Anisotropic spin-wave patterns generated by spin-torque nano-oscillators

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(Presented 17 November 2010; received 24 September 2010; accepted 11 January 2011; published online 11 April 2011)

Spin-wave excitations due to spin-momentum transfer in ferromagnetic thin films will enable new types of information processing and memory storage. Here, we show how arrays of spin-torque nano-oscillators (STNOs) can be used to create anisotropic spin-wave interference patterns, which can be used for information processing. We consider STNO arrays contacting a thin ferromagnetic film. Contacts to the film (including the STNOs themselves) can be used to detect the spin-waves and then, when coupled to a simple circuit, can create new excitation patterns. The propagating spin-wave patterns can be generated by pulsing transponders. Arrangements of transponders create resonant (reverberating) spin-wave activity—that may be the basis of polychronous wave computation of the arithmetic and Boolean functions as well as information storage. © 2011 American Institute of Physics. [doi:10.1063/1.3566000]

Spin-torque nano-oscillators (STNOs) consist of a point contact to a magnetic thin film multilayer, a free and fixed magnetic layer separated by a non-magnetic layer. In such structures, due to the spin-transfer effect, dc current densities greater than a critical value \( j > j_c \) generate a high-frequency dynamic response (1–100 GHz) in the free ferromagnetic (FM) layer and result in the emission of spin-waves. These spin-wave excitations have been inferred from the \( I-V \) characteristics of the contacts as well as their noise spectra. Phase locking between proximal STNOs oscillators has also been observed for distances up to 500 nm, and the main coupling mechanism responsible for phase locking is thought to be through spin-waves that propagate between the contacts.

Of interest is control of the direction of spin-wave propagation for a variety of purposes, including on-chip communication or information processing using waves. STNOs are interesting for such applications because they are highly localized spin-wave sources, in contrast to spin-waves generated using microwave antennas with rf magnetic fields. In this paper we show that multiple frequency locked STNO contacts result in anisotropic interference patterns, enhancing spin-waves activity in some regions and damping activity in others. We further illustrate how such patterns can be used to implement polycronous wave computation.

The response to a (polarized) current in a free magnetic layer is phenomenologically described with an additional current-dependent positive damping term in the Landau–Lifshitz–Gilbert equation. The magnetic excitations have a frequency that depends on the local field in the contact and depends nonlinearly on the amplitude of the excitation.

The oscillation of the magnetic moments is in the plane perpendicular to the effective magnetic field (i.e., the magnitude of the magnetic moment along the effective magnetic field direction is time independent for dc currents, see Fig. 1(b)]. If we consider a unit vector to represent the direction of the magnetization, \( \mathbf{m} \), then in the geometry considered in Fig. 1 with the field perpendicular to the \( xy \) plane, the out-of-plane magnetic moment, \( m_z \), does not oscillate and it represents the envelope of the modulated in-plane components, \( m_x \) and \( m_y \), \( (m_z^2 = 1 - (m_x^2 + m_y^2) = 1 - m_z^2) \), we call \( m = (m_x, m_y) \) (the in-plane component, for convenience). Note that the in-plane components have an oscillating nature in addition to the diffusive pattern \( (m_t = e^{i \omega t} \phi(r)) \); the out-of-plane component does not. Figure 1 depicts the magnetization for a small amplitude excitations, \( a \ll 1 \) is the maximum amplitude form; in (c) the oscillating in-plane component \( m_t \) and in (d) the amplitude of the excitation, \( |m| \). Figures 1(c) and 1(d) correspond to the solution of the linearized LLG equation with spin torque for a dc current in the nano-contact, which can be expressed in terms of Bessel functions.

The patterns shown in Figs. 1 and 2 are computed for a dc current. Applying a current pulse to an STNO creates diffusing spin-wave excitations in the magnetic layer. A single circular STNO produces a radially symmetric excitation that spreads and damps out as it moves away from the contact (see Fig. 3). Multiple point-contacts create multiple spin-wave packets (see Fig. 4).

Multiple contacts subject to current pulses (i.e., arrangements of STNOs spiking at the same time) ignite multiple spin-waves that interfere and enhance activity in preferred directions in the film’s plane. In this case, contact geometry, size, and distance can be used to control spin-wave patterns created by arrays of STNOs. Micromagnetic modeling of spin-waves excited by rf-magnetic fields has been done on waveguides and on double STNOs with boundary conditions. Figure 4 shows spatial-dependent excitations of magnetic moments (amplitude \( |m| \) is plotted), in a ferromagnetic thin film in response of an initial pulse, at time \( \tau_0 \), applied to a three STNOs in a triangular arrangement. In Fig. 4 the three point-contacts were simultaneously excited with a current pulse producing a magnetic excitation that diffuses and...
interferes throughout the two-dimensional thin film. Spatial-dependent amplitudes, \(|m|\), are plotted at times \(t_1, t_2 > t_0\).

The ability to create propagation spin-wave interference patterns enables a new type of information processing known as polychronous wavefront computation (PWC).\(^\text{11}\) The PWC idea is to encode information into time delays of propagating waves and accomplishes Boolean operations using constructive interference of wave packets. The key ingredients for PWC are a medium that can support interference patterns of propagating activity packets and transponders that can sense the size of incident activity and respond to super-threshold inputs by generating a propagating wave. The propagation times of peak-wave interference correspond to conduction-time delays. The analogy to excitation of a neuron is excitation of a transponder that may fire when a certain threshold...
of inputs, from other transponders, is exceeded. In this case, the transponder may generate a new current induced spin-wave excitation, perhaps after some time delay.

STNOs are used to create microwave-frequency excitations in thin films and the same (or other) contacts can also serve as detectors. STNOs may be used to read the state of the system (e.g., the amount of spin-wave activity, arriving spin-wave packets, etc.). The respective alignment of the fixed and free layers of an STNO determines its electrical resistance. Thus, small currents (that do not excite magnetization dynamics through the point-contacts) would serve to read the state of the free layer. In order to enhance the readout signal, a magnetic tunnel junction (MTJ) can be used as a detector (see Ref. 12).

In Ref. 12, we described a possible scheme for transponders that would detect spin-wave activity in the propagating medium and respond by initiating new spin-waves. They are basically integrate-and-fire circuits where a storage device (e.g., a capacitor or an inductor) accumulates charge that is discharged rapidly when a certain threshold level is achieved.

To add complexity to the system and hence create information-processing capacity, configurations that can maintain stable reverberating activity are needed. Detectors may be set to a threshold only reachable through more-than-one arriving energy packets. In Fig. 5 reverberating memory using three transponders is shown. Transponders spike at the same time the wave-front packets propagate from one to the others and intersect at each transponder reaching the detector threshold and creating new waves. Reverberation loops are closed and the activity is periodic with a period depending on the distance between transponders.

The state of the unit is time-dependent. We can encode information in the phase (i.e., timing) of excitation relative to some external timing signal. Any real number could be encoded into the phase of reverberating activity. Such controllable spin-wave patterns. The propagating spin-wave packets may be used to accomplish some brainlike behaviors through PWC, but on much shorter time scales and on smaller spatial scales. Micromagnetic simulations offer a useful way to design optimal STNO arrangements for specific interference, both steady and propagating patterns.

Supported in part by FENA/FCRP Grant No. 6160-G-FD211 and by ARO-MURI, Grant No. W911NF-08-1-0317. F.M. acknowledges support from a Beatriu de Pinós grant from the Catalan Government.