Spin transfer induced dynamics and synchronisation of coupled vortex-based oscillators

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The « vortex »...
The vortex state is parametrized by:

- Its polarity: $P = m_z(0) = +/- 1$
- Its chirality: $C = +/- 1$ (direction of the curling magnetization)

$\Rightarrow$ Without any external constraints, these 4 states are energetically identical.
The vortex dynamics:

Lowest frequency mode: « Gyrotropic » mode ↔ Gyration of the vortex core around its equilibrium position

Isolated mode → Easy excitation of a single mode

180° precession of the magnetization inside the orbit
Thiele equation:

\[ \vec{G} \times \frac{d\vec{X}}{dt} - D \frac{d\vec{X}}{dt} - k\vec{X} = 0 \]

\( \rightarrow \) Harmonic oscillator description

Thiele, J. Appl. Phys. 1974, 45, 377
Oscillations gyrotropiques entretenues

Thiele equation:

\[ f_0 = \frac{5}{18\pi^2} \gamma \mu_0 M_s \frac{L}{R} \]

Harmonic oscillator description

Fréquence typique d’oscillation:

100 MHz – 2 GHz

Thiele, J. Appl. Phys. 1974, 45, 377
STVOs: «Spin Transfer Vortex Oscillators»

Spin transfer

Magneto-Resistive effects (GMR, TMR)

Sustained magnetization oscillations

Trilayer

$I_{dc}$

$V_{AC}$

$V_{ac}$
t
The spin transfer action

Confinement

Gyroforce (viscous)

Damping force

Spin transfer force

\[ 0 = \mathbf{G} \times \frac{d\mathbf{X}}{dt} - D \frac{d\mathbf{X}}{dt} - k\mathbf{X} - \mathbf{\Theta}_{STT} \]

\[ \rightarrow \text{Oscillations auto-entretenues du vortex} \]
The first experimental results

- Improved coherence (FWHM~1MHz)
- Power increased with TMR
- All based on a fixed uniform polarizer

Mistral et al., PRL 100 (2008)

Pribiag et al., Nat. Phys. 3 (2007)

I. Coupled vortices in a single nano-pillar

- Can we excite dynamics with spin transfer?
- Will we observe coupled modes?
- RF features?

II. Synchronization of coupled vortex-based oscillators
Double vortex STNOs
Introducing the samples

$\text{I}_{dc} > 0$

Au
Py 4nm
Cu 10nm
Py 15nm
Cu

100-200nm
Influence of external parameters on the magnetic configuration:

• DC current $I_{dc} \rightarrow$ Oersted field $H_{oe} \rightarrow$ Vortex stabilized
• In plane field $\rightarrow$ Uniform state is stabilized

$\rightarrow$ The sign of the current defines the chirality of the vortices
Control of the configuration with current

Zero external field:

Can we have control on the relative polarities configuration?
Control of polarities configurations

→ Independent control of vortices polarities

→ 4 stable states at zero field:
  - P
  - AP

11 mA

Ø120nm

Out-of-plane Field (Oe)

Resistance (Ω)
No external field:

→ Do we expect to see spin transfer induced dynamics?
The spin transfer action

→ Perpendicular uniform polarizer
\[ \vec{F}_{\text{STT}} \perp \]

→ Circular planar polarizer
\[ \vec{F}_{\text{STT}} \parallel \]

→ For a vortex polarizer: the 2 contributions sum
For a fixed polarizer (centered vortex):

- $I_{dc} > 0$
- Identical chiralities
- Polarities $P_1$, $P_2$

Mutual spin transfer torque:

$F_{STT,1\rightarrow2} = -a_1 I_{dc} \left( F_{STT}^{\parallel} (X_2) - P_2 P_1 F_{STT}^{\perp} (X_2) \right)$

$F_{STT,2\rightarrow1} = a_2 I_{dc} \left( F_{STT}^{\parallel} (X_1) - P_2 P_1 F_{STT}^{\perp} (X_1) \right)$

$\rightarrow I_{dc} > 0$: Positive action only for the thick layer’s vortex
- Only one mode should be excited

$\rightarrow$ Dependence on the relative polarities?
Monitoring high frequency properties

- Signal?
- FWHM = 300 kHz
- Power density (pW/GHz)
- Frequency (MHz)
- Ø120nm
From P to AP state: HF emissions

Switching RF signal ON & OFF

Confirms excitation at zero field and in a 4000 Oe range
Excitation and large emitted power at zero field
- Linear dependence versus perpendicular field
- Easy detection of the polarity configuration through $df/dH$

Locatelli et al., Appl. Phys. Lett. 98, 062501 (2011)
Comparison of the signals obtained in single and double vortex states:

Thanks to coupled vortices oscillations:
Highly improved coherence → Quality factor $Q > 10000$
(linewidth ≈ 100kHz)
+ Excitations at zero field
Where does such a difference come from?

→ Difference in critical currents between P and AP configurations
• Uncentered vortex $\rightarrow$ Mean planar magnetization is non-zero
  $\rightarrow$ «Body-body» interaction dominates

$\rightarrow$ Modes for this coupled system?
• Centered vortex $\rightarrow$ Mean planar magnetization is zero
  $\rightarrow$ «Core-Core» interaction «Cœur–Cœur» for small distances

! The sign of interactions is determined by relative parameters
Gyrotropic mode for a unique vortex:

\[
\vec{G} \times \frac{d\vec{X}}{dt} - D \frac{d\vec{X}}{dt} - k\vec{X} = 0
\]

**Polarity: P=+1**

**Polarity: P=-1**

→ The gyration direction depends on the sign of the polarity, no influence of the chirality
Thiele equations: introducing a coupling term

\[
\begin{aligned}
\vec{G}_1 \times \frac{d\vec{X}_1}{dt} - D_1 \frac{d\vec{X}_1}{dt} - k_1 \vec{X}_1 - \mu \vec{X}_2 &= 0 \rightarrow 4\text{nm layer} \\
\vec{G}_2 \times \frac{d\vec{X}_2}{dt} - D_2 \frac{d\vec{X}_2}{dt} - k_2 \vec{X}_2 - \mu \vec{X}_1 &= 0 \rightarrow 15\text{nm layer}
\end{aligned}
\]

Linear coupling
What can we extract from these coupled equation?

\[
\frac{d}{dt} \begin{pmatrix} X_1 e^{i\theta_1} \\ X_2 e^{i\theta_2} \end{pmatrix} - \begin{pmatrix} \kappa_1 & \mu \\ G_1 i - D_1 & G_1 i - D_1 \end{pmatrix} \begin{pmatrix} X_1 e^{i\theta_1} \\ X_2 e^{i\theta_2} \end{pmatrix} = 0
\]

→ New modes: Eigenvalues (frequencies) + Eigenvectors

cf. theoretical study by Guslienko et al. for the special case of two identical layered dots

What can we extract from these coupled equation?

\[
\frac{d}{dt} \begin{pmatrix} X_1 e^{i\theta_1} \\ X_2 e^{i\theta_2} \end{pmatrix} = \begin{pmatrix} \kappa_1/G_1 i - D_1 & \mu/G_1 i - D_1 \\ \mu/G_2 i - D_2 & \kappa_2/G_2 i - D_2 \end{pmatrix} \begin{pmatrix} X_1 e^{i\theta_1} \\ X_2 e^{i\theta_2} \end{pmatrix} = 0
\]

→ New modes: Eigenvalues (frequencies) + Eigenvectors

**Parallel polarities:**

\[\omega_a \quad \omega_b \quad \omega_{\text{Thick}}\]

**Anti-parallel polarities:**

\[-\omega_{\text{thin}} \quad -\omega_a \quad \omega_{\text{Thick}}\]

Eigen modes of isolated vortices have the same sign

Eigen modes of isolated vortices have opposite signs
Symmetry of coupled modes

Parallel polarities:

\[ \omega_a \]
\[ \omega_b \]

\[ \omega_{\text{Thick}} \]

\[ \omega_{\text{thin}} \]

Anti-parallel polarities:

\[ \omega_a \]
\[ \omega_b \]

\[ \omega_{\text{Thick}} \]

ST
\[ I_{dc} > 0 \]

Small frequency splitting but opposite phase relation!

→ Influence on spin transfer excitation?
Two coupled free layers

- Uncentered vortex → Mean planar magnetization is non-zero
  → « Body-body » interaction dominates

- Centered vortex → Mean planar magnetization is zero
  → « Core-Core » interaction « Coeur–Cœur » for small distances
Importance of the core-core interaction at equilibrium:

At remanence (I=0): the cores are close one from another

- The dipolar interaction between them cannot be neglected
- This force acts against the confinement: the cores repel

Impact on critical current?

Can induce a shift of the cores away from the dots centers
Micro-magnetic simulations:

mutual spin transfer + magnetic interaction

\[ I_{dc} > 0 \rightarrow \text{A zero critical current is predicted for pillars with diameters } D > 200\text{nm}. \]
Importance of the core-core interaction at equilibrium:

At remanence ($I=0$) : the cores are close one from another

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→ This force acts against the confinement:
    the cores repel
Importance of the core-core interaction at equilibrium:

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Observation of double-vortex spin transfer excitations

Multiple contribution to the coupling between the two vortices:

- Mutual spin torque
- Coupled modes: phase relations have to be respected
- Core-core coupling: possibility to reduce the critical current (to zero) for opposite polarities

For every contribution, the relative parameters of the vortices have a crucial influence on the interactions.
STVO’s
synchronization: Lateral coupling
Synchronisation of two oscillators

\[ H_{\text{perp}} \]

\[ I_{\text{dc}} \]

Au
Py 4nm
Cu 10nm
Py 15nm
Cu

\[ \phi 200 \text{nm} \]

\[ 100 \text{nm} \]
Dipolar coupling

~100nm
Analytical model: Phase locking of two identical STNOs interacting through dipolar interaction.

→ We start again from coupled Thiele equations:

\[
\begin{align*}
-(iG + D)\dot{X}_1 - (k_1(X_1) - i\kappa J)X_1 - \mu(+)X_2 &= 0 \\
-(iG + D)\dot{X}_2 - (k_2(X_2) - i\kappa J)X_2 - \mu(+)X_1 &= 0
\end{align*}
\]

→ Here both vortices are auto-oscillating: coupling is a perturbation

\[
\varepsilon = \frac{X_1 - X_2}{X_1 + X_2} \quad \text{et} \quad \psi = \varphi_1 - \varphi_2
\]

→ We end up with a simple system of coupled differential equations:

\[
\begin{align*}
\dot{\varepsilon} &= 2\alpha\eta (\bar{\mu}(+) \cos \psi - \omega_0 ar_0^2) \varepsilon + \bar{\mu}(+) \sin \psi \\
\dot{\psi} &= 4 (\omega_0 ar_0^2 - \bar{\mu}(+) \cos \psi) \varepsilon + 2\alpha\eta \bar{\mu}(+) \sin \psi
\end{align*}
\]

A.D. Belanovsky, N. Locatelli et al., PRB 85 100409(R)
The differential equation system can be linearized around equilibrium to deduce the characteristic times for phase locking:

\[
\begin{align*}
1/\tau &= \alpha \eta \left( \omega_0 a r_0^2 - 2 \tilde{\mu}(+) \right) \\
\Omega &= 2 \omega_0 \sqrt{\left( \frac{\tilde{\mu}(+)}{\omega_0} \right)^2 - ar_0^2 \left( \frac{\tilde{\mu}(+)}{\omega_0} \right) - \frac{1}{4} (\alpha \eta)^2 (ar_0^2)^2}
\end{align*}
\]
Inverting these equations you can get to the coupling term $\mu$ and to the mean interaction energy associated to dipolar interaction:

$$\langle W_{int} \rangle (L) = \mu_+ X_0^2 = \frac{G}{2} \left( \sqrt{\frac{1}{(\alpha \eta \tau)^2} - \Omega(L)^2 - \frac{1}{\alpha \eta \tau}} \right) X_0^2 < 0$$

We reproduced simulations for several interpillar and we deduce characteristic times and mean energy fitting the approach of equilibrium:
Inverting these equations you can get to the coupling term $\mu$ and to the mean interaction energy associated to dipolar interaction:

$$\langle W_{int} \rangle (L) = \mu_{(+)} X_0^2 = \frac{G}{2} \left( \sqrt{\frac{1}{(\alpha \eta \tau)^2} - \Omega(L)^2} - \frac{1}{\alpha \eta \tau} \right) X_0^2 < 0$$

We reproduced simulations for several interpillar and we deduce characteristic times and mean energy fitting the approach of equilibrium:

$\rightarrow$ Once again, relative polarity matters!
Phase locking of identical oscillators

Parallel polarities:

- $W_{\text{dip.}} < 0$
- $W_{\text{dip.}} > 0$

→ Low synchronization efficiency

Anti-parallel polarities:

- $W_{\text{dip.}} < 0$
- $W_{\text{dip.}} > 0$

→ High synchronization efficiency
When the two vortices turn in opposite directions (opposite polarities), the mean energy is three time larger compared to the case when vortices turn in the same direction (identical polarities).

When phases are locked, the interaction energy is still not constant but oscillates at twice the gyrotropic frequency:

\[ W_{int}^{md} = C_1 C_2 \left( \mu_+ \vec{X}_1 \cdot \vec{X}_2 + \mu_- X_1 X_2 \cos(\varphi_1 + \varphi_2) \right) \]

Only the low frequency term plays a role in the synchronization process.
Experimental case: Two different oscillators

\[ \Delta D \implies \Delta \omega \]
Analytical model: Thiele equations + Adler model

\[ \dot{\psi} = \Delta \omega + \frac{2 \mu}{\alpha \eta} \sin(\psi) \]

The condition for synchronization:

\[ \Delta f < \frac{1}{\pi \alpha \eta} \mu \]

\( \Rightarrow \) Critical frequency splitting is proportionnal to the interaction coefficient
Identification of the two oscillators:

- Sweeping $H_{\text{perp}}$ we can change the shift between the two frequencies.
Identification of the two oscillators:

→ Sweeping $H_{\text{perp}}$ we can change the shift between the two frequencies.
AP polarities - Frequency versus perpendicular field dependence:
Evolution of frequency spectrum when $H_{\text{perp}}$ is varied:

When the frequency shift is small enough, the two auto-oscillators synchronize.
Evolution of frequency spectrum when $H_{\text{perp}}$ is varied:

When the frequency shift is small enough, the two auto-oscillators synchronize.
The opposite polarities case

AP polarities - Frequency versus perpendicular field dependence:

\[ I_{dc} \]

\[ \rightarrow \]

Effective coupling leading to synchronization of the two STNO’s, with a **10% frequency mismatch**
→ **Synchronisation** observed for frequency difference up to **70 MHz**

→ **Synchronization** ~3 times more efficient when **polarities are opposite**

→ **Interaction** ~3 times stronger than for identical polarities
Preparation of a 2 vortex states in nanopillars, and excitation of gyrotrropic motion through spin transfer

Coupled modes symmetry and synchronization efficiency shown to be strongly dependent on relative polarities

Single pillar: coupling demonstrated by relative polarities dependence + increases the coherence of the oscillations

Double pillars: demonstration of synchronization of 2 dipolarly coupled STNOs in their 2V states, starting from an AP polarities configuration
Towards synchronization of STNO networks:
Thank you for your attention!