve this issue, we use *mumax*^{3} [11], a micromagnetic simulation program that uses GPU, computing simultaneously (and more efficiently) various tasks.

Furthermore, we solve the differential equations simulating a thin grid formed by $512 \times 512 \times 1$ cubic cells of 4 nm of side with an external field of 0.8 T applied perpendicularly to the film. Playing with the size of the grid and the Landau-Lifshitz damping constant α, we can observe spin wave excitations without effects of finite size like waves bouncing on the walls. In our case we use $\alpha = 0.03$. We take a saturation magnetisation $M_{\text{s}} = 500 \cdot 10^3\text{A/m}$ and we take values of the magnetisation vector $\boldsymbol{m} = \dfrac{\boldsymbol{M}}{M_s}$, using the complex basis to describe the oscillations of the planar components m_x and m_y.

$$\boldsymbol{m} = (m, m_z) \text{ where } m = m_x + im_y.$$

Finally, we take a randomly polarised current and make it go through a perpendicularly magnetised fixed layer to polarise the current.

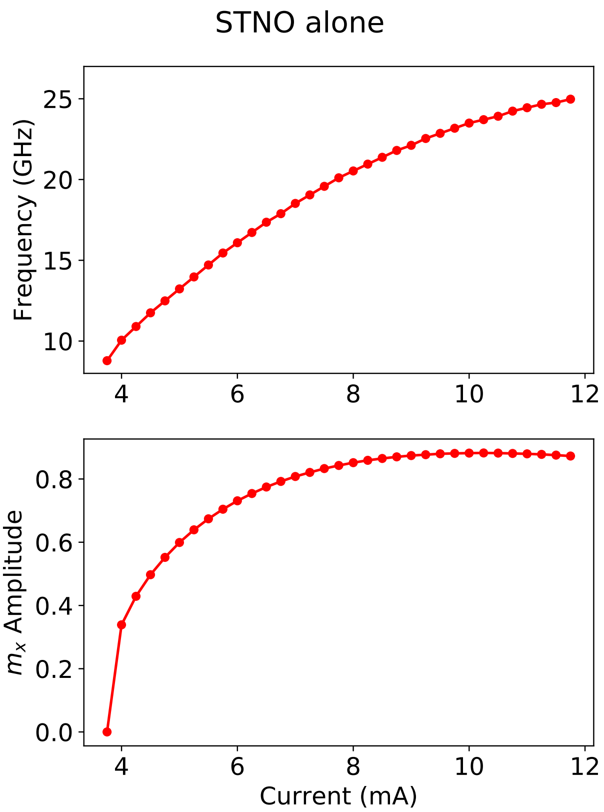

FIG. 2: Depencende of the frequency (*top*) and the amplitude (*bottom*) of the magnetisation component m_x one STNO as a function of the current applied.

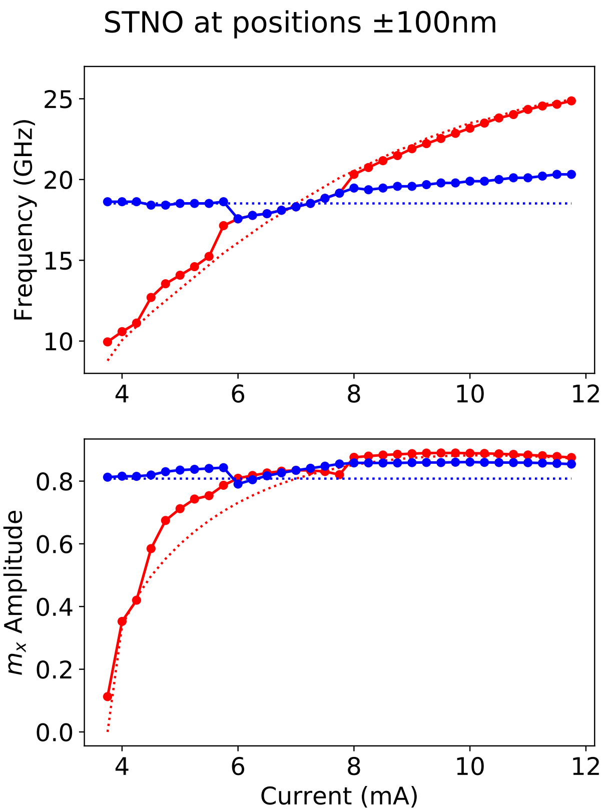

FIG. 3: Depencende of the frequency (*top*) and the amplitude (*bottom*) of two STNO placed at ±100 nm as a function of the current applied on one of them. *Blue* lines represent the STNO with a fixed current of 7 mA while *red* lines represent the other STNO whose current is plotted in the x-axis. Dotted lines describe the non interactive case described in section IV.

IV. SIMULATION OF 1 STNO

In our first simulation, we place one circle-shaped nanocontact of 25 nm of radius at the centre of the grid of 2048 nm of side and we apply an external perpendicular magnetic field of 0.8 T, as described in last section. Then, we apply a current through the contact, that gets spin-polarised in the fixed layer, and we study how the magnetisation component m_x (or, in equivalence, m_y) behaves in the contact region of the free layer. We obtain oscillations in m_x with certain frequency and amplitude. In Figure 1, we can obseve the propagation of the oscillations of m_x through the film with a wavelenght of approximately 3 times the radius.

To obtain the frequency, we calculate the discrete Fourier transform (DFT) of the signal, transforming the time variable into the frequency domain. The transformed data presents a peak in the most relevant frequency which we use to extract the frequency of the oscillations. To obtain the amplitude of the oscillations of m_x, we take a look at the minimums and the maximums of the oscillations.

Afterwards, we repeat the same measure changing the current applied on the STNO in intervals of 0.25 mA, with each interval taking 10 μs of simulation time. Then, we describe the dependence of the frequency and the amplitude on the current. In Figure 2, it can be observed than none of the variables shows a linear dependence on the current applied. However, both seem to increase when the current does so, in expection of high amplitudes. For applied currents lower than a threshold, which in this case it is 3.75 mA, the system does not oscillate since it is not able to overcome damping and the result given for the frequency is just some movement from the initial conditions. For currents above 12 mA the STNO would oscillate in other modes and even flip (negative m_z).

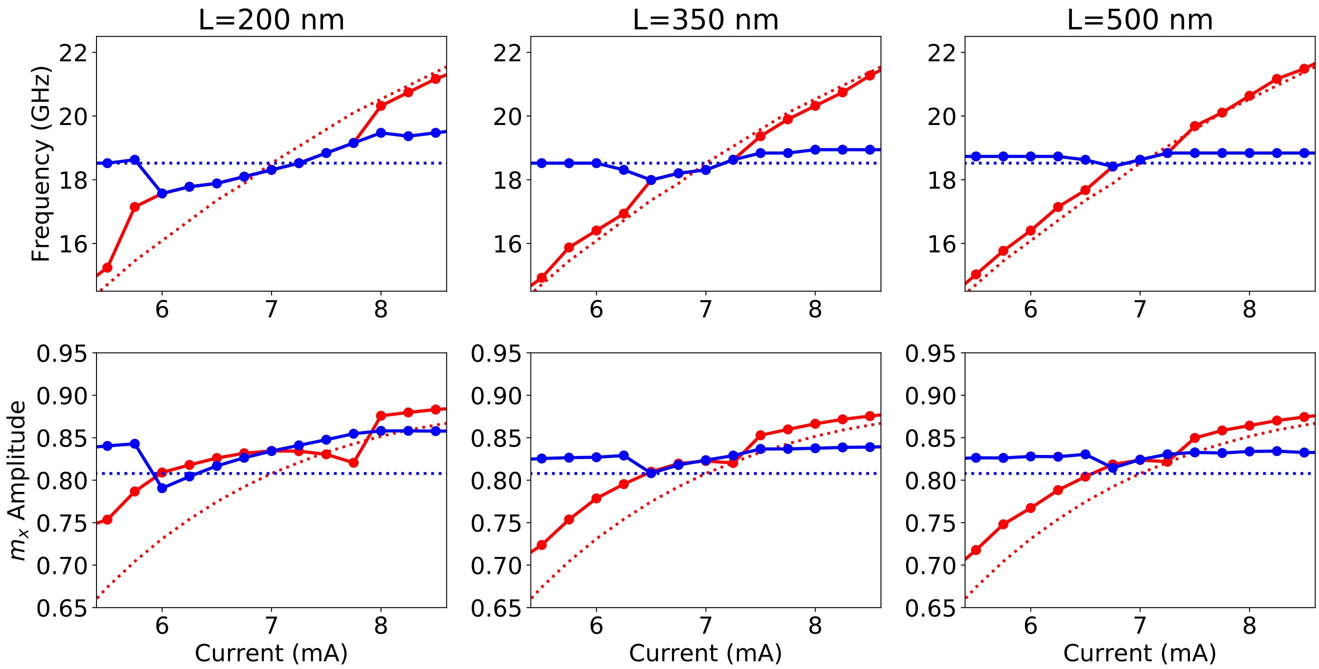

FIG. 4: Zoom on the synchronisation range of the frequency (*top row*) and the amplitude (*bottom row*) of two STNO as a function of the current applied on one of them. Three columns show three different distances between the two STNO: 200 nm (*left*), 350 nm (*middle*) and 500 nm (*right*). *Blue* lines represent the STNO with a fixed current of 7 mA while *red* lines represent the other STNO whose current is plotted in the x-axis. Dotted lines describe the non interactive case described in section IV.

V. SIMULATION OF 2 STNOS

A. Synchronisation process

For our next simulation, we place two STNO of the same radii (25 nm) separated 100 nm symmetrically from the centre of the grid. On one STNO, we fix a current of 7 mA, while on the other one, we change the applied current the same way as in the previous section. In Figure 1, we can observe an example two synchronised STNO with different applied currents describing a spin-wave pattern. Then, we calculate the frequencies and the amplitudes of both oscillators as done for the case one oscillator. In Figure 3, these magnitudes are shown for each oscillator and then compared to the magnitudes they would have if placed alone on the film as described in last section (dotted lines).

Results show that, when the frequency of the first STNO is close to the frequency of the second, both oscillators synchronise, suddenly jumping from their respective frequencies to an intermediate common one. There is a range of currents in which frequencies are close enough to synchronise. In this range, both oscillators exchange amplitudes and, since frequencies of both oscillators are the same, they create an interference pattern of spin waves on the film.

On the both sides of the synchronisation, the strongest current seems barely affected by the weak one, following the dotted line almost perfectly, while the weak one shows significant variations in both frequency and amplitude.

B. Distance between STNO

The conditions in which both STNO synchronise are one of the subjects of great interest. Manipulating those conditions is important in order to maximise their applications. In this section, we study how the range of currents in which the system is synchronised varies when the distance between both oscillators is changed. Following the same procedure as in last subsection, we calculate frequencies and amplitudes of both oscillators for three different distances between the oscillators: 200 nm, 350 nm and 500 nm. In Figure 4, the three scenarios are displayed and it can be observed how, in general, the range of currents in which the system is synchronised increases the closer the STNO are. The farther they are, the more damped the wave is and the weaker both oscillators can interact. In Figure 5, we plot the synchronised range in comparison of the distance between both STNO.

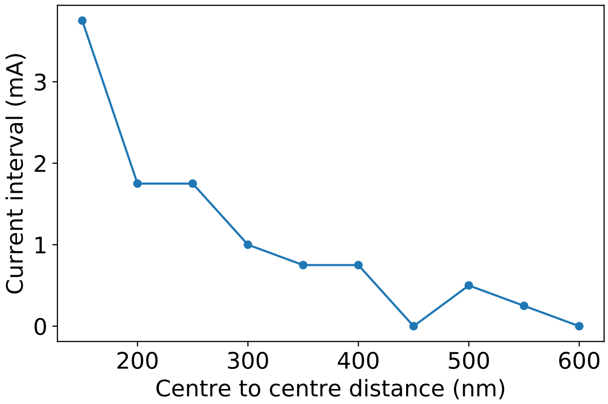

FIG. 5: Synchronisation range for different distances between two STNO.

In general, the curve decreases up to the point in which they barely interact. However, the slope of this decrease strongly depends on how strong the damping of the film is, that is to say, if the damping constant α is stronger, the distance for which the oscillators don't interact is closer.

VI. CONCLUSIONS

We have studied the spin-wave excitation emitted by STNO, describing the whole process in which direct current is transformed into magnetisation oscillations and reproducing experimental results by means of using simulations to solve the Landau-Lifshitz-Gilbert-Slonczweski differential equation. The most remarkable result lies on the description of the synchronised state. We have seen that, when two spin torque nano-oscillators are placed in the same thin film, there is a range of currents in which the system is synchronised. Furthermore, we have studied how this range of currents decreases almost monotonically when increasing the distance between the oscillators. The points that deviate from this monotonic decreasing behavior could be explained by how waves of both oscillators interact constructuvely or destructively depending on the distance between them.

Acknowledgments

I would like to thank my tutor Ferran Macià Bros for his help and guidance throughout this project, as well as his department colleagues for occasionally lending me a hand.

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