Large amplitude vortex gyration sustained by topological insulator

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We consider the excitation of large amplitude gyrotrropic vortex core precession in a Permalloy nanodisk by the torques originating from the in-plane microwave current along the surface of a topological insulator. We consider analytically and by micromagnetic modelling the dependence of this excitation on the frequency and magnitude of the microwave current. These findings opens the possibility to excite gyrotrropic vortex motion with the current densities far lower than by any other means.

Magnetic vortices are very interesting nanoscale magnetic states which attracted research interest from both fundamental and applied perspectives ¹⁷,¹⁸. Magnetic vortices are formed by in-plane magnetization that curls clockwise or counter-clockwise around the small volume of out of plane magnetization in the center which is called the vortex core. This magnetization distribution in nanopillars ¹⁵,¹⁶ represents an energy favourable state for a wide range of geometries ¹⁷,¹⁸.

The increased attention to magnetic vortices is largely related to their excited states, which can be maintained by an external stimuli (field, current etc.). Among the dynamic modes of magnetic vortices in nanopillars, the gyrotrotropic mode is of the greatest interest, because it is the lowest energy collective excitation ⁷,⁸,¹⁹. It is represented by the circular (or gyrotrropic) motion of the vortex core, accompanied by corresponding high-amplitude oscillations of the mean magnetization of the whole nanopillar. There are promising reports on the possibility of using this property to build vortex-based non-volatile memories ²⁰,²¹. Spin Transfer Nano-Oscillators (STNOs) ⁹,¹², spin diode frequency sensors ²², and even more sophisticated systems based on collective vortex dynamics ²³.

The key issue in this context is the manner of the vortex gyrotrotropic mode excitation. Initially, it was proposed to excite vortices by an external microwave magnetic field (see for instance Refs. ¹⁰,²¹). An alternative approach is to use dc spin-polarized current to excite the gyrotrropic motion of the vortex (see for instance Refs. ⁹,¹¹,¹²). Although the latter approach is more easily implemented in practice and appears to be more energy efficient, the issue of reducing the required current amplitude remains a high priority.

An original solution could be to use pure spin currents, which can lead to the generation of large spin torques acting on magnetization. Such torques, which can be due to the interfacial Rashba effect but are more often the result of the bulk spin Hall effect, are considered for the ferromagnetic metal layer with asymmetric Pt and AlO₅ interfaces ²⁶ as well as a graphene/Pt interface ²⁷. Also such torques are observed in the case of ferromagnetic/Pt ²⁸ or ferromagnetic/Ta ²⁹ bilayers, and more generally in systems with a ferromagnet in contact with a layer of large spin orbit coupling material (Pt, Ir, W, Ta, Pd etc.). Using these torques, it is possible to excite domain wall motion ³⁰,³¹, to prevent Walker breakdown ³², to switch the magnetization of a ferromagnetic disk ²⁹,³³,³⁴ and also to excite magnetization oscillations ³⁵,³⁶. In this context, an important question is to find new materials with properties favourable the generation of larger spin currents. Nowadays, topological insulators (TI) become one of the most promising candidates as a source of pure spin current and the associated spin orbit torques. This is because of the properties of the surface states in which an electron spin orientation is intrinsically fixed relative to its propagation direction, thereby exaggerating the effects of spin-orbit coupling. In 2014, the bias current induced spin polarization of the TI was detected experimentally ³⁷. Moreover, recent experimental works demonstrate that charge current flowing at the surface of a thin film of the topological insulator at room temperature can exert a spin-transfer torque on an adjacent ferromagnetic permalloy (Py) film, with the strength greater than of any other sources of spin-transfer torque measured thus far ³⁸,³⁹.

This is one of our objectives: to evaluate the feasibility and effectiveness to excite gyrotrropic vortex motion using torque originating at the TI/Py interface. The studied system (see inset in Fig. ¹) is represented by a Ni₈₁Fe₁₉ disk with radius R₉ = 100 nm and vortex magnetization distribution on top of a TI film. Such a system is very attractive for direct observations of magnetization dynamics by optical means since the ferromagnetic layer is open at the top in contrast to conventional STNOs or spin-diode effect which require a capping electrode ³⁵. First, we demonstrate by micromagnetic modelling that although the torque associated with the direct in-plane current leads only to a finite vortex position shift, the ones associated with radio-frequency (rf) in-plane cur-
rent through the surface of the TI can efficiently excite large rotation of the vortex core. We consider the dependence of this excitation on the frequency and the magnitude of the rf current. The analytical description of this phenomenon is proposed.

Here we study the magnetization dynamics in the nanodisk under the action of an rf in-plane current. The disk thickness is \( d = 10 \text{ nm} \). The magnetization dynamics in the NiFe disk is described by the Landau-Lifshitz-Gilbert (LLG) equation with an additional term responsible for the spin-transfer torque caused by TI:

\[
\dot{\mathbf{M}} = -\gamma \mathbf{M} \times \mathbf{H}_{eff} + \frac{\alpha}{M_S} (\mathbf{M} \times \dot{\mathbf{M}}) + \mathbf{T}_{\text{STT}}, \tag{1}
\]

where \( \mathbf{M} \) is the magnetization vector, \( \gamma \) is the gyromagnetic ratio, \( \alpha \) is the Gilbert damping constant, \( M_S \) is the saturation magnetization and \( H_{eff} \) is the effective field consisting of the magnetostatic field, the exchange field and the anisotropy field. The spin-transfer torque \( \mathbf{T}_{\text{STT}} \) can generally be represented by two components: a parallel (in-plane) torque \( \mathbf{T}_\parallel = \gamma_\parallel \mathbf{m} \times (\mathbf{e}_z \times \mathbf{m}) \) and a perpendicular torque \( \mathbf{T}_\perp = \gamma_\perp (\mathbf{m} \times \mathbf{e}_z) \), where \( \mathbf{e}_z \) is a unit in-plane vector perpendicular to current direction and \( \mathbf{m} \) is a unit vector along the magnetization. In materials such as TI, a giant Rashba interaction is commonly present. This interaction causes significant spin accumulation at the surface [37], that can interact directly by exchange with the magnetic moment of the adjacent NiFe disk. The diffusive spin current inside the adjacent ferromagnet (similar to the spin Hall effect) can create a parallel torque, and the combined actions of the Rashba effect and the exchange interaction can produce a perpendicular one. The microscopic details of these effect in studied system are still not completely clear, but the first experimental evidence of the existence of both torques has already been obtained [38]. In this case, the torque densities can be expressed as \( \tau_{\parallel i} = -\text{div} \mathbf{j}_S \), where \( \mathbf{j}_S \) is a spin current. Substituting the spin torque ratio \( \theta = (j_S/j)(2e/h) \), one can obtain torque density \( \tau_{\parallel i} = h\theta j/2ed \) (with \( i = ||, \perp \)), where \( j \) is the current density and \( e > 0 \) is the charge of the electron.

To investigate the possibility of vortex core excitation by the current flowing through the TI, we have performed a series of simulations using our micromagnetic finite-difference code SpinPM based on the fourth-order Runge-Kutta method with an adaptive timestep control for the time integration and a mesh size \( 2 \times 2 \times 8 \text{ nm}^3 \). The larger mesh size in the z-direction has been chosen because the modelling the magnetization almost does not change with the z-axis. To focus on TI action, we have not included the Oersted field in our simulations, because its value is not enough for vortex core expulsion and even for significant excitation. The Py magnetic parameters used in the modelling are: \( M_S = 800 \text{emu/cm}^2 \), the exchange constant is \( A = 1.3 \times 10^{-6} \text{erg/cm} \), \( \alpha = 0.01 \) and the bulk anisotropy is neglected.

We find in micromagnetic modelling that the in-plane direct current cannot excite vortex gyration, but only slightly shifts the vortex core from the equilibrium position. Thus, subsequently, we will focus on the influence of rf currents. According to the micromagnetic modelling, after the application of an in-plane rf current with a density of \( j = j_0 \sin(\omega t) \), the vortex starts gyrotropic motion after a transitional period. Then it reaches a stationary orbit due to the action of the spin torque created at the TI/Py interface. The dependences of the vortex core orbit \( R_{\text{core}} \) on the frequency of the input RF signal for three different alternating current density amplitudes \( j_0 \), are shown in Fig.[3] with the vortex core being resonantly excited. At the same time, an increase of the current amplitude \( j_0 \) leads to an increase in the stationary orbit of the vortex core. Moreover, if the value \( j_0 \) becomes higher than critical value \( j_0^{\text{cr}} \), the vortex core gets ejected out of the dot (corresponds to the region on Fig.[3] where the red line overtakes the \( R_D \) value). It is also worth mentioning that the excitation have nonlinear behaviour for high current values, similar to the Ref. [14]. For further analysis, let us introduce the dimensionless currents ratio \( j/j_{\text{th}} \), where \( j_{\text{th}} \) is the characteristic current density for the considered system.

For analytical insight into the vortex excitation we analyze the Thiele equation which can be deduced from Eq. (1):

\[
G(e_z \times \dot{\mathbf{R}}) = k(\mathbf{R})\mathbf{R} + D\dot{\mathbf{R}} - \mathbf{F}_{\text{ST}} \tag{2}
\]

where \( \mathbf{R} \) is the vortex core position, \( G = -2\tau p M_S h/\gamma \) is the gyroconstant, \( p \) is the core polarity, and \( e_z \) is the unit vector along the \( z \)-axis. The confining force is given with \( k(\mathbf{R}) = \omega_0 G(1 + a \mathbf{R}^2/R_D^2) \) where the gyrotropic frequency is \( \omega_0 = \frac{\gamma}{20} M_S h/R_D \) and \( a \approx 0.25 \).

Figure 1. (Color online) Vortex core orbit \( R_{\text{core}} \) as a function of frequency of the input RF signal for \( j_0 = j_{\text{th}} \) (black line), \( j_0 = 1/2 \times j_{\text{th}} \) (green line) and \( j_0 = 3 \times j_{\text{th}} \) (red line), where \( j_{\text{th}} \) is the characteristic current density for the considered system. Inset: the system under investigation from afar. The black arrows represent magnetization direction, while the red region represents the vortex core with positive \( m_z \).
The damping coefficient is 

\[ D = \alpha G(\frac{1}{2}\ln(\frac{B_0}{J_0}) + \frac{3}{8}) \]  

where \( l_e = \sqrt{\frac{4}{2\pi M_z}} \). As mentioned before, the spin-transfer force \( \textbf{F}_{ST} \) consist of two contributions: a perpendicular torque and a parallel torque. The first one modifies the energy of the vortex with the additional term \( E_{\perp} = -\delta (H_{\text{eff}} \times \textbf{e}_z) \textbf{R} \), therefore it can be represented as \( \textbf{F}_{\perp} = \delta (\textbf{e}_z \times H_{\text{eff}}) \), where \( H_{\text{eff}} \) is the effective field corresponding to the perpendicular torque. This formula is already in use in the case of external magnetic field \( E_{\perp} \). Because the perpendicular torque has exactly the same symmetry, hence it can be used here with the effective field: \( H_{\text{eff}} = \tau_{\perp}^0 \sin(\omega t) \textbf{e}_z \). Micromagnetic modelling gives \( \delta = 5.6 \text{ emu/cm}^3 \). Using the Feldtkeller ansatz \( \textbf{F}_{\parallel} \) for describing the vortex configuration, the in-plane torque contribution can be represented by \( \textbf{F}_{\parallel} = \beta G \cos(\phi) \textbf{e}_x - \sin(\phi) \textbf{e}_y \), where \( \beta = \frac{\gamma \tau_{\parallel}^0}{2} \rho_c \gamma V \gamma \tau_{\parallel}^0 \sin(\omega t) \), \( \rho_c \) is the vortex core width, \( V \) is the vorticity and \( \phi \) is the polar angle of the core. Using this, Eq.\( \text{[2]} \) can be represented in polar coordinates \((R, \phi)\) in the following form:

\[ \frac{\dot{R}}{R} = \frac{D}{G} \cdot \sin(\phi) - \frac{\beta}{G} \cos(\phi) + \frac{\beta}{R} \cos(2\phi) \]

\[ \dot{\phi} = \frac{k(R)}{G} \cdot \frac{D R}{G R} - \frac{\delta H(t)}{G R} \cos(\phi) + \frac{\beta}{R} \sin(2\phi) \]

where \( H(t) = \tau_{\parallel}^0 \sin(\omega t) \).

The dependence of the stationary orbit of the vortex core on the amplitude \( j_0 \) of the rf current density is represented in Fig.\( \text{[2]} \). The resonant frequency of excitation increases with the increase of the current amplitude \( j_0 \) (see inset in Fig.\( \text{[2]} \)b). Hence, we consider two different dependencies of the orbit on the amplitude \( j_0 \): with fixed frequency, which is resonant for the average value of \( j_0 \) (see Fig.\( \text{[2]} \)a), and with adjusting of the frequency for every \( j_0 \) (see Fig.\( \text{[2]} \)b). The first regime is more easily implemented, while the second one demonstrates greater efficiency of excitation, because it always deals with resonant frequency. The dependencies of the orbit \( R_{\text{core}} \) on the amplitude \( j_0 \) for constant frequency, which is resonant for \( j_0 = j_{ti} \), obtained by the micromagnetic modelling (black dots) and by numerical solution of Eq.\( \text{[3]} \), \( \text{[4]} \) (red line), are shown on Fig.\( \text{[2]} \)a. The jump of the function, corresponding to a sharp change of orbit, arises from the fact that at the left side of the current \( j_{ti} \), which is resonant for the selected frequency, the excitation efficiency is reduced due to the frequency mismatch. At the same time, this frequency mismatch is compensated by increasing of the amplitude at the right side of the resonance current.

In Fig.\( \text{[2]} \)b, the dependence of the orbit on the amplitude \( j_0 \) for the frequency is adjusted for every \( j_0 \) obtained by the micromagnetic modelling (blue crosses) and by the numerical solution of Eq.\( \text{[3]} \), \( \text{[4]} \) (red line). It should be noted that the orbit in case of fixed frequency is always less than in case of adjusted frequency, except for the jump point, where they are equal. As follows from these results, the analytical solution demonstrates good coincidence with the micromagnetic predictions.

Both the numerical simulations and analytical Thiele modelling demonstrate that the instant frequency of vortex core rotation oscillates during the period with the deviation amplitude less than 4%, while the mean frequency is equal to the frequency of the alternating current. Taking this into account, we can integrate Eq.\( \text{[3]} \), \( \text{[4]} \) over...
the period under the approximation that the frequency is constant. In this case, some oscillating terms vanish, while others return constant values after integration, and the Eq. (3) then takes the form:

$$\dot{\rho} = -\dot{D}\omega_0 \rho - \dot{D}\omega_0 \rho^3 + h$$  \hspace{1cm} (5)

where $\rho = R/R_D$, $\dot{D} = D/G$ and $h = \delta\tau_{ti}/2GR_D$. Let us define function $F$ as $\dot{\rho} = -\partial F/\partial \rho$. Then using Eq. (5) function $F$ can be represented in the form:

$$F = -h\rho + \dot{D}\omega_0 \rho^2 + \dot{D}\omega_0 \rho^4/4$$  \hspace{1cm} (6)

This function is similar to a typical free energy functional in Landau theory, if we consider $\rho$ as an order parameter and $h$ as an external field conjugate to the order parameter. In this notation, Eq. (5) is equivalent to the Landau-Khalatnikov equation. The stationary orbit due to Eq. (5) can be found by solving $\partial F/\partial \rho = 0$. This condition coincides with energy functional minimum condition. These analogies are valid not only for rf torques produced by TI, but also for all possible oscillating torques with the same symmetry (for example produced by the Rashba interaction or by the external magnetic field or by the Oersted field). In this case, the dependence of the stationary orbit of the vortex core on the amplitude $j_0$ of the rf current can be represented in the form:

$$h/\dot{D}\omega_0 = \rho + a\rho^3$$  \hspace{1cm} (7)

The solution of Eq. (7) is shown on Fig. 2b (dash black line). It demonstrates good agreement with Thiele modelling and the numerical solution of Eq. (3), (4) until the orbits about $R_D/2 = 50 \text{ nm}$. For orbits greater than this value, the larger oscillations of the frequency during the period appears, which makes our approximation no more valid.

Experimental observation of spin torque ratio for a topological insulator with an 8 nm permalloy layer atop TI gives $\theta_|| \geq 3.5$. It is important that this value already take into account shunting by the Permalloy layer. According to Ref. 38, the spin torque ratio for the perpendicular torque can be estimated as $\tau_{pi} \approx (0.4-0.6)\tau_{ti}$ depending on the material relaxation parameters. If we consider $\theta_\perp = 3.5$ and $\tau_{pi} = 0.4\tau_{ti}$ which is a lower bound for studied system, even in this case the comparison between torques produced by perpendicular current injection and by topological insulator gives $\tau_{pi}/\tau_{pp} = \theta/P \approx 10$ (where $P$ is a typical spin polarization of the current for a Magnetic Tunnel Junction). These estimations give us the following value of $j_{ti} = 1.7 \times 10^6 \text{ A/cm}^2$. It means that TI can create a torque significantly more effectively than perpendicular current injection, which is mostly used nowadays.

In conclusion, we have demonstrated the possibility of vortex oscillations excitation by the torques caused by a topological insulator (TI). Using micromagnetic modelling, we prove that in-plane rf current through the surface of TI can excite vortex core rotation with a required current density several times lower than previously observed. We consider the dependence of vortex excitation on the frequency and the magnitude of the rf current both by micromagnetic modelling and by analytical theory. An analytical description of the system under consideration is proposed. The analogy between the used approach and the Landau theory of phase transitions is demonstrated. On this basis, the vortex excitation by the RF current through the topological insulator becomes a very promising option for practical applications in spin-transfer nanooscillators, spin-torque diodes and so forth.

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