MASTER FINAL REPORT

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MASTER – FINAL REPORT

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4.1 Final publishable summary report

a) Executive summary:

The strategic objective of the European project MASTER has been to explore innovative approaches for microwave signal generation for tomorrows needs in integrated microwave components and wireless communications systems inside Europe. The importance of this field is the ever-increasing number of applications which necessitate covering a broad frequency range (0.1- 60 GHz) while at the same time significantly decreasing the size of individual components. The project MASTER concentrates on spintronic devices, the so-called Spin Transfer Nano-Oscillator (or STNO), which is a nano-scale microwave source. STNO can provide breakthrough solutions due to their specific spin polarized transport properties that appear at nanoscale dimensions (100nm lateral, and 2-5 nm vertical), and due to their easy integration onto existing CMOS technology, as has been demonstrated already in the memory sector. Going beyond current research, this project aims at exploiting the coherent coupling intra and inter STNO devices developed in array to improve the microwave emission performance in terms of phase noise, emission power and to operate in different frequency ranges. Ultimately, the MASTER project aims to demonstrate that such novel nanoscale spintronics components provide a true alternative solution to existing microwave components to achieve miniaturization, combined with new functionalities that simplify concepts of mircrowave source, frequency mixing and also microwave detection.
Federation of complementary European experts working in the field of thin film deposition, nano-fabrication, transport measurements, and developers of innovative spin-wave spectroscopy experiments and novel simulation tools has been a key step to progress efficiently in a worldwide competitive field. Through a systematic methodology around the study of four coupling mechanisms that may lead to phase locking between STNOs (*i*- coupling through the common self-generated microwave current, *ii*- coupling through the dipolar magnetic field, *iii*- coupling through the spin-diffusion of the conduction electrons, *iv*- coupling mediated by spin-waves) a roadmap towards optimization of STNO performances has been obtained. As such, the European project MASTER has helped European teams to bring STNO components from a curiosity developed inside research laboratories to a high performance device, whose characteristics allow the integration inside more elaborated microwave circuit.
With the help of an Industrial Consultant Board, the consortium has then tried to secure the device level knowledge acquired by the partners of MASTER by identifying 1) the discrete systems as potential industrial devices breaking bottleneck issues of current technologies and 2) the European industrial partners to be associated with. The beneficiaries of this know-how established by MASTER are now federated inside a new project named MOSAIC, recently supported by the FP7-ICT-2011-8 call towards objectives 3.1 "*Very advanced nanoelectronic components: design, engineering, technology and manufacturability*" whose plan is to exploit the benefits of STNO optimization obtained by MASTER in order to develop novel spintronic components for the wireless telecommunications and data storage industry.

b) Summary description of the project context and the main objectives:

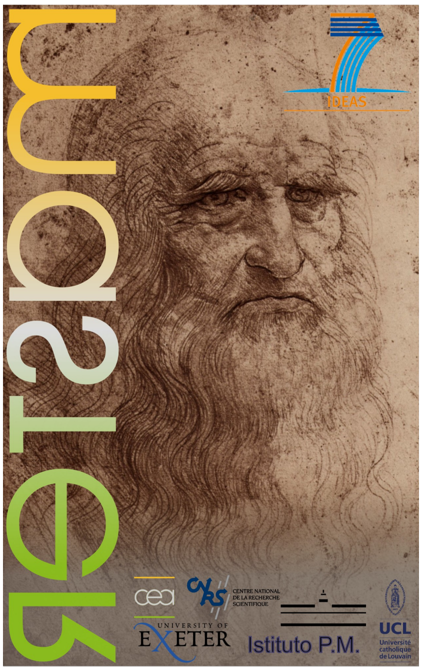


FIG 1: Logo of MASTER

The intended aim of the MASTER project has been to explore the potential of novel *Spin-Transfer Nano-Oscillators* (STNO) for use as *tunable* and *ultra-narrow band* microwave radiation sources for **mobile** and **wireless telecommunication** technology. The strategic technological interest of STNO devices, made of **nano-structured magnetic** multilayers, driven by a spin-polarized electrical current, and emitting microwave radiation, is their nanoscale size and compatibility with monolithic on-board integration.
Our proposal has specifically addressed the bottleneck issue of improving the microwave performances in terms of phase noise, emission power and operation in different frequency ranges. Our project proposes to take advantage of the phase-locking effect between coupled nano-oscillators to dramatically increase the generated microwave power and, at the same time, reduce its linewidth. Our *main deliverable* has been the fabrication within 42 months of an **array of coherently coupled (phase-locked)** spin-torque nano-oscillators emitting at the microWatt power level with a quality factor above the 10^4 range. The challenge has been to overcome the unavoidable distribution of STNO characteristics during the nano-fabrication process. Since individual biasing of each nano-oscillator is impractical for large *N*, we have used instead the enhancement of the strength of the coherent coupling between the elements. To achieve this goal, four different coupling mechanisms between the STNO that may lead to their phases being locked, have been investigated:

- Coupling through the common self-generated microwave current.
- Coupling through the dipolar magnetic field.
- Coupling through the spin-diffusion of the conduction electrons.
- Coupling mediated by spin-waves.

Using the results of this investigation, an array of *N*-vortex state nano-pillars coherently coupled by the magneto-dipolar interaction has been identified as the optimum configuration leading to synchronization. The objectives in terms of power output and linewidth have been obtained by coupling the magnetization motion of the two layers that constitute an STNO. We have reported enhanced performance up to *N=4*. The performance characteristics of the optimized array has been studied both theoretically and experimentally.

Achieving phase-locking between neighboring oscillators has also required substantial progress in our understanding of the **fundamental** mechanisms that are involved in the transfer of spin angular momentum from spin-polarized current to the precessing moment of the magnetic layer. Our secondary objective has been to address both experimentally and theoretically the following three *knowledge gaps*:

1. Identification (spatio-temporal profile and relaxation times) of the fundamental spin-wave eigen-modes excited by a dc current in nano-structured magnetic heterojunctions.
2. Investigation of the magnetization dynamics of a nano-structure in the non-linear regime.

3. Understanding of the fundamental mechanism underlying non-local effects associated with the diffusion of spin-polarized electrons and its action on the dynamics of the whole system.

The wider technical and societal **impacts** of the proposed project has been to put several European academic teams at the forefront of research on spintronics application. Federation of complementary European experts working in the field of thin film deposition, nano-fabrication, transport measurements, and developers of innovative spin-wave spectroscopy experiments and novel simulation tools has been here a key element to progress efficiently in a worldwide competitive field. In this regard the NMP program has helped **cross-disciplinary research** between the magneto-transport and microwave technology communities, and to bring together a consortium with expertise covering different technological aspects of spintronics research, from nano-fabrication and spin-transfer experts, to spin-wave spectroscopists specializing in the dynamics of nano-objects and theoreticians. The quality of the research obtained by the consortium can be illustrated by the large number of high impact factor publications: 5 natures, 5 PRL, 10 PRB (5 Rapid Comm) and 13 APL. This high research quality has helped to set the recognition of European team work. The work of MASTER has been referenced 189 times so far. It has also helped to train inside Europe some of the brightest students. It has helped the transmission of know-how in this core technology of the future. MASTER has thus helped to produce highly **trained scientists and engineers** to help meet Europe's need for skilled people, to support investments in spintronics and wireless telecommunication technology and to disseminate the results to the wider international scientific community. The NMP funding thus achieved a very cost effective mean to develop **nano-scale microwave spintronics components** with target technological breakthroughs not only to generate, but also to process (mix, modulate, synchronize) and to detect microwave frequencies. Another objective of the MASTER project has been the identification of different high performance discrete components exploiting STNOs. An Industrial Management and Consultant Board (IMCB) has helped the consortium to identify 1) the discrete systems as potential industrial devices breaking bottleneck issues of current technologies and 2) the European industrial partners to be associated with. It has helped Europe to bring STNO components from a curiosity developed inside research laboratories to a whose characteristics allow the integration inside more elaborated microwave circuit. Examples for the field of wireless telecommunications, one proposes the ultrawideband frequency synthesis provided by spintronics microwave components with novel circuit design on CMOS for realization of a adapted phase locked loop (PLL); and the ultrafast frequency detection by using frequency discriminating level detection. For the data storage one proposes the novel dynamic readout schemes for detecting frequency shifts implemented for realization of high data rate read heads.

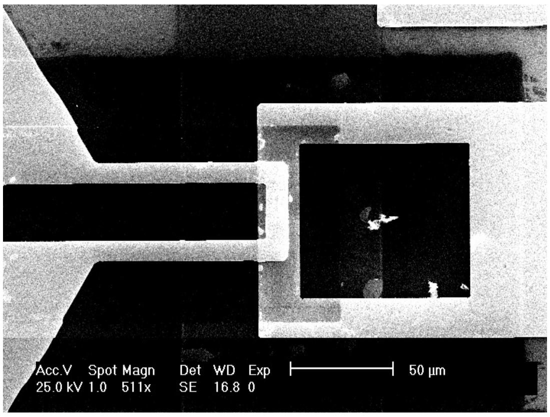


FIG 2: Microcircuit of an integrated microwave source based on Spin Transfer Nano-Oscillators. The top antenna is an additional excitation circuit that allows to perform standard FMR spectroscopy on the device.

Another objective of the project has been to develop **innovative spectroscopy instruments** to characterize individual nano-objects. One pivotal idea of MASTER has been to progress **beyond the state of the art** in terms of *the type of experiments* performed on spin-torque devices, by bringing within the project *innovative* spin-wave spectroscopic techniques, which can **excite** *and* **detect** the magnetization dynamics of individual STNO **independently** of spin-transfer effects.

Incorporation of these novel instruments within **MASTER** has been **fundamental** to understanding the basic mechanisms that are involved in spin momentum-transfer from a spin-polarized current to the precessing moment of the magnetic layer.
Within the **MASTER** project, the proposed experiments that address the coupling performance within the STNO array has been performed using five complementary instruments. The central instrument is the magneto-transport measurement in the current perpendicular to the plane giant magneto-resistance (CPP-GMR) geometry, which has been almost the only instrument used in spin-transfer studies so far. Progress has been made through the development of new STNO designs that allows us to study the dynamical behavior of a pair of STNOs (the basic unit of the array) of small separation, and which may be adapted so that the different instruments can independently characterize the nature of the coupling between nano-oscillators. Through careful design of the STNO geometry, we were able to share the same device between different instruments allowing a direct comparison of the different spectroscopic signature. One originality of the project was to incorporate an independent impedance matched microwave antenna close to the STNO (see Figure 2). Its purpose is to produce a uniform microwave magnetic field at the multi-layer device. The aim is to compare the spin wave spectrum excited by a **microwave field** and by a **continuous current**. Indeed experimental identification of the spin-wave modes allowed in the sample requires a well-defined excitation, and associated selection rules that determine the symmetry of the excited spin-waves. Ferro-Magnetic Resonance (FMR) is a technique that uses a uniform microwave field created by a stripline antenna to excite the longest wavelength spin-wave modes inside the sample. However, the limited sensitivity of standard FMR spectrometers restricts their use to arrays of micron-size samples, which statistically averages the spectrum of the individual elements and prevents differences between individual elements being resolved. We therefore have proposed to use in parallel new tools to **detect** the FMR signal of an individual STNO. To image the SW oscillations of the device, three novel and complementary microscopy techniques have been used:

1) Mechanical Ferromagnetic Resonance (MRFM) detects the **longitudinal** part of the microwave susceptibility (*phase insensitive*). Although it requires an external excitation scheme to modulate the signal, it has sufficient sensitivity to measure the dynamics of a Py element of 100nm lateral size and 5nm thickness down to the linear regime (angle of precession less than 1°). Another important point is that it can detect buried structures.
2) Micro Brillouin Light Scattering (μ-BLS) is another *phase insensitive* technique that can measure the **wavevector** dependence of the spin wave spectrum. No external excitation is required here since it has the sensitivity to detect thermal spin waves. It does however require optical access, and it has a spatial resolution of 300nm.
3) Time-Resolved Scanning Kerr Microscopy (TRSKM) performs a 3D **vectorial** analysis of the **time dependent** magnetization and is thus *phase sensitive*. It requires pulsed or harmonic field excitation and optical access. and it has a spatial resolution of 300nm.

These complementary techniques, which are unique within Europe and internationally leading, have contributed to a better basic understanding of the spin-torque-effect since they allow both local (behavior of the STNO being excited) and non-local (behavior of the STNO adjacent to the STNO being excited) effects to be explored on 100nm to 1μm length scales where fabrication of multiple independent electrode contacts is challenging.

The final objective of the MASTER project has been the development of a high performance micromagnetic solver to perform micromagnetic simulations on a very large array of coherently coupled STNOs.
The micromagnetic solver includes:

- Plug & Play user-friendly GUI

- FFT-accelerated magnetostatics
- time integration using 4th order Runge-Kutta solver
- time step auto-adaptation
- very flexible system definition
- STT with both Slonczewski and Field-like torques

This new solver developed by Istituto PM has allowed very high simulation volume (up to few μm x few μm x100 nm), non-regular structure (multilayered structures), non-regular dynamics (very short-wavelength modes are excited), and huge computational times (> 50 ns). Furthermore, many new features have been added to the code to define the structures and to help the analysis of the calculation of the magnetization dynamics of the system. A new time integration algorithm based on 4th order Runge-Kutta method has been developped as well as a new exchange energy calculation algorithm. New features that provide a much better flexibility in object specification and appear to be crucial for the goals of the Project have been added to the code. Now we can emulate polycrystalline films, with the parameters of magnetic materials being distributed randomly over the crystallites. The polycrystalline texture of a magnetic film is defined using the Voronoi tessellation. For the computational cells constituting a grain (crystallite), the magnetic parameters are equal; however these parameters vary from one grain to another. The following magnetic parameters can be distributed over the grains: anisotropy constant, anisotropy easy axis direction, exchange constant.

These parameters can be distributed randomly with a flat or Gaussian distribution, within a specified range of values. Normally, the parameters of a magnetic/non-magnetic computational layer are defined globally for all cells constituting the layer. Local specification of some of the parameters can be also done, so that one region of a magnetic layer should have a different value of these parameters than their value for the layer globally. We introduced this new possibility to the code and now a user can easily specify local values of the following parameters of the layer or of computational sublayer of nominally physically uniform layer:

FIG 3: Logo of the SpinPM solver

- initial distribution
- current density
- current polarization
- anisotropy constant value and easy axis direction
- damping.

Another objective of the simulation has been to develop a simple theoretical framework for transport in magnetic multilayers, based on the Landauer-Büttiker scattering formalism and random matrix theory. A simple transformation allows one to go from the scattering point of view to theories expressed in terms of local currents and the electromagnetic potential. In particular, our theory can be mapped onto the well-established classical Valet-Fert theory for collinear systems. The Landauer-Büttiker formalism which expresses the problem of transport inside a quantum conductor as a scattering problem. This approach is well suited for a coherent system and is equivalent to the Keldysh approach. However, the classical concepts of chemical potential or local equilibrium do not arise naturally in the scattering approach so that classical intuitions do not easily transfer into its language. It was thus necessary to take the scattering formalism as our starting point and develop a theory which fully captures Valet-Fert and (generalized) circuit theory and to incorporate it inside a micromagnetic solver.

c) Description of the main S & T results/foregrounds.

Overview of the progress towards objectives:

The strategic objective of the European project MASTER is to explore innovative approaches for microwave signal generation for tomorrows needs in integrated microwave components and wireless communications systems inside Europe. The importance of this field is the ever-increasing number of applications which necessitate covering a broad frequency range (0.1- 60 GHz) while at the same time significantly decreasing the size of individual components. The project MASTER concentrates on spintronic devices, the so-called Spin Transfer Nano-Oscillator (or STNO), which can provide solutions due to their specific spin polarized transport properties that appear at nanoscale dimensions (100nm lateral, and 2-5 nm vertical), and due to their easy integration onto existing CMOS technology, as has been demonstrated already in the memory sector. Going beyond current research, this project aims at exploiting the coherent coupling intra and inter devices developed in large array to improve the microwave performances in terms of phase noise, emission power and to operate in different frequency ranges. Ultimately, this projects aims to demonstrate that such novel nanoscale spintronics components provide a true alternative solution to existing microwave components to achieve miniaturization, combined with new functionalities that simplify concepts of mircrowave source, frequency mixing and also microwave detection.

The methodology of MASTER was to propose a systematic approach in our understanding of the underlying physics. The aim was to perform a thorough experimental study of all the fundamental mechanisms that are involved in the transfer of spin angular momentum from spin-polarized current to the precessing moment of the magnetic layer. Progressive roadmap performed first on individual device (*N=1*) or on the characterization of the elementary constituents of a working STNO: the dynamical properties of the different layers, the optimum composition of the multi-layer stacks, the geometry of the device and the detection of the spin-transfer dynamics with innovative spin-wave spectroscopy experiments. We wanted to establish a fundamental understanding of the four coupling mechanisms between the STNO that may lead to their phases being locked: 1) coupling through the common self-generated microwave current, 2) coupling through the dipolar magnetic field, 3) coupling through the spin-diffusion of the conduction electrons, 4) coupling mediated by spin-waves. In parallel we have worked towards establishing the analytical and simulation tools to predict the behavior of STNO. Based on this solid ground we then slowly progressed to *N=2*, *N=4* and *N=10.*

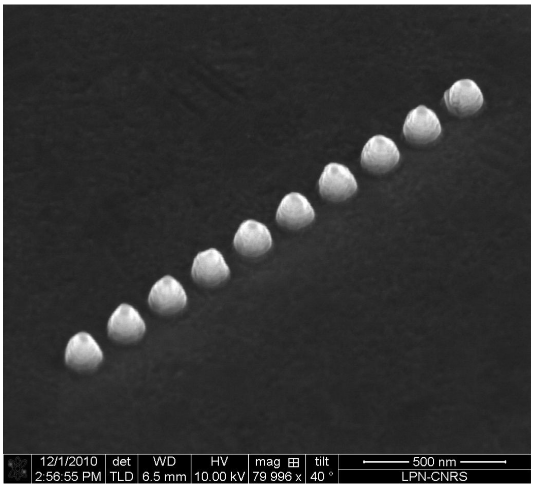


FIG4: Array of 10 STNOs laterally coupled by the magneto-dipolar interaction

Although much progress towards optimization of STNO performance it terms of power output and linewidth has been achieved on a single device (*N=1*), during the last 42 months we have tried up to *N=10* STNOs (= 10x2 layers).

- We have obtained very interesting results for *N=2x2* STNOs, both in the vortex and saturated states.
- *N=4* is the limit so far of coherently synchronized different STNOs achieved by MASTER.
- But quality of emission characteristics for *N=2* and *N=2x2* has already been greatly improved thanks to the dipolar interaction.
- <u>Coupled modes is the key for coherence</u>. After the MASTER project, STNO linewidth is not anymore an issue.
- Tunneling Magneto-Resistance (TMR) stacks are required to increase emitted power.
- Lots of effort have been put in MASTER to achieve synchronization. Still, lots of investigations (experiments, simulations, theory) are under progress to understand better *N=2x2*, *N=4*, and *N=10*.

Highlights of the main results:

The principal progress obtained by MASTER is the enhancement of the device performance in terms of output power and phase noise. One bottleneck issue identified at the beginning of the proposal has been the weakness of the output power emitted by a single STNO. During the last three years, the state of the art for STNO power performances has increased by more than 60dB. From output power in the 10^{-12}W range back in 2007, a single device can now reach the microWatt range (A. Dusseaux Nature Com. 2010), which is almost enough for applications. Such drastic improvement has been obtained by first optimizing the coherent coupling intra STNO. Through careful tailoring of the choice of the equilibrium magnetic configuration, a 30dB increase in the output power has been demonstrated in a single device using coupled vortex state disks (N. Locatelli APL 98 062501). Here most of the progress in output power performance is obtained through a reduction of the phase noise associated with the coherent coupling of the dynamics of the different layers comprising an oscillator. An outstanding quality factor of Q=25000 has been recently published in the vortex state (N. Locatelli APL 98 062501). This is a factor 100 improvement compared to what was known at the start of the project in metallic devices. This is even a factor 3 better than the highest Q ever measured in FMR (a perfect sphere of Yttrium Iron Garnet). Further improvement could be obtained by coherently coupling nearby STNOs (see figure, showing the output power as a function of the coupling in a 2x2 array). However the ability to sychronize STNOs depends on the coupling strength. A 2nd important achievement of MASTER has been to demonstrate that one can produce coupling strength inter STNO that can overcome the inherent distribution of STNOs characteristics during fabrication. By doing so, we believe that the MASTER project has successfully brought spintronic technology on the verge of becoming a potential microwave break-technology in the same way as the discovery of Giant Magneto Resistance (GMR) did in the 1990's for data storage. The important drawback of phase synchronization, is that the improvement of the device quality factor has been obtained at the expense of agility. The foreseen applications of nanoscale spintronics devices with large market opportunities will thus draw on the specific strength of this new technology as **miniaturized microwave components** used for instance as either passive components (mixer,

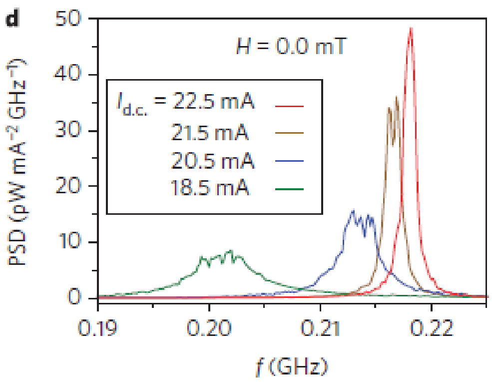


FIG5: Phase synchronization of four point contacts, under different biasing by a continous current.

limiters, passive detectors) or specific applications as local oscillators : e.g. interchip connections, or local source generator for resonant switching of memory devices (see IMCB report below).

The aim of the first period of the project was to perform a thorough experimental study of all the fundamental mechanisms that are involved in the transfer of spin angular momentum from spin-polarized current to the precessing moment of the magnetic layer. Most of the experimental work performed for the first 18 months has concentrated on the behavior of either an individual device ($N=1$) or on the characterization of the elementary constituents of a working STNO: the dynamical propeties of the different layers, the optimum composition of the multi-layer stacks, the geometry of the device and the detection of the spin-transfer dynamics with innovative spin-wave spectroscopy experiments. In parallel we have worked towards establishing the analytical and simulation tools to predict the behavior of STNO.

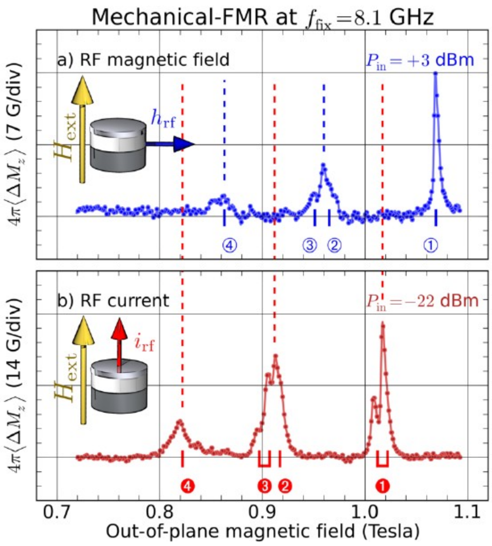


FIG 6: Illustration of the selections rules. Different spin-wave spectra are excited by a rf magnetic field or a rf current.

During the first period, it was established that the coupling by a rf current requires to control the symmetry of the magnetic configuration of the fixed layer. The MRFM experiments shown below indicate that rf current excitation flowing through a nanopillar excite in priority spin-waves with axial symmetry, because of the orthoradial Oersted field. In the saturated state these axial spinwaves are not the ones that are excited when a dc-current is flowing through the pillar and they have no coupling to the spin-waves excited by a uniform field. Since both mechanism are competing, and are influencing the current threshold, the result suggests that the best coupling requires that the thick layer is in the vortex state. This fundamental progress in understanding has prompted us to explore the dynamics of the vortex state which offer promising coupling capabilities (see work below). On the other hand the coupling by a a dipolar magnetic field (see below) could be the most appropriate for saturated device. Here the use of an external antenna as a mean to provide the coupling between nearby oscillator could be explored and compared with the other mechanisms. Cavity-FMR experiments have shown that the coupling mediated by the diffusion of the conduction electron exist and they have a very long coupling range (of the order of the spin diffusion length). However the strength of this coupling still needs to be compared with the strength of the dipolar field. Concerning the coupling mediated by the spin-waves, the result so far obtained by µBLS using the in-plane magnetizing field, shows that the excitation is mainly localized close to the contact and thus do not have a long coupling range. Understanding of the implications of such result are still under investigation, as well as the change requires to overcome this unexpected result.

Controlled synchronization of two vortex-state layers:

In a recently published work (*APL 98 062501*), we have demonstrated that extremely narrow linewidth (compared to the state of the art spin transfer nano-oscillators) can be obtained just by coupling the dynamics of the two magnetic layers inside a STNO and thus by tackling the important issue of spectral coherence of this kind of oscillators. Here, we intentionally design STNO samples such that both the active and polarizer layers can contain a magnetic vortex. In addition, the separation between the two magnetic thin films is much smaller here compared to previous works (only 10nm) thus leading to a more complex but interesting situation of coupled vortices. The problem of interacting vortices has rarely been treated even for a field driven excitation and never for a current-induced excitation. Taking benefit of this two-vortex configuration, our objective is to establish some selection rules for the observation of highly coherent coupled vortices in terms of their relative chiralities and polarities. Consequently, we can provide some clear evidence that the microwave features associated with the coupled dynamics greatly depend on the characteristics of each vortex, notably here their relative core polarities. In the following, we denote, respectively, the chirality and polarity of the vortex in the thin (thick) layer by c1 and p1 (c2 and p2). A patent on this has been filed. In this invention, the objective is to provide innovative solutions in order to address some of the critical issues of Spin Transfer Nano-Oscillators i.e. integration capability, quality factor, operation at zero field, power level, modulation, etc. The concept is to propose a device based on coupled magnetic vortices as a source of microwave power.

For our convention, positive chirality is defined by the Oersted field direction for positive current, and positive core polarity ("up") is associated with the positive field direction. What was shown first in this work is that the respective vortex chiralities are independently controllable by the current through the Oersted field. Furthermore, it is also possible to independently control the polarities of each vortex, by placing then the sample in an out-of-plane magnetic field. We have noted that the device emits a significant power, even at zero field when prepared in a state of opposite polarity and same chirality. Notably, a peak linewidth at zero field of only 200 kHz with a 100 pW/GHz intensity for Idc=+20 mA has been obtained. Such outstanding result can be further enhanced and narrower peak can be obtained by applying a down field $H_{\perp}$ =−60 mT, with a maximum intensity of 3 nW/GHz at the fundamental frequency together with a minimum linewidth of 46 kHz. These experimental findings have raised fundamental question about the observation of microwave emission in double vortex state disks and about the actual sources of spin torque, in particular about the role played by the static and/or dynamic behavior of the polarizer. A theoretical model has been proposed and developed about this issue.

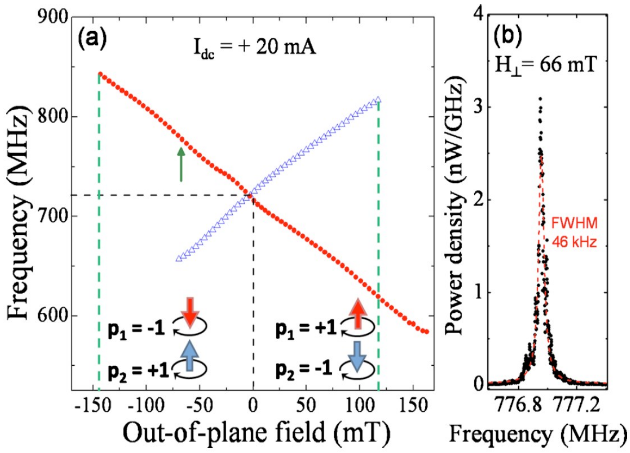


FIG 7: Record of linewidth reduction observed in dynamically coupled vortex state disks.

Noise generation amplitude and linewidth of STNOs:

The effect of current on the magnetic configuration results from the modification of the dynamical properties of nanomagnets by the spin transfer torque . In particular, STT changes the effective magnetic damping. Moreover, studies of magnetization reversal in nano-elements showed that STT can modify their thermal activation rates, which was interpreted as evidence for the effect of STT on thermal fluctuation. This is a very important issue since the miniaturization of these devices is beneficial for reducing their power consumption, but thermal fluctuations of the nanoscale

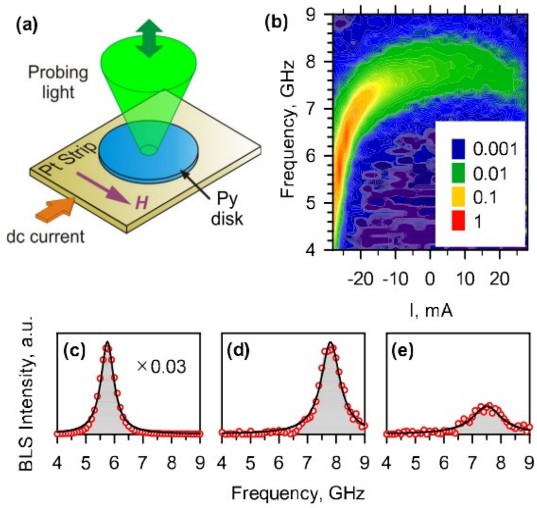


FIG8: (a) Schematic of the experiment. (b) Pseudocolor logarithmic map of the BLS intensity vs current and frequency. (c)–(e) Representative spectra acquired at I= -26, 0, and +26 mA, respectively. Curves are Lorentzian fits to the data.

magnets increasingly compromise their stability. The ability to suppress thermal fluctuations will enable development of smaller and more efficient spintronic devices. In a recent published work (PRL 107 107204) we have investigated the thermal noise of the eigen-modes as a function of a dc pumping current. The optical observation was made possible by using the Spin Hall Effect which allowed the injection of a spin-current into a non-contacted ferro-magnetic layer. The obtained suprising results are displayed in FIG.8. Using a pseudocolor plot of the BLS intensity as a function of current and frequency. As shown in Figs. 1(c)–1(e) for I = -26, 0, and +26 mA, respectively, the BLS spectra exhibit a peak with a Lorentzian line shape. The characteristics of the peak exhibit a strong dependence on I that is asymmetric with respect to the current direction. For I > 0, for which the magnetic moments in the spin current are parallel to the magnetization, the intensity of the peak monotonically decreases with increasing I, while its central frequency remains approximately independent of I. In contrast, for I < 0, for which the magnetic moments in the spin current are antiparallel to the magnetization, the intensity of the peak increases with increasing I and the central frequency exhibits a dramatic redshift at I < -26 mA. Using Lorentzian fits of the BLS spectra to determine the current dependence of the integral intensity of the spectral peak, and the spectral full width at half maximum, the striking result was that modification of damping alone cannot account for the dependence of the integral intensity on current. The integral intensity of the BLS peak is proportional to the average fluctuation energy of the FMR mode. If the magnetic system were to behave simply as if the damping were changed while maintaining thermal equilibrium, then in the classical limit the average fluctuation energy associated with each dynamical mode would remain at a value of kB T. In this case, the integral intensity would remain constant, contrary to the data. These results clearly demonstrate that, besides modifying the damping, STT drives the magnetic system into a nonequilibrium state. We show below that these behaviors are consistent with the established theories of STT once different contributions to the dissipation and the associated fluctuating fields are separately considered. Analysis given below predicts a linear dependence of the inverse integral intensity on current, in agreement with the data shown. It can be shown that STT disproportionately enhances the intensity of the low-frequency modes, resulting in a strongly non-equilibrium spin-wave distribution.

We have also shown (see FIG.9) that a magnetic resonance force microscope can monitor the power emitted by an STNO vs. the bias dc current and perpendicular magnetic field. This has allowed us to demonstrate that the noise power is dominated by the dynamical behavior of the lowest energy, spatially most uniform mode of the thin layer. We then show that this mode synchronizes only to an external source sharing its spatial symmetry, namely in the case of perpendicularly magnetized nano-pillar, a uniform microwave magnetic field, and not the common microwave current passing through the device.

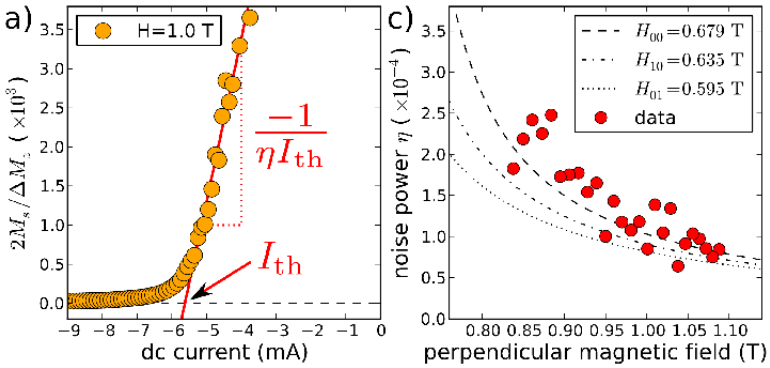


FIG 9: Determination of the threshold current and noise power from the linear fit of the inverse MRFM signal in the subcritical regime. The MRFM data suggests that only the lowest energy mode dominates the noise power.

Quantification of the dipolar coupling between layers:

During the Exeter meeting, it was decided that the dipolar interactions between adjacent magnetic elements will play the leading role in the phase synchronization of spin transfer nano-oscillators (STNOs). So far most dynamical studies have been performed on large arrays of nano-elements where inter-element dipolar interactions lead to collective excitations, while structural variations at the nanoscale lead to inhomogeneous broadening. It is well known that the spin wave spectrum of a nano-element can be complicated by the non-uniform profile of the internal field. Typically the nano-element supports a series of confined modes from which a quasi-uniform center mode and localized edge modes have the lowest frequencies. Edge modes may exhibit strong inter-element dipolar interactions but are highly sensitive to the shape of the element and to structural and magnetic edge roughness. The center mode is largely unaffected by such imperfections but gives rise to weaker inter-element dipolar interactions. The large number of normal modes and the presence of inhomogeneous broadening make the dynamics of an array difficult to understand and control. We present an investigation of the dipolar interactions between pairs of $Ni_{81}Fe_{19}$(15 nm) disks with nominal diameter of 300 nm and nominal separation/diameter (w/d) ratios of 2, 1, 0.6, and 0.3 (see Fig. 10).

A pair of interacting elements is the fundamental sub-unit from which a large array of STNOs may be constructed, and until now it has not been explored by experiment. We have used time resolved scanning Kerr microscopy, with spatial resolution ~ 500 nm and minimal drift, to perform **phase resolved Ferromagnetic Resonance measurements** in which the response of each disk is measured separately. We show that the resonance field of nominally identical disks can vary for different separations leading to a significant phase shift between the dynamic response of each disk with respect to the uniform excitation field. We confirm that the variations in the resonance field are larger for the edge mode than for the center mode. Finally, we present evidence that the variation of the edge mode resonance field can be reduced if the edge-to-edge separation is reduced to less than one radius. We explain this observation in terms of the **dynamic dipolar field generated by the edge mode of one disk acting on the edge mode of the other** (Fig. 10). Optimization and control of this mechanism is essential if phase coherence of edge modes is to be achieved within large arrays of nanomagnets and utilized in STNO applications.

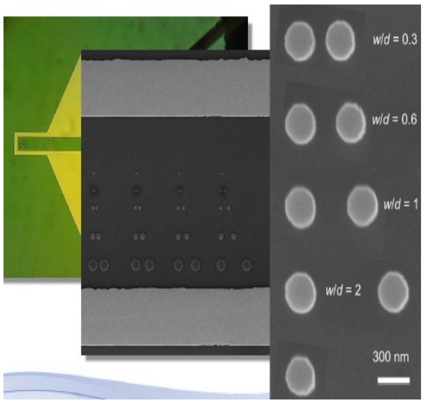
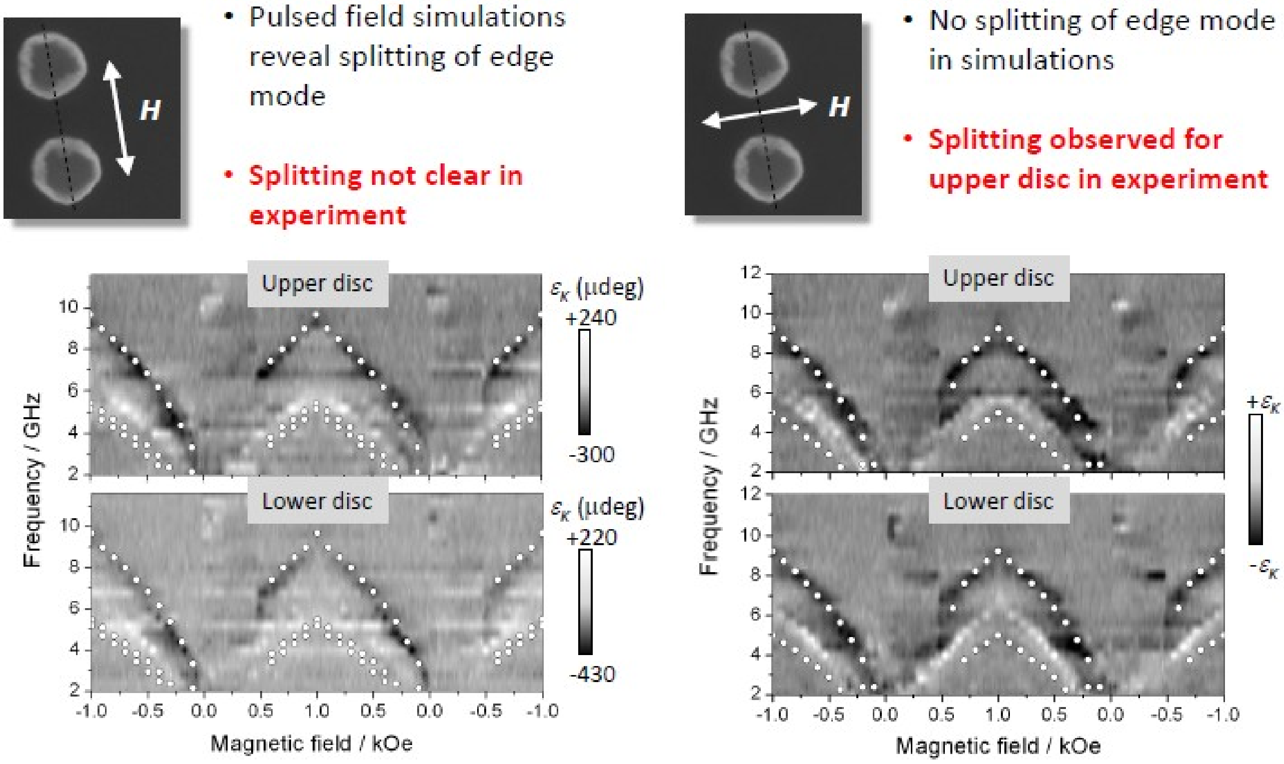


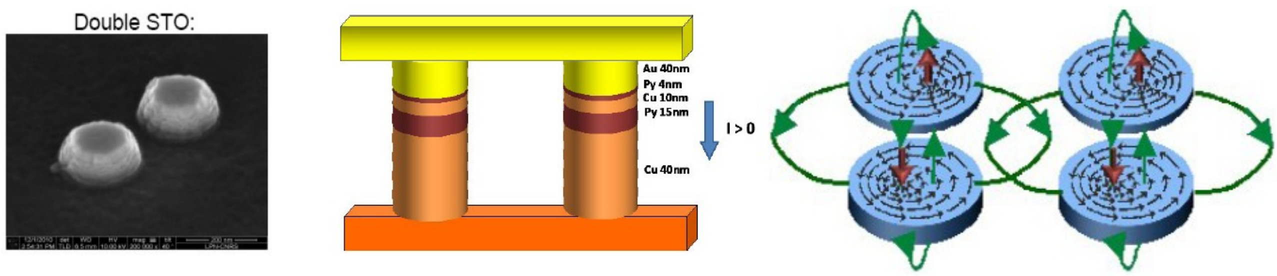
FIG. 10. Optical and SEM images of the investigated sample.



Limit on the number N of oscillators coherently coupled

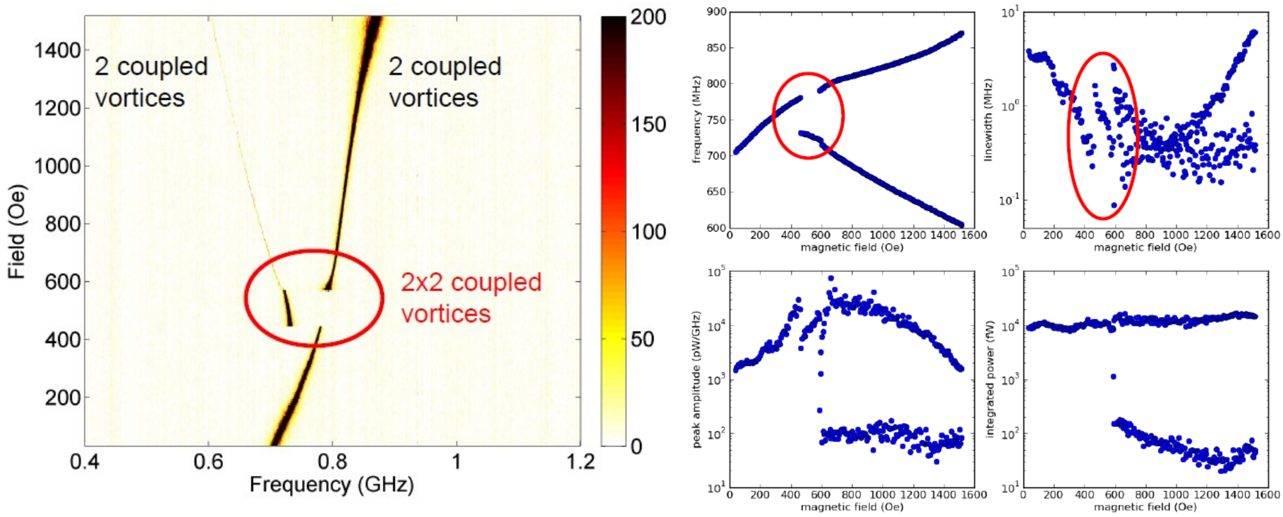
The important conclusion of MASTER is that the coherent coupling of STNOs arranged in a regular array is not required to improve the emission power. MicroWatt power level, which represents 6 orders of magnitude improvement compared to power levels observed back in 2008, at the start of the project, are now routinely measured in the auto-oscillation regime of single STNO made from magnetic tunnel junction stack. Such emission levels are sufficient to permit implementation inside an integrated microwave circuit. Never the less the reduction of the linewidth in the autonomous oscillation regime requires still synchronization of several of these nano-oscillators to improve substantially the performance figure in terms of selectivity. Improvement is obtained here at the expense of agility, which is reduced. The trade-off between agility and selectivity implies that the optimal *N* figure cannot be a too large number. Certainly achieving synchronization of *N=100* STNO will be associated with a quasi-absence of agility, a feature that degrades strongly the interest of such a large array. A finer evaluation of the optimal *N* is treated in more details in the deliverable DC1-6 and references. Since complexity in the synchronization also increases with *N*, MASTER has stopped at around *N=4*. Further enhancement is still possible but it will require an asymptotic effort to solve the challenge of finding the optimal configuration which enhances the coupling for such a large *N*.

1 – Pair of double vortex STNOs (*N*=2x2)



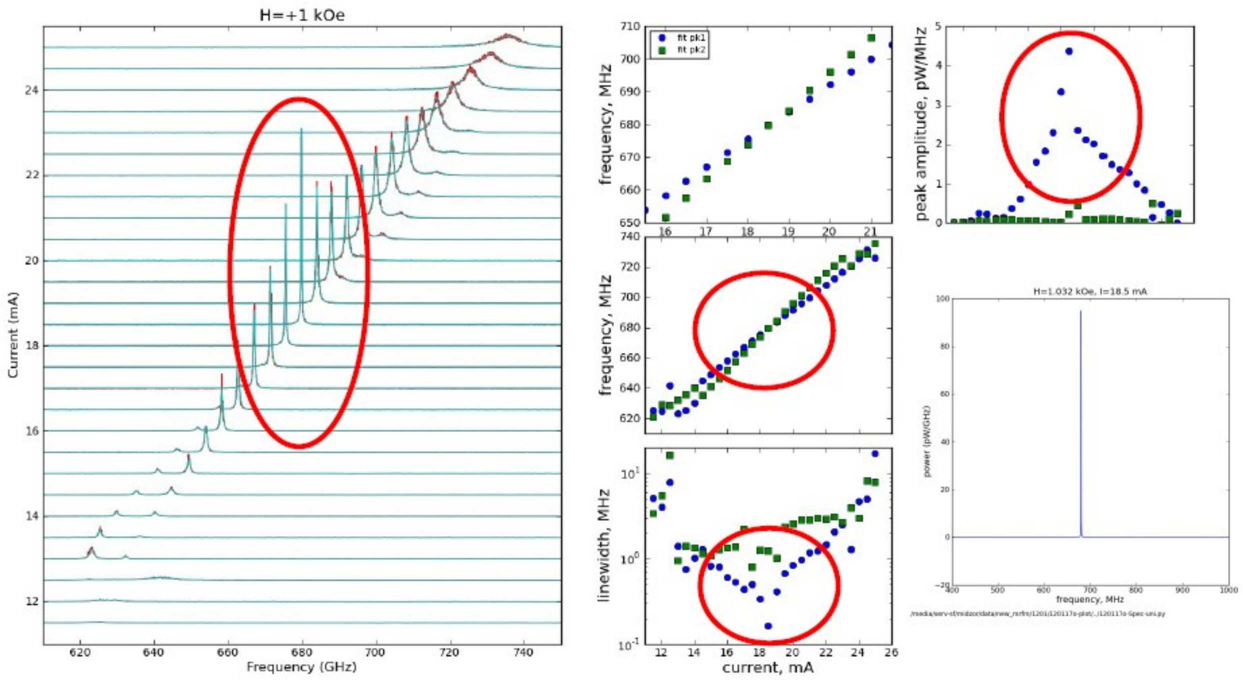
We have investigated the synchronization of vortex auto-oscillations in a pair of adjacent STNOs (left SEM image) connected in parallel with common bottom and top electrodes (middle sketch). Each of them is composed of a thick (15 nm) and thin (4 nm) NiFe layers. Due to the Oersted field associated to the DC current flowing through these two ferromagnetic layers, both are in the vortex state. Therefore, *N*=2x2 vortices are in dipolar interaction in our system (right sketch).

1) Diameter 200 nm, edge-to-edge separation 100 nm

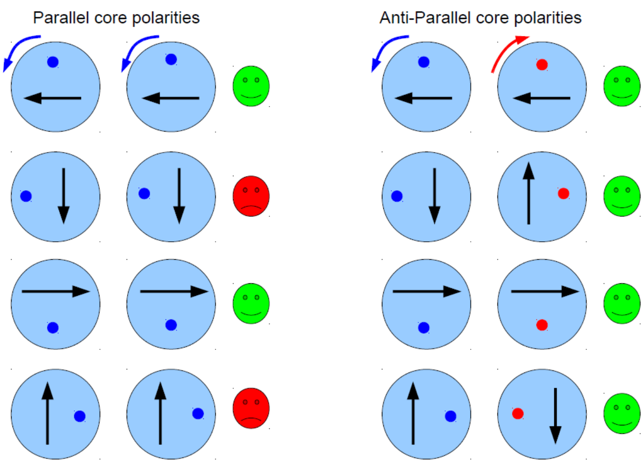


In this first experiment, a constant DC current of 48 mA is applied through the device, i.e. about 24 mA in each STNO. The left panel above shows the evolution of the auto-oscillation peaks measured on the spectrum analyzer as a function of the perpendicular applied magnetic field. This color map clearly shows that two auto-oscillation peaks coexist. By varying the bias field, it is possible to bring together the two different oscillation frequencies. In fact, we know that parallel- and anti-parallel-to-the-field core polarities in the thick layer lead to opposite frequency-field dispersion relations. In this experiment, we purposely prepared a state where the vortex core polarities in the thick layers of each STNO are opposite. When the two oscillating frequencies get closer, the dynamical dipolar interaction gets larger, and it eventually leads to the **synchronization of the vortex oscillations**, as indicated here by the fact that only one large amplitude peak subsists. In this experiment, there is obviously a **strong attraction between the two oscillation peaks** (some pulling is observed in the frequency-field dependence, followed by a sharp jump), but at the same time, the narrowing of the peaks that is expected to accompany the phase locking is rather weak (still, the peak narrows down to 100 kHz). Also, a surprising feature observed in this experiment is the fact that the weakest peak can attract the strongest one in some range of the external parameters (here, between 400 and 600 Oe). In order to elucidate these non-trivial results, we are currently conducting additional measurements on similar samples (same diameter and separation, but also smaller diameters and separations).

2) Diameter 150 nm, edge-to-edge separation 50 nm



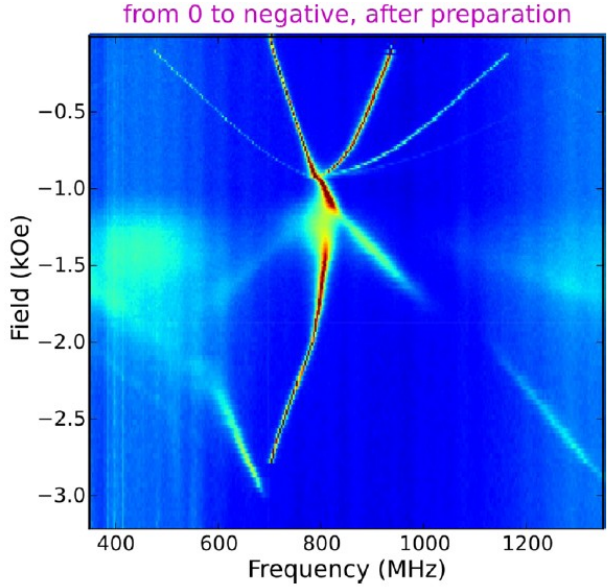
Here, we study the dependence on bias current of the high-frequency dynamics of a pair of vortex-based STNO. The bias perpendicular field is fixed to 1 kOe, and the vortex cores in each of the thick layers of the two STNO are parallel to the applied field. At low current (~14 mA), one can observe two auto-oscillating peaks of similar amplitude. As the current increases, the frequencies of both oscillators increase (as reported on a single STNO,). As both STNOs are not exactly similar (or the bias DC current that flows in each of them is slightly uneven), it happens that the two oscillator frequencies can cross each other, as indicated in red on the graphs. The crossing observed in this case is not accompanied by any pulling or jump of the two frequencies, in contrary to what was observed in the previous experiment. But here, the **phase-locking** manifests itself by a **strong reduction of the linewidth** (see middle bottom plot in log scale) and by a **large increase of the amplitude** (see top right plot).

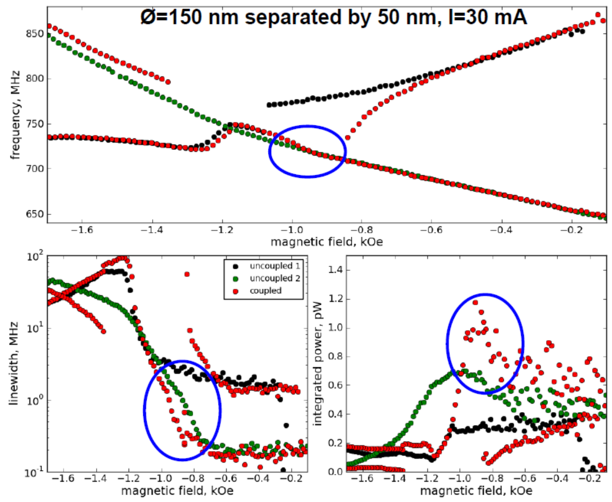


In order to understand the different behaviors observed in the two synchronization experiments presented above, it is quite convenient to analyze how the dipolar interaction varies over a precession period.

For simplification, we only consider the dipolar interaction between the thick layers, which is dominant here. We recall, that the strong Oersted field induced by the DC current forces the chiralities in each layer to be parallel. When both core polarities are parallel, the two vortices gyrate in the same direction (see left panel), while when they are anti-parallel, they gyrate in opposite directions. These two situations are not equivalent: contrary to the latter case, the dipolar interaction is not always minimized in the former case, as depicted by the green and red signs. Therefore, the dipolar interaction averaged over one period of precession is larger when the core polarities are anti-parallel, which should then favor synchronization.

To confirm this picture, we now purposely prepare this state of opposite polarities in the thick layers: we use the fact that the switching fields in the two layers differ, by performing a minor loop.





Here, we exploit one more time the fact that opposite polarities follow opposite frequency-field dispersion relations. In this experiment, we can clearly see that when the auto-oscillation peaks are close enough in frequency, a **strong pulling** occurs, that makes them meet each other (synchronize). It is analyzed in the top right graph, where the data (red dots) corresponding to the strong coupling regime presented in the left color map are compared to the case where the core polarities are parallel to each other (black and green dots). It can also be seen that the strong dipolar coupling in the case of opposite polarities (red dots) **improves both the linewidth and amplitude**. One can also note the appearance of signals at mixing values of the two oscillating frequencies in the pulling regime at field above -0.9 kOe (before the vortices phase-lock their motion). This is again a **clear signature of the mutual interaction** between the two oscillators, that is also observed when we synchronize a single vortex STNO to an external source (the RF field produced by an external microwave antenna, see figure).

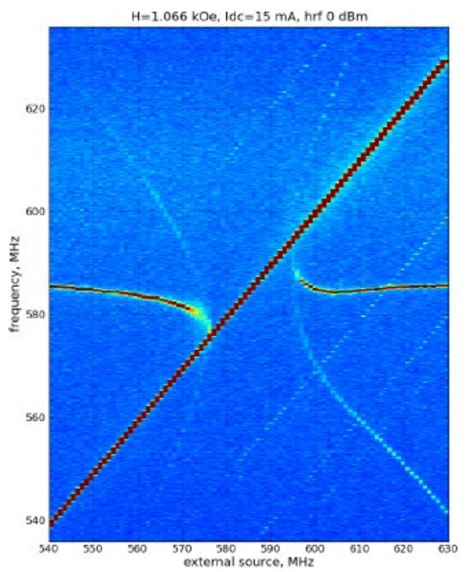
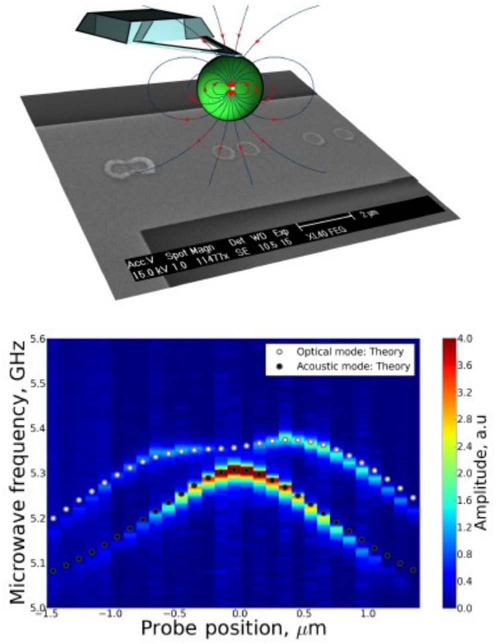


Fig. 17 Synchronization of a single STNO a an external RF field.

In summary, the synchronization of two adjacent vortex-based STNOs has been achieved for the first time. Different regimes of synchronization can be observed depending on the equilibrium case (relative orientation of the core polarities in the thick layers, but also probably, equilibrium state of the thin layers). Experimental measurements and calculations are still in progress to understand more deeply the mutual synchronization in *N*=2x2 vortex STNOs.

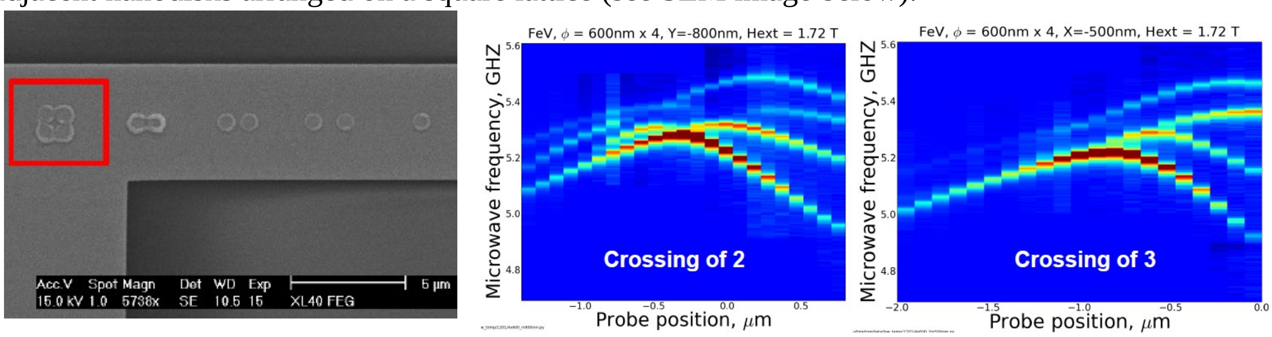
<u>2 – Poker (*N*=*4*) of adjacent STNOs</u>

In the case of two adjacent oscillators, one can tune their emission frequencies relative to each other, even with the easiest design of common injection electrodes. This is possible due to their different tunability on the external bias parameters (field or current, see part B). In the case of *N*=4 adjacent STNOs, the situation can be quite more complex. Due to limitations of the nanolithography process, there will always be some distribution of the emission frequencies of the different STNOs. In the absence of individual injection electrodes (which are quite a challenge for nanofabrication due to the close spacing < 100 nm required between adjacent oscillators to optimize the dipolar interaction (see deliverable DF-7), one needs another button to tune their frequencies. Such a button can be provided by the strayfield of the MRFM probe, as it was already presented in deliverable DC2-4 in the case of *N*=2 and recalled in the figure on the right, where the frequency anti-crossing reveals the strength of the dipolar coupling.



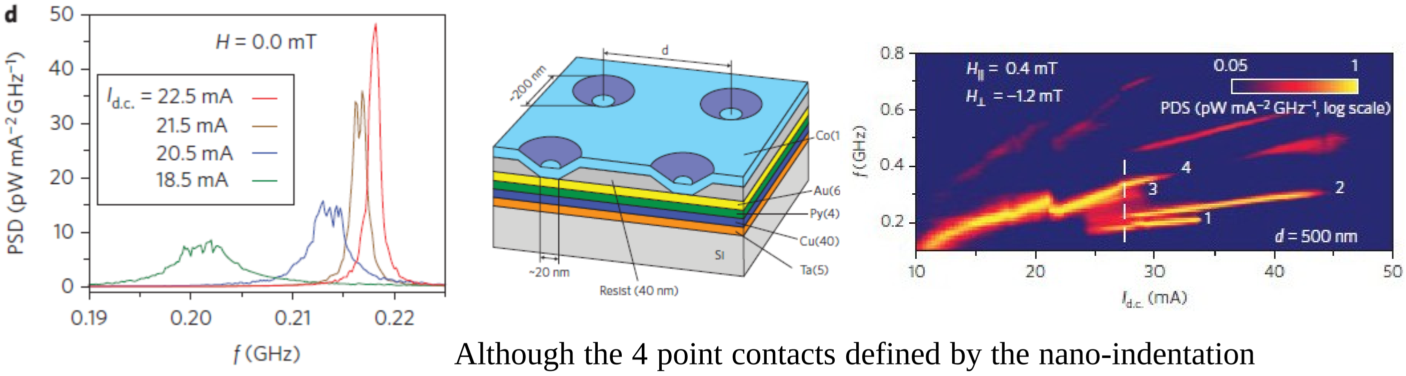
Fi. 18 Continuous tuning with the MRFM probe and frequency anti-crossing (N=2).

We have tried to use the same technique in order to tune continuously the frequencies of *N*=4 adjacent nanodisks arranged on a square lattice (see SEM image below).



As one can see, we were unsuccessful to make the 4 peaks cross (i.e., to phase-lock the 4 oscillators) by scanning the MRFM probe above them. The maximum number of oscillators that we could synchronize using this method was *N*=3 (see right panel above). However, we note that in this experiment, the nanodisks were saturated along their normal, resulting in a dynamical dipolar coupling strength that is weaker than in the vortex state.

Another experiment to achieve the synchronization between *N*=4 vortex-STNOS was attempted during the MASTER project. The sample consists here of 4 point contacts made on a continuous 15 nm thick Cobalt film, see left sketch.

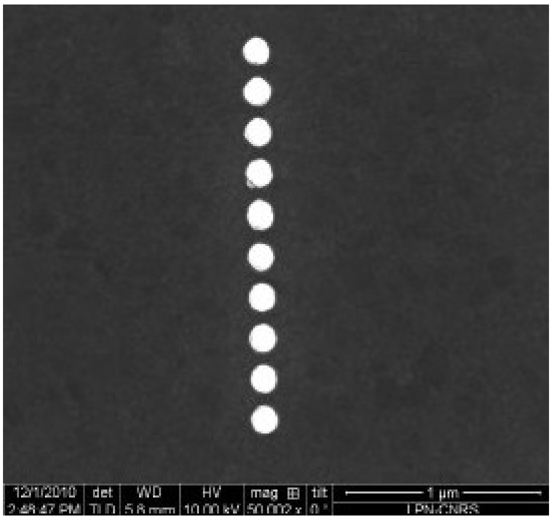


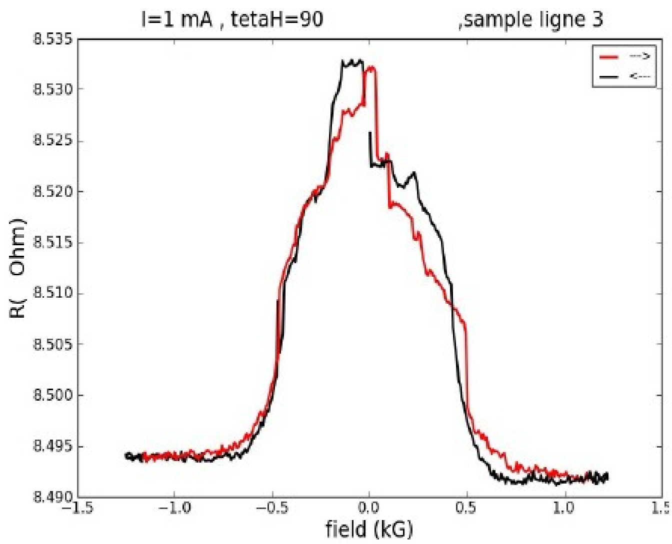
Although the 4 point contacts defined by the nano-indentation method employed here are not exactly identical, it was still possible to observe the **phase-locking of the *N*=4 vortex oscillators** in that case, by ramping the common dc current flowing in parallel through the 4 nano-contacts (middle and right panels). The coupling mechanism between the 4 vortices is indeed reinforced from the pure dipolar case owing to the presence of anti-vortices in the continuous layer of Cobalt (exchange + dipolar interaction).

In summary, we have shown that in the absence of a mean to tune individually the bias conditions of each oscillator, the synchronization of N>3 STNOs can be particularly challenging. Still, it is possible to phase-lock several dislike oscillators if the coupling mechanism is strong enough, as e.g. in the above presented work.

3 – Attempt on *N*=10

During the last period of the MASTER project, we have measured several samples consisting of *N*=10 adjacent STNOs arranged in a line.





We have first performed standard DC transport measurements on these *N*=10 samples. A typical GMR curve obtained at small bias current (1 mA) is presented in the graph on the right. The bell shape together with the numerous small resistance steps is similar to the one observed on nano-wires containing many GMR stacks. This qualitative resemblance indicates that many (up to 10) STNOs are electrically connected in parallel, although there is no way to know exactly how many.

It turns out that these samples are **quite fragile**. Although we were able to inject high enough dc current (> 10 mA) through one of them in order to observe spin transfer induced vortex oscillations (we could see two oscillation peaks merging into one with the increase of the dc current), it died before we could record any data on the spectrum analyzer. Therefore, we have decided to investigate the high frequency properties of these *N*=10 samples in the **passive regime**, where a small RF current (i_{rf} ~ 100 µA) is injected through the sample in order to excite spin-wave modes, and the DC voltage is monitored. This technique was successfully employed to study *N*=1 STNO and to extract useful material and geometrical parameters. Moreover, by adding a DC current, it is also possible to determine whether a mode is auto-oscillating in the sample. We performed this study on two different *N*=10 samples, in the perpendicular saturated state.
Although the *N*=1 spectrum looks already quite complicated, it can be fully understood above the saturation field (6 kOe), which takes into account the dipolar interaction between the thick and thin layers of a single STNO. Here, it is interesting to note that the spectra of the *N*=10 samples, instead of displaying discrete, well separated peaks, display peaks which look **multiple or broadened**, the signature of the presence of several similar oscillators in the device. In order to reveal this better, adding a DC current to the RF excitation is useful. In fact, as spin transfer torque comes into play, the thin layer modes should be strongly affected at negative currents.
This is indeed what can be observed in the two above spectra. On the left spectrum, one can see a collection of peaks (at least 6) growing at negative current, in magnetic fields ranging between 8 and 10 kOe. The right graph is even more interesting. It can be seen that already at current < 8 mA, some peaks get really distorted, a signature that these particular spin-wave modes start to auto-oscillate. Contrary to *N*=1, there are several of them (up to 4), implying that **several STNOs are oscillating at the same time in this *N*=10 sample**.
In summary, we were not able to directly record the spin transfer driven oscillations characteristics of *N*=10 samples due to their fragility. Nevertheless, we conducted experiments which unambiguously demonstrate that such a STNO array can auto-oscillate under spin transfer torque. The detailed understanding of the spin-wave mode spectra in these arrays containing 10 similar (but not alike) oscillators is challenging. In fact, the mutual dipolar interaction between them should lead to collective modes. By studying the dependence on the angle of the applied field, and by taking into account the fact that DC and RF currents flowing through STNOs in this array also induce in-plane dipolar magnetic fields, we the main features of these excitation spectra could be understood.

Perspectives of the bottom up activities:

The bottom-up approach for the fabrication of STNOs nanowires using electrodeposition into nanoporous templates is simple, flexible, and cheap. This technique thus provides an interesting alternative to lithographic processes used for the fabrication of nanopillars.

Electrodeposition into nanoporous ordered AAO (anodic aluminium oxide) templates entails unidirectional growth of nanowires with monodisperse diameters. Both wire diameters and periodicities are controllable to a large extent. Yet nanowires with ultralow diameters (a few nm) can be produced using AAO that are otherwise difficult (or even impossible) to prepare using lithographic methods. However, in the present work, pore diameters of 80-100nm were considered for the fabrication of the nanowires.

Electrodeposition technique makes it easy to design the stacking of multilayered nanowires in the axial direction, thus making spin-valve stacks, such as Co/Cu/Co and NiFe/Cu/NiFe, with individual layer thicknesses controlled with a resolution of ~1 nm for typically 1Onm thick layers.

The use of alumina templates supported on Si substrate prevents one from breaking the fragile template during handling and/ or nanocontact fabrication process. In addition, the template can be thinned down to ≈100-200 nm by mechanical polishing with a resolution of a few tens of nm in such a way that the lengths of the electrodeposited nanowires are uniform and equal to the thickness of the template. As a result, nanowires with controlled aspect ratio can be obtained.

Different approaches have been successfully developed to connect separately individual nanowires in a large assembly of wires embedded in AAO templates (using nanoindentation - UMPh CNRS-THALES) or a limited number of nanowires ($2 \leq N \leq 5$, using e-beam lithography – UCL). In both cases, it was possible to inject a sufficiently high current density perpendicular to the plane of spin-valve nanowires to measure spintronic effects like GMR, spin-transfer-torque, and even microwave emission.

By successive electrodeposition of STNOs into the pores of alumina template, each of them being separated by a non-magnetic spacer, the desirable STNO stacks connected in series can be obtained (which is a huge technological challenge using the standard top-down lithography processes).

As a result, up to 1011 spin-valves per cm2 may be growth into a 1 μm thick AAO template.

Drawbacks

1. linked to the limits of the electrodeposition technique

Using electrodeposition into nanopores, the control of the thickness in the individual layers as well as the flatness of these layers is not so good as the one obtained using physical vapor deposition. Therefore, the geometry of the magnetic layers may differ significantly from flattened cylinders with possible non-uniformity in the magnetic properties of the successive magnetic layers of the STNO stacking.

The STNO nanowires are prepared using a single bath electrodeposition technique, where both Co and Cu ions are present in the solution, so a small amount of Cu is incorporated into the Co layers (Ms also slightly decreases consequently) with potential and still undetermined reduction of spin diffusion length in the magnetic layers.

The concentration of Cu in the electrolytic solution is quite low (around 15 mM) giving rise to a rather poor crystalline quality of the Cu layers in the electrodeposited STNOs. As a result, the current density that can be injected through the system is somewhat reduced compared to the lithographically defined STNO pillars.

Another drawback of the multilayer electrodeposition process is that the magnetic metal dissolves during the deposition of the more noble metal. However, for the Co/Cu system, even if the dissolution of cobalt cannot be completely eliminated it can be strongly reduced by the appropriate choice of the deposition potential of Cu.

Electrodeposition under hydrodynamic condition (leading to more uniform and reproducible deposits as a steady state can be attained rapidly and the rate of mass transfer at the electrode surface are larger than the rates of diffusion alone) cannot be achieved by considering electrodeposition into nanopores.

2. *others*

The dense array of STNOs embedded in the AAO template may lead to complex magnetic interaction between the neighbouring nanowires that may hamper the synchronization between STNOs. In principle, it is possible to limit this dipolar interaction by tuning the geometrical arrangement of the nanopore array (interpore distance and pore size) from the anodization process (anodization potential, nature and acid concentration in the commonly used electrolytes for the preparation of porous AAO)

Breakthroughs and perspectives

Both current-driven magnetic excitations (microwave emission) and switching phenomena by spin-transfer effect were clearly demonstrated in electrodeposited Py/Cu/Py and Co/Cu/Co trilayer nanowires. These results were obtained under specific applied magnetic field and current conditions.
Comparison with previous experimental works on vortex-based STNOs and with our numerical results, leads us to conclude that in our system, the emission is due to spin-transfer-driven vortex excitation.
Main features : relatively low frequency of the emission (1-3 GHz), low linewidth (4 MHz) and tunability ($\partial f/\partial I \simeq 50$ MHz/mA) + linear field dependence of the frequency.
Our system is promising for microwave device applications since it allows connection of a huge number of metallic spin-valves in series and/or parallel, which could lead to high-quality coherent emission by synchronization.
Using micromagnetic simulations, we have evaluated optimal thickness conditions of the non-magnetic spacer layer for a series connection of two STVOs considering the two vortex states (spacer ≤ 80 nm at zero field and spacer ≤ 45 at Hz = 500 Oe).
The single nanowires measured so far have 6 spin-valves connected in series by non-magnetic spacers of about 100 nm. There is no evidence about the synchronization of at least two STNOs (spin-valves) according to our measured spectra but no evidence doesn't mean no synchronization. Indeed the signals obtained at zero field gave for instance a better spectral quality (lower linewidth and larger peak height).
New samples are at the final processing step with suitable spacer thicknesses (40-60 nm). Furthermore, even more recently, samples containing only 1 and 2 spin-valves were fabricated to make the fundamental dynamics easier to understand.

Comparison of the different couplings:

All the experimental studies performed inside MASTER were not able to clearly distinguish the coupling mediated by the diffusion of the conduction electrons inside the metallic base from the coupling mediated by the magneto-dipolar interaction. The size of the STNO nano-objects, in the hundreds of nanometer of lateral size, combined with the experimental measurement of the spin-diffusion length in Cu, found to be of the same order of magnitude, has prevented us to find a discriminating regime, where one coupling could be tailored dominant compared to the other. Experimental studies have consisted in cavity-FMR measurements performed on two different series of regular arrays of STNO, each having undergo a different etching procedure – STNOs patterned up to the $Si0_2$ substrate and STNO patterned up to the common Cu base –. The results obtained (see attached document) did not show evidence of drastic differences in terms of coupling strength, suggesting that for our standard STNO stack the coupling by the diffusion of the conduction electron was at best of the same order of magnitude as the magneto-dipolar coupling. These results were presented during the MASTER's meeting in Exeter. Since a focus in the sample fabrication list was necessary, it was decided during this meeting that the project should concentrate first on the magneto-dipolar coupling for three reasons:

1. its existence is established
2. this coupling can be easily calculated by micro-magnetic simulations, and thus a reliable roadmap towards optimization can clearly be within reach
3. contrary to the coupling by the conduction electrons, the dipolar coupling does not require the presence of a common metallic base having large spin-diffusion length between the STNOs. The absence of this constraint allows a substantial simplification of the nanofabrication process.

The conclusion of MASTER on this issue, is that, although the coupling by the diffusion of the conduction electrons might be promising in some particular instance, the magneto-dipolar coupling is, according to our current state of knowledge, the best choice if one wants to synchronize STNOs separated by distances of the order of their diameter.

Synergy between the partners:

Federation of complementary European experts working in the field of thin film deposition, nano-fabrication, transport measurements, and developers of innovative spin-wave spectroscopy experiments and novel simulation tools has been key to progress efficiently in a worldwide competitive field.
The work program of MASTER has involved cross experimental studies between different nodes, sharing and exchange of PhD students and postdoctoral associate between different locations have been effective. The reality of this synergy can be concretely illustrated by the numerous joint publication listed below. During the 2nd period N. Locatelli, CNRS PhD student, and V. Naletov, CEA PostDoc, have performed joint MRFM and transport experiments on the vortex state allowing cross seeding of expertise between these two techniques. This collaboration has led to two joint papers one on the vortex dynamics, the other on the behavior in perpendicular magnetic field. K. Zvezdin form IPM, has spend some time at the CNRS node, to calculate the dynamics and spin transfer selection rules inside vortex state nano-disks. This simulation effort was also extended to the experimental effort by the UCL group to help them design an optimized electro-deposided nanowires containing vortex state coupled STNOs in series. Still on the theory side, S. Borlehghi-Garoia a PhD student from the CEA node, has also spent time on the C-RMT theoretical model developed in collaboration with the CNRS group to simulate the dynamical behavior of perpendicularly magnetized nano-pillar in the mode competition regime. Finally, we shall mention that H. Hurdequint CNRS, P. Keatley and V. Demidov has been very involved together with cross sharing of information between the cavity-FMR, μBLS and TR-MOKE.

Patents :

Another spin-off of this research, which might have impact on the magnetic data storage technologies, has been the discovery of new types of magnetic memories exploiting the vortex state (APL 96 132506). New physics on resonant induced magnetization reversal of the vortex core has been

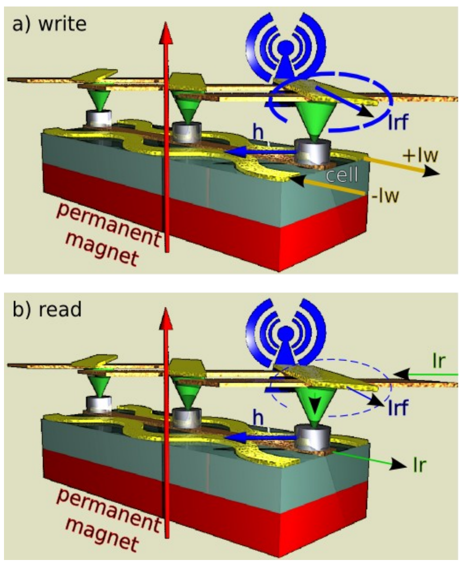


Fig. 22 Schematic of the solid state vortex memory

achieved to enhance our ability to develop modern ultra-high-density Magnetic Random Access Memory by strongly reducing power dissipation. A patent has been filled for a frequency controlled magnetic memory. By purposely splitting the resonance frequencies of the two different vortex polarity states used to store the binary data, deterministic local addressing of information is achieved thanks to resonant processes. Besides the facts that such a frequency controlled magnetic memory is a new concept based on a recently discovered physical process – the dynamical reversal of the vortex core – and is demonstrated by top of the art experimental techniques, it also shows an extremeely interesting technological advance, namely an optimized energy consumption. This point is of crucial importance in these days, when energy saving technologies are urgently needed. In our frequency controlled memory concept, the energy gain is due to three key ingredients:
i) No electrical power is required to hold the stored information (non volatile memory) ii) The weak energy cost due to the extremely small magnetic volume which is reversed (the nanometer size vortex core). Iii) The high efficiency of the reversal process (resonant effect). For a comparison, while a 3kG static magnetic field is required to switch the vortex polarity, a 0.002kG field is sufficient to resonantly reverse the same magnetic body. Combining this effect with the local RF produced by a STNO might open a new field of application, whose economical potential is huge.

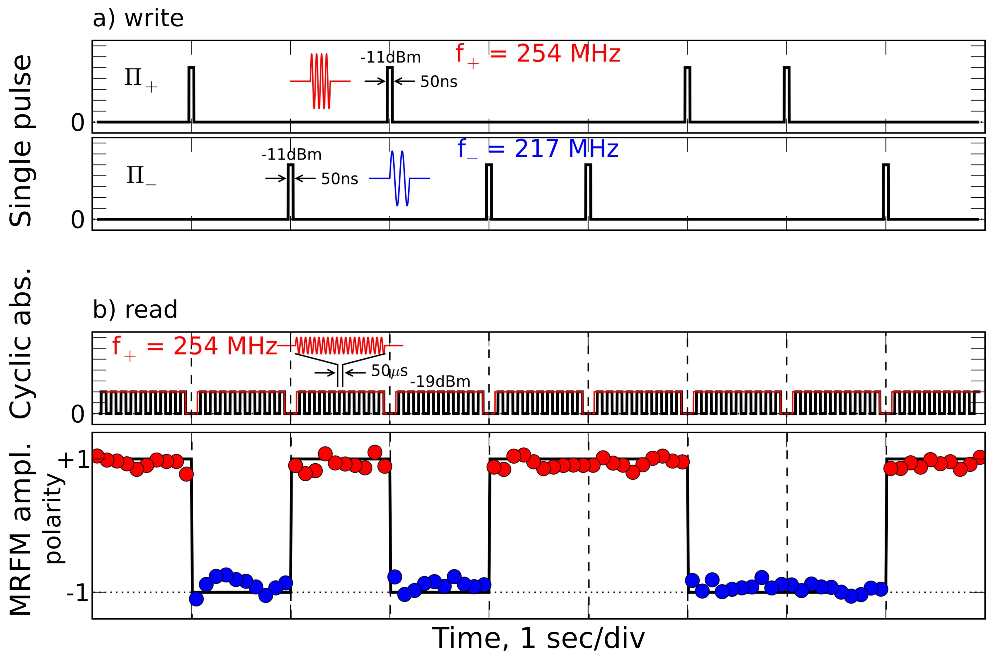


Fig. 23 Concept of frequency controlled memory: illustration of the read-write control of the polarity of the vortex state by a rf-pulse.

d) Description of the potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and the exploitation of results.

Industrial applications:

Telecommunication technology relies on the development of high-performance microwave components that ideally combine both high-agility and high-selectivity. The table below provides a review of the different state of the art technologies. The lowest possible phase noise oscillators at microwave frequencies so far are sapphire loop oscillators, which however are barely tunable (the best tuning range demonstrated was 50 kHz). A more widely developed microwave oscillator is the YIG-tuned electrical oscillator. The latter is noisier but highly tunable. Applying an external magnetic field can easily change the resonance frequency of the device thanks to its gyromagnetic nature. Applying a 15mA current inside a microscopic line produces a 30 mT Oersted field at distance of 100 nm . This leads to an outstanding tuning range in excess of 1GHz. Furthermore YIG has low phase noise (-140 dBc/Hz) and is considered the best material for high selectivity. The drawback of such narrow line-width materials (equivalent to long characteristic time) is of course the relatively slow speed of response to changing conditions. The discovery in 2003 of Spin Transfer Nano-oscillators (STNO)[1] has completely changed the picture, allowing electrical control of damping for the first time. Thus one could possibly combine ultra-high selectivity (low damping) and high-speed agility (large damping) within the same device.

Technology	Agility	Speed	Q, selectivity	Phase noise	Size	Freq (GHz)	Integration
Quartz, SAW	very low	high	high	good	mm	1	external
Ring osc	medium	high	very low	very poor	µm	20	integrated
LC circuit	medium	high	low	poor	cm	40	hybrid
Cavities	low	very low	high	very good	cm	100	external
Dielectric	very low	high	high	very good	cm	100	hybrid
YTO	high	low	high	very good	cm	20	external
STNO	very high	high	medium	medium	nm	100	integrated

Another advantage that the industry has foreseen in STNO devices are first their true nanoscale, allowing to concentrate the dynamics at the nanoscale level. Furthermore, their fabrication relies on a technology compatible with CMOS technology. Another important property is their very large tunability. Adding a current through the device or applying an external field allows large change of the carrier frequency, where competitive technology considers that 10% changes are outstanding performance. This tunability is further enhanced by the possibility to tune the damping parameter by an external control. Thus one could possibly combine within the same device ultra-high selectivity (low damping) and high tunability speed (large damping). Another unique feature of STNOs is their propensity to reach easily the non-linear regime. Nonlinear devices have important application for such important elements such as mixers or limiters that protects sensitive device such as low noise amplifier. Another potentially important quality of STNOs so far unexplored, is their ability to reach the millimeter frequency range (100GHz to 1THz) through for example anti-

[1] S.I. Kiselev,et al. Nature **425**, 380 (2003)

ferromagnetic resonance. But the list of advantage enumerate above must be balanced by a series of limitations. STNOs suffer from low output power, but more importantly from very large phase noise. Their characteristic impedance also requires the use of impedance matching circuits either low Z for spin-valves or high Z for magnetic tunnel junctions (MTJ). Another drawback of these devices is that the magnetization dynamics in such confined geometry is at the forefront of fundamental research. Basic questions such as the nature of the eigen-mode auto-oscillating, the nature of the damping or the non-linearities remain to be done. As such, the European project MASTER has helped European teams to bring STNO components from a curiosity developed inside research laboratories to a high performance device, whose characteristics allow the integration inside more elaborated microwave circuit.

During the last three years the state of the art for STNO power performances has increased by more than 4 orders of magnitude (40dB in the microwave technology jargon). From output power in the picoWatt (10^{-12}W) range back in 2007, a single device reaches now the microWatt range, which is enough for applications. The best power output obtained in 2011 in a single MTJ device in the vortex state is 0.6microWatt (0.6 10^{-6}W), integrated power. The coherent width is 500kHz. The exact structure is a hybrid GMR and TMR devices produced by S. Yuasa in the National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan. Most of the gain is extracted from the magnetoresistance ratio. The power output scales as the magnetoresistance square. To compare the performance in terms of linewidth, one should keep in mind the typical Q oberved in FMR. The reference material here is a perfect sphere of YIG, whose linewidth at 10GHz is about 1G. YIG is an insulator. The damping increases significantly already with semi-metals such as Heusler alloys, whose linewidth at the same frequency is more around 10G. This should be compared to the best alloy, wich is a Ni and Fe micture in the 20% - 80% ratio. This alloy, called permalloy leads to a linewidth at 10GHz which is about another order magnitude larger, ie 100G. In the mean time in Europe, progress obtained by Spintec have allowed the fabrication of competitive layered structure based on MgO technology. Current state of the art at Spintec is RA=1.8 Ohm. um^2 TMR= 80%, linewidth= 20MHz. The wafer is a LETI trademark under a joint project with Aviza. Until recently, other source of MTJ wafers are made by Singulus, where the wafers were processed by IMEC. The challenge for MTJ has been to decrease the RA. Spintec has also shown that it is possible to boost the MTJ output performance by about 10dB using an impedance matched high impedance amplifier. In terms of oscillator performance the benchmark is the Quartz oscillator such as the ones used in synthetizer. The carrier frequency is in the RF range, typically 10MHz, with a phase noise close to thermal noise -174dBm. On the wings of the resonance the power decreases as $1/f^3$ ie -9dB/octave. Reaching the thermal requires a decrease in the wing of the resonance of -150dBc compare to the carrier at 0dBm. This point is called the corner frequency. The point where noise increases by 3dB from the floor. For good X band oscillators, the corner noise is at about 1 MHz. Such number is usually not good enough for radar applications. If one takes an oscillator output and pass it through a gain amplification of 10^3, noise is also mutliplied by the same ratio and it receives a 60dB increase. One trick that is used to take advantage of both world is the phase lock loop on quartz, so the oscillator at resonance is the phase noise of Quartz and the phase noise outside resonance approaches thermal noise -174dBm far. But the cut-off frequency of the PLL (bandwidth of PID loop) introduces a noise plateau. For the sake of information the quality factor of a VCO is about 10 to 100.

Fig 25: Packaging of a RF switch

Another market of the microwave field that will benefit from this project is application of STNOs as passive devices such as non-linear elements, magnetic memories and so on... One particular case is microwave detection. The state of the art technology at the moment is the Shottky diode. The diode rectifies the incident power, providing a signal that is of one polarity (either all positive or all negative) to the bypass capacitor, with an amplitude proportional to the input power level (square-law). These diodes are usually made of semiconductor on GaAs or Si. Diodes are the workhorse of the solid-state microwave switch industry and they are found in RF switches, attenuators, and photodetectors. A diode acts like a current controlled resistor. In a PIN diode the more current that you inject through the I region, the lower the RF resistance. The sensitivity of a diode to detecting weak AM signals can be improved by adding just a DC voltage to move the operating point slightly closer to forward conduction. Most detectors are not biased; they are referred to as "zero-bias detectors". Typical sensitivity of a PIN diode is 1V for 0dBm. These materials are usually bulky (bipolar technology), and thus have large capacitance. One direct consequence of this capacitance is that PIN diode have usually a poor reverse recovery time. By replacing the diode with a all metallic structure, one can benefit both from the miniaturization of the device and larger electronic density of metallic multilayer structures. This reduces dramatically the capacitance, leading to very fast switching time. Other important advantages of using metals instead of semiconductors is an increase in precision: diodes are very sensitive to thermal stability, hereby limiting their dynamical range. This confers to STNOs the remarkable quality of having their relative sensitivity being conserved through large temperature changes thus allowing to use them in particularly stringent environment. One particular interest for example space applications is very good behavior under radiation, like from cosmic rays. Sensitivity wise spin-valve arrives to somewhat equivalent characteristics with variation of the resistance that could be as high as 100mV for 0 dBm.

Another idea will be to increase further the size of the signal by using stochastic resonance. By biasing the device with a large perpendicular magnetic field, it is possible to arrive at the compensation point where the internal effective magnetic field vanishes (soft mode). In this case, it is possible to switch the magnetic configuration between two bi-stable state using microwave radiation. In this case the amplitude of the signal generated by the microwave incident power could be anhanced by several orders of magnitude.

Finally it is useful to mention that another important parameter that has been investigated by MASTER in magnetic oscillators is the magnetic ground state. One case that has attracted a lot of attention is the vortex state. Magnetic vortices are singular topological states found in the equilibrium magnetic configuration of sub-micron size ferromagnetic dots. In a certain range of dot aspect ratios the equilibrium ground state of the static magnetization consists of the curling in-plane magnetization and a nanometer size core of the out-of-plane magnetization at the dot center. The magnetization of the vortex core can point either up or down, both polarities being degenerate at zero field. This bi-stable property of magnetic vortices, as well as the switching from one polarity to the other, have been intensively studied in the past few years because of their possible applications in magnetic storage devices. It has already been established : (i) that the lowest excitation mode of the vortex state is the gyrotropic mode corresponding to a rotation of the vortex core about the dot center, (ii) that the frequency of this mode is linearly proportional the dot aspect ratio, and (iii) that the sense of gyration of the vortex core is determined by a right-hand rule to the core polarity. During the gyrotropic motion, the magnetization inclosed inside the orbit of the core motion, undergoes a full rotation during a period. Concentrating a current in this region allows to generate the maximum oscillation of magnetoresistance in a magnetic system. Another important property of the dynamics of the vortex state is that it does not require any additional bias magnetic field. Finally, it is worth to mention that the magnetic core of a vortex has lateral dimension of the order of the exchange length. Thus it constitutes one of the smallest volume in magnetic object stable at room temperature. This ensures that process such as reversal of the magnetic core should require the minimum power consumption. There are however some drawback in using the gyrotropic mode for application. The principle is that this is usually a very low energy mode due to the very weak restoring force of the confinement potential of the core. Using the largest magnetization material, such as Fe, will still limit the frequency of the gyroptropic mode below 2 GHz. There are still tricks that could be implemanted to increase this threshold, through local increase f the anisotropy or local implantation of ion, but this topic is still in the domain of fundamental research.

Drawing from the MASTER pool of knowledge established by the academic partners, four systems where spintronics components and their unique microwave properties can have tremendous impact have been identified with the help of an Industrial Consultant Board. More specifically, their aim is to demonstrate alternative paths for (i) ultrawideband microwave frequency synthesis, (ii) high data rate field sensors, (iii) Instantaneous microwave frequency detection and (iv) broad bandwidth and high slew rate proximity detection, thus widening substantially the panel of potential applications to different industrial sectors.

● A first potential spintronics microwave system to be developed is a highly integrable and tunable frequency synthetizer integrated in a specific phase locked loop (PLL). Here the STNO replaces the voltage controlled oscillator (VCO) of conventional technology. Such a PLL represents a basic building block in telecommunications applications and its main purpose is to improve phase noise characteristics of the stand alone oscillator. In STNOs, the non-linear phase-amplitude coupling, as well as their exceptionnal frequency tuning capabilities via a small applied current and/or a small applied magnetic field, provide innovative and original solutions[2] to realize single as well as higher level PLLs adapted to the STNO properties.

● A second spintronics microwave system to be developed is a dynamic magnetic read head (called STNO reader or dynamic reader) used in data storage in order to push the limits of high data rate access. Currently the magnetic stray field of the magnetically stored bit is read out via a change in the *static* magneto-resistance of the device. Scaling down can be pushed substantially when using a dynamic read out. This innovative read-out concept derives from the large sensitivity of the STNO precession frequency to small changes in the bit “0” and bit “1” magnetic stray fields. These changes in frequency are then converted into a DC voltage signal via a specially designed demodulation RF circuit. Besides data storage applications, this concept provides a very versatile and sensitive magnetic field sensor to detect nanoparticles for instance such as magnetically tagged molecules in biological/pharmaceutical applications.

● A third spintronics microwave system to be developed is a wide band instanteneous frequency detector in the low (0.2-2GHZ) and the high (2-20 GHz) frequency range used in telecommunications applications (e.g. cognitive radio, RADAR, spectrum control and regulation). The detector function derives from the capability of STNO to become µwave sensor detector to convert an RF input signal via a rectification effect into a DC signal when the input signal frequency of the input signal is equal to the internal frequency of the µwave sensor detector. Interestingly, this new type of devices are able not to detect the frequency but also to measure the level of the external rf signal. Such a type of detector has a major advantage over traditional diode detectors where many signals exist simultaneously as in transceivers or other frequency converting systems. High efficiency (input power/output voltage) and low signal to noise ratios are predicted using tunnel magneto-resistive devices. The innovative solution is to use arrays of µ-wave sensor detectors, designed to have different internal frequencies. In this way instanteneous parallel

[2] U. Ebels et al, CEA Patent 2010

detection of a wide frequency range is possible, thus providing instanteneous frequency detection compared to existing system where the frequency is continuously sweeped.

● A fourth spintronics microwave system to be developed is a broad bandwidth and high slew rate proximity sensor for Automation, Control & Security (ACS) applications, derived from the signal generation and modulation capabilities of STNOs. The advantage over conventional sensors is that no passive circuits are required for oscillation; STNOs are extremely small and can operate at very high fundamental frequencies, providing very high resolution in short distance measurements, which is of interest for close in proximity sensors. Here discrete systems, on PCB boards can be developed and characterized.

The beneficiaries of this know-how established by MASTER are are now federated inside a project named MOSAIC, recently submitted to the FP7-ICT-2011-8 call towards objectives 3.1 "*Very advanced nanoelectronic components: design, engineering, technology and manufacturability*" whose plan is to exploit the benefits of STNO optimization obtained by MASTER in order to develop these novel spintronic components for the wireless telecommunications and data storage industry.

Simulation software

Another outcome of the project is the development of the simulation software SpinPM.

Subject of the modelling: spin wave excitation by spin-polarized current and spin-diffusion effect in normal metal near a junction.

Models: finite difference micromagnetic solver of the *Landau Lifshitz Gilbert* differential equation.**Type of numerics used:** The micromagnetic package SpinPM is a generalized Landau Lifshitz Gilbert solver based on 4th order Runge-Kutta scheme with INTEL MKL FFT acceleration. It integrates:

- Plug&Play user-friendly GUI
- FFT-accelerated magnetostatics
- time integration using 4th order Runge-Kutta solver
- time step auto-adaptation
- very flexible system definition
- Spin Transfer Torque with both Slonczewski and Field-like torques

- **Achievements of the modelling beyond experiments:**

The model can predict the magnetization dynamics in an array of hetero-structure. This dynamics cannot be computed analytically. Simulations are here useful to optimize the design. Optimization by experimental means would be too costly.

References to articles that may be useful for review :

A.V. Khvalkovskiy, KAZ, et al Phys. Rev. B. 80, 140401(R), (2009)
A. Chanthbouala, AVKh, KAZ, et al., Nature Physics 7, 626 (2011)
A. Dussaux, AVKh, KAZ et al., Nature Com. 1, 1 (2010)
A.D.Belanovsky, KAZ, et al, Phys. Rev. B 85, 100409(R), (2012)

Added value: Computer modelling simulations and virtual prototyping of coupled STNOs with realistic geometries. This application of existing micromagnetic packages allowed us to reveal the influence of geometry and structural defects upon the STNO phase diagram, phase-locking

performance, and line width, and to create a virtual prototype of the STNO array with optimized properties. The role of the thermal fluctuations in the phase-locking mechanism has also been investigated within the framework of a full scale 3D micromagnetic model, allowing the optimization of the array to be carried out.
Magnetization dynamics have been investigated in polycrystalline films, with the parameters of magnetic materials being distributed randomly over the crystallites have been emulated.

New physics features which include the incorporation of the Berger / Slonczewski transport term inside micromagnetic code has been developed. SpinPM allows to simulate spin current-related effects. A model that includes Spin Transfer-induced torque has been developed.

We have also developed a simple theoretical framework for transport in magnetic multilayers, based on the Landauer-Büttiker scattering formalism and random matrix theory. A simple transformation allows one to go from the scattering point of view to theories expressed in terms of local currents and the electromagnetic potential. In particular, our theory can be mapped onto the well-established classical Valet-Fert theory for collinear systems. The Landauer-Büttiker formalism which expresses the problem of transport inside a quantum conductor as a scattering problem. This approach is well suited for a coherent system and is equivalent to the Keldysh approach. However, the classical concepts of chemical potential or local equilibrium do not arise naturally in the scattering approach so that classical intuitions do not easily transfer into its language. We have taken the scattering formalism as our starting point and develop a theory which fully captures Valet-Fert and (generalized) circuit theory. Our theory referred as C-RMT (for Continuous Random Matrix Theory) can be tabulated by the same set of (experimentally accessible) parameters as Valet-Fert. We are actively pursuing now an effort to incorporate C-RMT inside the micromagnetic solver.
We enhanced and improved a high performance micromagnetic numerical solver in order to define the structures. The code has been elaborated to be able to deal with high simulation volume (up to few micrometer lateral sizes), non-regular structure (multilayered structures), non-regular dynamics (very short-wavelength modes are excited), and huge computational times (> 50 ns). On the numerical side features have been added to the code to define the structures and to help the analysis of the magnetization dynamics of the system.

The new software SpinPM whose most important improvements are:

1. New time integration algorithm based on an integration procedure that includes an adaptive time-step control with a 4th order Runge-Kutta method.
2. New exchange energy calculation algorithm: a new, energy-conserving, numerical algorithm has been developed and implemented allowing very simulations on very long time range
3. Fine system specification allowing much better flexibility in object specification.
4. Spectra calculations: This tool provides us with a possibility to calculate these spectra for a batch of projects

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Training of PhD students and Postdocs:

Another benefit of the project MASTER has been to produce highly **trained scientists and engineers** to help meet Europe's need for skilled people, to support investments in spintronics and wireless telecommunication technology. The project has helped the hiring of 10 post-doctoral associates and 12 PhD students. Overall the induced synergy between complementary expertise has helped to develop **cross-disciplinary research** between the magneto-transport and microwave technology communities, and to bring together a consortium with expertise covering aspect of the STNO device, from nano-fabrication and spin-transfer experts, to spin-wave spectroscopists specializing in the dynamics of nano-objects and theoreticians. This team work has helped to push the European research involved in this very competitive topic at the forefront of the research that is being down internationally on spin transfer effects.

Postdoc and students that have worked on the project MASTER (by node):
CEA: Abbass Hamadeh, Vladimir Naletov, Simone Borlenghi, Valentin Rychkov, Benjamin Pigeau
CNRS: Paolo Bortolotti, Nicolas Locatteli, Antoine Dussaux, Vincent Castel
Münster: V. Demidov, Alexander Dzyapko
Exeter: Paul Keatley, Pim Gangmei, Uday Al-Jarah,
UCL: Maria Matefi-Tempfli, Sébastien Tuilard, Loïk Gence, Pascale Lipnik, Sébastien Adam, Michael Darques
IPM: Alexey Khvalkovskiy, Grisha Avenesyan

All students and post-doctoral associates that have worked on the project MASTER during this past 42 months have found a job at the end of their training period. Positions found were either inside academic institutions or industrial groups (Grandis, EDF), which value the research experience gathered during this project.

Conferences and Publications

Another important achievement of this project has been to put several European academic teams at the forefront of research on spintronics application. During this period important fundamental progress have been obtained. The quality of the research obtained by the consortium can be illustrated by the large number of high impact factor publications so far: 5 natures, 5 PRL, 10 PRB (5 Rapid Comm) and 13 APL. This high research quality has helped to set the recognition of European team work.

Statistics and impact of the bibliography of MASTER:
36 publications have been produced by the MASTER project:
5 in Nature Journals
5 in Physical Review Letters
10 in Physical Review B (5 Rapid Communications)
13 in Applied Physics Letters

1 in Journal of Physics D: Applied Physics
1 in Philosophical Transactions Of The Royal Society A
12 are **multipartners** (2 UCL/IPM/CNRS, 5 CEA/CNRS, 6 CNRS/IPM); 1 is a review by Exeter.
2 patents:

- WO/2010/122126: O. Klein, G. de Loubens, B. Pigeau, Magnetic vortex storage device[3],
- N. Locatelli, V. Cros, J. Grollier, J.C. Mage, A.V. Khvalkovskiy, B. Marcilhac, "Oscillateurs spintronique et utilisation de celui-ci dans des dispositifs radiofréquence" French patent n° 11 02192 (2011) (12/07/2011)

The total number of articles that cite the work of MASTER is currently at 256 papers. If one removes self-citations, the figures drops down to 189. This implies that 189 times external groups have used the results of our consortium for their research. The average citation per publication (or impact factor) is 7.76, which is considered a very high figure in our community (it is equivalent to the impact factor of a review such as Physical Review Letters). We have also tentatively calculated the h-index of our project. The h-index is an index that attempts to measure both the productivity and impact of the published work. The index is based on the set of the scientist's most cited papers and the number of citations that they have received in other publications. The index was suggested by Jorge E. Hirsch, a physicist at UCSD, as a tool for determining theoretical physicists' relative quality and is sometimes called the Hirsch index or Hirsch number. In physics, a moderately productive scientist should have an h equal to the number of years of service. The h-index grows as citations accumulate and thus it depends on the 'age' of a research project. The h-index of MASTER is 9 after only 4 years, which translates as a highly productive output.

We would like to add, that the consortium has been careful to limit the number of submission to private editors, with a particular boycott of Elsevier[4]. Awareness that the scientific results were obtained through publicly funded grant, the research publications have been mostly given to public society, such as the European or American Physical Society (APS). To enhance the impact of the publications, open access to the work was favored. One extensive review about the main results obtained in MASTER was published using the creative common licence of the APS – concerned reference PHYSICAL REVIEW B 84, 224423 (2011) – . For other publications, open access was granted through the submission of online preprint either to arxiv[5] or to hal[6].

To advertise the progress obtained in the project and amplify is impact, a research workshop has been organized. The Spin Master Voice workshop "Challenges and opportunuities of Spin-Transfer Nano-Oscillators" was held between 14-16 December 2011 at the Château de Villiers-le-Mahieu, France. The aim of the workshop was to emulate discussions about the challenges and opportunities of these devices for microwave applications by bringing together scientists and engineers interested in recent developments of spin transfer nano-oscillators. To organize this workshop a web site has been created, :http://iramis.cea.fr/meetings/SpinMV/
Lead researchers in the field have been invited to give plenary lectures. This is the list of invited speakers:

J. Åkerman (Univ. of Göteborg, SWE)
C. Back (Univ. Regensburg, GER)

Fig. 26 Logo of the SpinMV workshop.

[3] http://www.wipo.int/patentscope/search/en/WO2010122126
[4] http://www.guardian.co.uk/science/2012/apr/24/harvard-university-journal-pul
[5] http://arxiv.org/
[6] http://hal.archives-ouvertes.fr/

A. Fert (UMΦ, FRA)
B. Gurney (Hitachi, GBR)
K.Y. Guslienko (Univ. del Pais Vasco, ESP)
J.-V. Kim (IEF, FRA)
V. Novosad (Argonne, USA)
Y. Otani (Univ. Tokyo, JAP)
H. Kubota (AIST, JAP).
C. Serpico (Univ. of Napoli, ITA)
A. Slavin (Univ. Oakland, USA)
J. Slonczewski (IBM, USA)
A. Thiaville (Univ. Paris-Sud, FRA)
S. Urazhdin (Univ. of W. Virginia, USA)
K. Zvezdin (Istituto PM, ITA)

This workshop was a large success within the community, with 99 participants (one Nobel laureate) from 17 different countries and 3 continents (Belgium, China, France, Germany, Ireland, Italy, Japan, Korea, Nederland, Poland, Russia, Spain, Sweden, Swiss, Taiwan, United Kingdom, and U.S.A)

This workshp featured 14 invited talks (see list above) and 18 contributed talks (Bürgler D., Baraduc C., Berkov D., de Loubens G., Dussaux A., Hurdequint H., Keatley P., Locatelli N., Manfrini M., Mangin S., Min B. C., Miron M., Pigeau B., Sierra J. F., Sinha J., Valet T., Viret M., and Zvezdin K.) All members of the MASTER consortium were given an opportunity to present orally their progress to a large audience.

The proceedings of the workshop is available has an item in the deliverable list.

We would like to mention that the members of the consortium have been invited to numerous conference during this last 42 months. Adding the numbers found in the 3 periodic reports, we have recorded more than 65 invitations to conferences linked to activities inside the project. (see attached document MASTER_NMP212257_conferences)

Over the duration of the project the travelling expenses included cost to travel to 10 events organized by MASTER: 8 periodic meetings (every 6 months), the Industrial and Management Board meeting and to the workshop spinMV. In addition, the work of MASTER has been presented to the 65 invited conferences mentioned above, plus the numerous contribution to other conference, all listed in the periodic reports.

Annex: Biliography of MASTER

1) Multipartner UCL/IPM/CNRS
Belanovsky, A. D.; Locatelli, N.; Skirdkov, P. N.; Araujo, F. A.; Grollier, J.; Zvezdin, K. A.; Cros, V. & Zvezdin, A. K.
Phase locking dynamics of dipolarly coupled vortex-based spin transfer oscillators
Physical Review B, APS, **85**, 100409(R) (2012)

2) Monopartner Münster
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Diffraction of spin waves from a submicrometer-size defect in a microwaveguide
Applied Physics Letters, AIP, **95**, 122510 (2009)

3) Multipartner UCL/IPM/CNRS

Darques, M.; Dussaux, A.; Khvalkovskiy, A. V.; la Torre Medina, J. D.; Araujo, F. A.; Guillemet, R.; Bouzehouane, K.; Fusil, S.; Grollier, J.; Avanesyan, G. G.; Zvezdin, K. A.; Cros, V. & Piraux, L.
Bottom-up approach for the fabrication of spin torque nano-oscillators
Journal of Physics D: Applied Physics, IOP, **44**, 105003 (2011)

4) Monopartner Münster
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Applied Physics Letters, AIP, **99**, 172501 (2011)

5) Monopartner Münster
Demidov, V. E.; Buchmeier, M.; Rott, K.; Krzysteczko, P.; Münchenberger, J.; Reiss, G. & Demokritov, S. O.
Nonlinear Hybridization of the Fundamental Eigenmodes of Microscopic Ferromagnetic Ellipses
Physical Review Letters, APS, **104**, 217203 (2010)

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Control of spin-wave phase and wavelength by electric current on the microscopic scale
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10) Monopartner Münster
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Excitation of short-wavelength spin waves in magnonic waveguides
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Physical Review Letters, APS, **107**, 107204 (2011)

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Large microwave generation from current-driven magnetic vortex oscillators in magnetic tunnel junctions
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