Field-like torque induced synchronized oscillation in spin torque oscillators

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Synchronization of two spin torque oscillators coupled in parallel through current is investigated by taking into account the influence of field-like torque. It is shown that the presence of such torque can cancel out the effect of damping and thus can induce synchronized oscillations in response to the direct current. Further, our results show that the existence of positive field-like torque enhances the frequency of the synchronized oscillations without affecting the power. The validity of the above results is confirmed by numerical and analytical studies based on the Landau-Lifshitz-Gilbert-Slonczewski equation.

I. INTRODUCTION

Synchronization phenomenon in spin torque oscillators (STOs) has been the subject of active research in recent years due to its potential applications to generate microwave power in nanoscale devices. A number of significant efforts have been made to study magnetization dynamics and synchronization of STOs driven by spin polarized current, injection locking, external ac excitation, spin waves, magnetic fields and electrical couplings. The synchronization of STOs greatly enhances the output microwave power when compared with the low output power of an individual STO. Also it is more desirable for an enhancement of efficiency, quality factor and oscillation frequency of the practical STO devices such as wireless communication, brain-inspired computing and microwave assisted magnetic reading. In particular, it has been observed that an STO with the configuration of perpendicularly magnetized free layer and in-plane magnetized pinned layer is suitable for high emission of power, narrow line width and wide frequency tunability. The oscillation properties of this STO have also been investigated both experimentally and theoretically in Refs. Further, the existence and stability of the synchronized state and the conditions to synchronize the individual precessions have also been studied in an array of N serially connected identical STOs coupled through current, also clearly demonstrated in Ref. Recently, the mutual synchronization between two parallelly connected STOs, coupled by current, has also been identified.

However, the major issues in the system of coupled STOs are the formation of multistability and the decrease of frequency with respect to current. The nature of multistability prevents the system to exhibit stable synchronized oscillations for all initial conditions. Removing this multistability and making the system to exhibit stable synchronized oscillations are challenging tasks and have not yet been fully clarified. Also, a decrease in the frequency of synchronized oscillations while increasing current limits the enhancement of frequency beyond some value.

In this paper, we study the mutual synchronization between two parallelly coupled STOs in the presence of field-like torque. By solving the Landau-Lifshitz-Gilbert-Slonczewski (LLGS) equation with the configuration of perpendicularly magnetized free layer and in-plane magnetized pinned layer, the analytical formula for the frequency of synchronized oscillations is derived. The existence of multistability is confirmed and the impact of field-like torque on the STOs for the various strengths of coupling is observed. In the absence of field-like torque the two STOs show the existence of multistable states that include synchronized oscillations and steady state. The presence of field-like torque removes the multistability and makes the system to oscillate with in-phase synchronization. Further, the frequency of synchronized oscillations is also enhanced in the presence of field like torque. The onset of multistability in the absence of such a torque and the onset of monostability due to it are analytically verified.

II. MODEL DESCRIPTION OF TWO PARALLELLY COUPLED STOS

We consider a system that consists of two parallelly coupled spin-torque oscillators. Each oscillator consists of a perpendicularly magnetized free layer, where the direction of magnetization is allowed to change and an in-plane magnetized pinned layer where the direction of magnetization is fixed along the positive x-direction.
Both free and pinned layers are separated by a nonmagnetic conducting layer. The two free layers are labeled as \( j = 1, 2 \) and the material parameters of the two oscillators are kept identical for simplicity. The unit vector along the direction of magnetization of the free layers is given by \( \mathbf{e}_x, \mathbf{e}_y, \mathbf{e}_z \). The two free layers are labeled to the plane of the free layer and \( \mathbf{e}_x, \mathbf{e}_y, \mathbf{e}_z \) are unit vectors along positive \( x, y, z \) directions respectively. The unit vector along the direction of magnetization of the pinned layers is given by \( \mathbf{P} = (\mathbf{e}_z) \). The magnetization of the free layers \( (j = 1, 2) \) is governed by the following LLGS equation,

\[
\frac{d\mathbf{m}_j}{dt} = -\gamma \mathbf{m}_j \times \mathbf{H}_{\text{eff},j} + \alpha \mathbf{m}_j \times \frac{d\mathbf{m}_j}{dt} + \gamma \mathbf{H}_{Sj} \mathbf{m}_j \times \mathbf{P} + \gamma \beta \mathbf{H}_{Sj} \mathbf{m}_j \times \mathbf{P}, \quad j = 1, 2. \tag{1}
\]

Here \( \mathbf{H}_{\text{eff},j} \) is the effective field, given by \( \mathbf{H}_{\text{eff},j} = [\mathbf{H}_a + (\mathbf{H}_k - 4\pi M_s)\mathbf{m}_j]e_z \), which includes externally applied field \( \mathbf{H}_a \), crystalline anisotropy field \( \mathbf{H}_k \) and shape anisotropy field (or demagnetizing field) \( 4\pi M_s \). \( M_s \) is the saturation magnetization, \( \gamma \) is the gyromagnetic ratio, \( \alpha \) is the Gilbert damping parameter, \( \beta \) is the strength of the field-like torque and \( H_{Sj} \) is the strength of the spin-transfer torque, given by

\[
H_{Sj} = \frac{\hbar \eta I_j}{2eM_s V(1 + \lambda \mathbf{m}_j \cdot \mathbf{P})}. \tag{2}
\]

In Eq. (2), \( \hbar = h/2\pi \) (\( h \) - Planck’s constant), \( V \) is the volume of the free layer, \( e \) is the electron charge, \( \eta \) and \( \lambda \) are dimensionless parameters which determine the magnitude and the angular dependence of the spin-transfer torque respectively. \( I_j \) is the total current passing through the free layer which is given by \( \beta = 0.1 \)

\[
I_j = I_0 + I_j^{\text{coupling}} = I_0 + I_0 \chi [m_{jx}(t) - m_{j'x}(t)], \tag{3}
\]

where \( j, j' = 1, 2, \ j \neq j' \) and \( I_j^{\text{coupling}} \) is the current injected from the free layer \( j' \) to \( j \). In Eq. (3) \( I_0 \) is the current flowing through the free layer when there is no coupling between the oscillators. The second term in Eq. (3) describes the current flowing through the connection between the two STOs and \( \chi \) is the coupling strength which characterizes the energy loss in the connector. The oscillating electric current generated by the STO is proportional to \( [2\mathcal{V}_i/(R_P + R_{AP})][1 + \Delta R(\mathbf{m}_j \cdot \mathbf{P})/(R_P + R_{AP})] \) as pointed out in [31], which implies that the electric current generated by the oscillator depends upon the component of the free layer’s magnetization along the pinned layer’s magnetization. Here \( \mathcal{V}_i \) is the external voltage, \( R_P \) and \( R_{AP} = R_P + \Delta R \) are the resistances of the STO when the magnetization of the free layer is parallel and antiparallel to the magnetization of the pinned layer, respectively.

FIG. 1. (Color online) Time evolution of \( m_{1x} \) and \( m_{2x} \) for (a) \( \beta = 0 \) and (b) \( \beta = 0.1 \) when the currents passing through the first, second oscillators and the applied field are instantaneously switched off at 500 ns and switched on at 1500 ns. Time evolution of \( m_{1x} \) and \( m_{2x} \) for (c) \( \beta = 0 \) and (d) \( \beta = 0.1 \) when the currents passing through the first oscillator, second oscillator and applied field are cut off at 504 ns, 500 ns and 496 ns respectively and switched on simultaneously at 1500 ns. Here the currents passing through the two oscillators are given values 2.0 mA and the coupling strength is 0.5. The inset figures show the corresponding time evolution of \( m_z \).
III. EFFECT OF FIELD-LIKE TORQUE

A. Destabilization of steady state by field-like torque

To understand the dynamics of the magnetization of the free layer, Eq. (I) is numerically solved by Runge-Kutta 4th order step-halving method for the material parameters 28 29 31 $M_s = 1448.3$ emu/c.c., $H_k = 18.6$ kOe, $\eta = 0.54$, $\lambda = \eta^2$, $\gamma = 17.64$ Mrad/(Oe s), $\alpha = 0.005$, and $V = \pi \times 60 \times 60 \times 2$ nm$^3$. Throughout our study $H_0$ is fixed at 2.0 kOe. The dynamics of the coupled spin torque oscillators is more complicated than that of a single oscillator. Here we show that the dynamics of the two oscillators can be altered when there is a lack of simultaneity between the currents passing through the individual oscillators and the external magnetic field when they are switched off at different times with even nanosecond difference. As an example, initially the currents to the first and second oscillators are switched on at $\tau_{a1}$ and $\tau_{b1}$, respectively, and the field at $\tau_{a1}$. After the oscillators attain synchronized oscillations, the currents and field are switched off at $\tau_{off}$, $\tau_{off}$, and $\tau_{off}$, respectively. At some time they are again switched on at $\tau_{a2}$, $\tau_{b2}$, and $\tau_{a2}$, respectively. Figs. (a)-(d) show the time evolution of $m_{ax}$ and $m_{bx}$ for the initial conditions chosen for $0.99 < m_{1z}, m_{2z} < 1.00$, when $I_0 = 2.0$ mA, $\chi = 0.5$. The corresponding values of $m_{1z}$ and $m_{2z}$ are plotted as inset figures. Figs. (a) and (b) have been plotted for $\beta = 0$ and $\beta = 0.1$, respectively, when $\tau_{a1} = \tau_{b1} = \tau_{a2} = \tau_{b2} = 0$, $\tau_{a1} = \tau_{b1} = \tau_{a2} = \tau_{b2} = 500$ ns, and $\tau_{a1} = \tau_{b1} = \tau_{a2} = \tau_{b2} = 1500$ ns. Figs. (a) and (b) show that irrespective of whether the field-like torque is present or not, both the oscillators reach steady state after 500 ns and regain synchronized oscillations after 1500 ns as confirmed in Ref. 31. To mimic the actual experimental situations, the currents passing through the individual oscillators and the external field may not reach the value zero simultaneously at the moment when they are switched off, Figs. (c) and (d) are plotted for $\tau_{a1} = \tau_{b1} = \tau_{a2} = \tau_{b2} = 0$, $\tau_{a1} = \tau_{b1} = \tau_{a2} = \tau_{b2} = 504$ ns, $\tau_{a1} = \tau_{b1} = \tau_{a2} = \tau_{b2} = 496$ ns and $\tau_{a1} = \tau_{b1} = \tau_{a2} = \tau_{b2} = 1500$ ns. It is observed that in the absence of field-like torque, the oscillations of the two oscillators damp out after 500 ns to the steady states at different hemispheres, formed by the unit vector $\mathbf{m}$ around the origin, and continue in the same steady states even after the currents and field are applied at 1500 ns as shown in Fig. (c). On the other hand in the presence of positive field-like torque, both the oscillators attain the steady state at the northern hemisphere after the currents and field are switched off around 500 ns and reach synchronized oscillations after the currents and field are switched on at 1500 ns. From Figs. (a) & (c) it is understood that the lack of simultaneity in switching off the currents and field transforms the system from getting synchronized oscillatory state to steady state. However, the presence of field-like torque destabilizes the steady state at the southern hemisphere and makes the magnetization vectors of the two oscillators to stay in the northern hemisphere and exhibit synchronized oscillations after the currents and field are switched on. It has also been verified that the positive field-like torque makes synchronized oscillations even when $\tau_{a1} = \tau_{b1} = \tau_{a2} = \tau_{b2}$ differ by nanoseconds. Also, we checked that a negative field-like torque does not produce synchronized oscillations when the currents and field are switched on again after switching off at different times.

From the above studies we understand that there is a definite possibility for the oscillators to reach steady states in different hemispheres, and therefore it is essential to verify the existence of multistability and the possibility of its removal by suitable means. Hence, Eq. (I) is numerically solved for 100 numbers of randomly chosen initial conditions, chosen from both the hemispheres, and the corresponding probabilities for steady state (SS) and synchronized oscillations(SYN) are computed. The values of SS and SYN are plotted against current in Figs. (a) and (b) for $\beta = 0$ and $\beta = 0.61$ respectively, when $\chi = 0.5$. Fig (a) shows that, in the absence of field-like torque, there is a nonzero probability for both steady state and synchronized oscillations beyond a critical current strength, whereas in the presence of positive field-like torque the system exhibits synchronized oscillations only, as shown in Fig (b).

B. Frequency and power of synchronized oscillations

Further, the frequency of synchronized oscillations is derived by transforming Eq. (I) into spherical polar coordinates using the transformations $m_j = (\sin \theta_j \cos \phi_j, \sin \theta_j \sin \phi_j, \cos \theta_j)$ as follows:

$$\frac{(1 + \alpha^2) \theta_j}{dt} = -2\pi \alpha F \sin \theta_j$$
$$- \gamma H_{Sj} [((\alpha - \beta) \sin \phi_j + (1 + \alpha \beta) \cos \theta_j \cos \phi_j], \quad (4)$$
$$\frac{(1 + \alpha^2) \phi_j}{dt} = 2\pi F \sin \theta_j$$
$$+ \gamma H_{Sj} [(1 + \alpha \beta) \sin \phi_j - (\alpha - \beta) \cos \theta_j \cos \phi_j], \quad (5)$$

FIG. 2. (Color online) Probabilities of synchronized oscillations (SYN) and steady state (SS) in the (a) absence ($\beta = 0$) and (b) presence ($\beta = 0.61$) of field-like torque when $\chi = 0.5$. 


where \( F = (\gamma/2\pi)[H_a + (H_k - 4\pi M_s) \cos \theta_i] \). From Eqs. (4) and (5), it can be numerically verified that in the synchronized state the values of \( \theta_1 \) and \( \theta_2 \) are the same and can be approximated to a constant value \( \theta^* \). Also, \( \phi_1 = 2\pi f t \) and \( \phi_1 - \phi_2 = 2\pi n, n = 0, \pm 1, \pm 2, \ldots \). Here, \( f \) is the frequency of the synchronized oscillations \( \theta^* \) derived from Eq. (6) as

\[
f(\theta) = \left( \frac{1}{1 + \alpha^2} \right) \left[ F + \frac{(\beta - \alpha)\gamma h\eta I_0 \cos \theta}{4\pi e M_s V \lambda \sin^2 \theta} \left( 1 - \frac{1}{\sqrt{1 - \lambda^2 \sin^2 \theta}} \right) \right]. \tag{6}
\]

The frequency and power of the synchronized oscillations against current in the absence (\( \beta = 0 \)) and presence (\( \beta = 0.61 \) and \( \beta = -0.61 \)) of field-like torque have been plotted in Figs. 3(a) and 3(b) respectively for \( \chi = 0.5 \). The solid line in Fig. 3(a) corresponds to numerically computed frequency and the open circles correspond to analytically computed frequency from Eq. (6). From Fig. 3(a) it is observed that the frequency of the synchronized oscillations is enhanced by positive field-like torque and decreased by negative field-like torque.

In order to elucidate the experimental consequences of enhancement of the frequency of synchronized oscillations due to field-like torque, we have plotted the spectral power in the frequency domain in Fig. 4(b) for \( \beta = 0, \beta = 0.61 \) and \( \beta = -0.61 \) when \( I_0 = 2.0 \text{ mA} \) and \( \chi = 0.5 \). It is evident that there is no change in the power due to the field-like torque and the frequency is indeed enhanced without any loss in the power. Though the enhancement of the frequency is in the MHz range, there is no loss in the power due to field-like torque.

C. Removal of multistability by field-like torque

To analyze the impact of field like torque on coupling strength, we plot the probabilities of SYN and SS for 100 randomly chosen initial conditions for \( I_0 = 8 \text{ mA} \). Figure 4(a) shows that in the absence of field-like torque the probability of synchronized oscillations (steady state) reduces (increases) from 1(0) when the coupling strength is increased. This evidences that the system does not exhibit synchronized oscillations for all initial conditions beyond some critical value of coupling strength in the absence of field-like torque. From Fig. 4(b) it is observed that the oscillators do not get synchronized for all initial conditions in the absence of field-like torque. However, beyond certain critical value of positive field-like torque both the oscillators oscillate synchronously for all initial conditions, which is confirmed from Fig. 4(b) where the probability for synchronized state reaches 1 when the strength of field-like torque is increased beyond the critical value (\( \beta_c = 0.33 \)).

D. Steady states and critical values of \( \beta \) and \( \chi \) for synchronized oscillations

The steady state solution of the system (1) is found around \( \phi^*_1 = \phi^*_2 \approx 3\pi/2 \), and

\[
\theta^*_1 = \sin^{-1} \left( \frac{H_{SO}}{H_a + G} \right), ~ \theta^*_2 = \pi - \sin^{-1} \left( \frac{H_{SO}}{H_a - G} \right),
\]

where \( H_{SO} = h\eta I_0/2eM_sV \) and \( G = H_k - 4\pi M_s \). From the linear stability analysis, in the absence of field-like torque the steady state is found to be stable when \( [36] \)

\[
\sum_{i=1}^{2} \left( \frac{\partial f_i}{\partial \theta_i} \right) \left( \theta^*_{1,2} - \phi^*_{1,2} \right) < 0. \tag{7}
\]

Here, \( f_i \) and \( g_i \) are derived from Eqs. (4) and (5) as \( \dot{\theta}_i = f_i(\theta_1, \theta_2, \phi_1, \phi_2), \dot{\phi}_i = g_i(\theta_1, \theta_2, \phi_1, \phi_2) \), \( i = 1, 2 \). From the condition (7), the critical value of coupling strength \( \chi_c \) above which the system exhibits stable steady state solution in the absence of field-like torque (\( \beta = 0 \)) is derived as

\[
\chi_c = \lambda + \frac{\alpha}{2H_{SO}} [2G\mu - 2\alpha H_a \tau_- - G\tau_+], \tag{8}
\]
where \( \tau_\pm = \left( \sqrt{1-T_+} \pm \sqrt{1-T_-} \right) \), \( T_\pm = H_0^2/(H_a \pm G)^2 \) and \( U = (T_+ + T_- - 1) \).

However, in the presence of field-like torque, the critical value of \( \beta_c \), above which the steady state loses the stability, so that the synchronized state is the only stable state, can be found to be

\[
\beta_c = \frac{\alpha G(\tau_+ - 2U) - 4H_{SO}(\lambda - \chi) + 2H_0 \alpha \tau_-}{2H_{SO}(\lambda - \chi) + H_0 \tau_+ + G \tau_+}.
\]  

The values of \( \chi_c \) and \( \beta_c \) match well with the numerical values, as confirmed by the vertical lines in Figs. 3(a,b).

E. Stability of synchronized oscillations in the presence of field-like torque

In the absence of field-like torque the stability of the synchronized oscillations has already been confirmed by Taniguchi et al. [31]. However, in the presence of positive field-like torque the stability of the synchronized oscillations is confirmed by perturbing \( \phi_1 \) as \( \phi_1 = \phi_2 + \delta \phi \) after synchronization is reached, and the time evolution of \( \delta \phi \) is analysed over \( n \) periods of oscillations. By substituting \( \phi_1 = 2\pi ft + \delta \phi(t) \), \( \phi_2 = 2\pi ft \) and \( \theta_1 = \theta_2 = \theta \) in Eq. (9) and after averaging over \( n \) oscillations we can obtain [31]

\[
\frac{1}{nT} \int_0^{nT} d\delta \phi \frac{d\delta \phi}{dt} \approx -\chi \gamma H_{SO}(1 + \alpha \beta)/(1 + \alpha^2) \int_0^{nT} \delta \phi.
\]  

The solution of Eq. (10) is \( \delta \phi(t) \approx \exp\left(-\chi \gamma H_{SO}(1 + \alpha \beta)/(1 + \alpha^2)\right)t \), indicating

the small deviation(\( \delta \phi \)) between \( \phi_1 \) and \( \phi_2 \) exponentially decreases to zero as time increases. This implies that the presence of field-like torque does not affect the stability of the synchronized oscillatory state of the two parallelly coupled spin torque oscillators.

IV. CONCLUSION

In conclusion, the synchronization between two parallelly coupled spin torque oscillators in the presence of field-like torque has been investigated theoretically, with a physical configuration of perpendicularly magnetized free-layer and in-plane magnetized pinned layer. The numerical simulation of the LLGS equation has revealed that the existence of field-like torque can cancel out the damping effect and thus can induce synchronized oscillations with respect to applied current. One can also note that the multistable behavior in coupled STOs can be efficiently removed by introducing the field-like torque and the frequency of the synchronized oscillations gets enhanced by positive field-like torque.

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