Excitation of spin waves by a current-driven magnetic nanocontact in a perpendicularly magnetized waveguide

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It is demonstrated both analytically and numerically that the properties of spin wave modes excited by a current-driven nanocontact of length \( L \) in a quasi-one-dimensional magnetic waveguide magnetized by a perpendicular bias magnetic field \( H_y \) are qualitatively different from the properties of spin waves excited by a similar nanocontact in a two-dimensional unrestricted magnetic film (“free layer”). In particular, there is an optimum nanocontact length \( L_{opt} \) corresponding to the minimum critical current of the spin wave excitation.

This optimum length is determined by the magnitude of \( H_y \), the exchange length, and the Gilbert dissipation constant of the waveguide material. Also, for \( L < L_{opt} \) the wavelength \( \lambda \) (and the wave number \( k \)) of the excited spin wave can be controlled by the variation of \( H_y \) (\( \lambda \) decreases with the increase of \( H_y \)), while for \( L > L_{opt} \) the wave number \( k \) is fully determined by the contact length \( L \) (\( k \sim 1/L \)), similar to the case of an unrestricted two-dimensional free layer.

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I. INTRODUCTION

The geometry of magnetic nanostuctures used to construct spin-torque nano-oscillators (STNO) (e.g., Ref. 1) could have a strong influence on the properties of spin wave modes excited in these STNO structures by the spin-transfer torque\(^2\,^3\) carried by the spin-polarized current. Traditionally, two main geometries were used: magnetic nanocontacts\(^4\,^5\) and magnetic nanopillars.\(^6\) In the nanocontact geometry, the STNO “free layer” (FL, where the current-induced precession of magnetization takes place) is a continuous magnetic film unrestricted in both in-plane dimensions. In this geometry, depending on the direction of the bias magnetic field, the spin-polarized current excites usually either propagating spin waves, with the wave number determined by the nanocontact radius,\(^7\,^10\) or a self-localized nonlinear bullet mode\(^10\,^12\) with a frequency that is below the spectrum of propagating spin waves. It is also possible to excite other types of spin wave modes (e.g., magnetic droplet solitons\(^13\,^14\)) or to excite spin waves in magnetic nanostructures by other means (e.g., by specially prepared light pulses\(^15\,^16\)) and achieve a certain level of control of the wavelength of the excited spin waves. However, these methods of spin wave excitation mostly deal with the highly nonlinear solitonic spin wave modes for which independent control of the wavelength and amplitude is impossible.

In the case of a nanopillar geometry, the magnetic FL has finite lateral sizes and reflecting boundaries in the plane of the layer and represents a thin magnetic resonator.\(^6\) The spin wave eigenmodes of this resonator, which have discrete frequencies determined by the finite in-plane sizes of the pillar, can be excited by the traversing spin-polarized current.

However, another STNO geometry might be useful for the development of novel microwave signal processing devices based on the spin-transfer torque effect\(^17\,^18\) (Fig. 1). In this geometry, the FL of STNO has the shape of a quasi-one-dimensional waveguide, where spin waves excited by a nanocontact attached to the waveguide can propagate and provide a synchronization signal for other nanocontacts attached to the same waveguide, thus forming a synchronized linear STNO array with enhanced output power and reduced generation linewidth.\(^19\)

The main goal of our paper was to study analytically and numerically the properties of spin wave modes excited by a current-driven magnetic nanocontact in such a quasi-one-dimensional magnetic waveguide and to analyze the potential of this geometry for the development of practical spintronic microwave devices. Our analysis demonstrates that the properties of spin wave modes excited by a current-driven nanocontact of the length \( L \) in a quasi-one-dimensional magnetic waveguide magnetized by a perpendicular bias magnetic field \( H_x \) (Fig. 1) are qualitatively different from the properties of spin waves excited by a similar nanocontact in two-dimensional unrestricted magnetic film.\(^7\) In particular, there is an optimum nanocontact length \( L_{opt} \) corresponding to the minimum critical current of the spin wave excitation. This optimum length is determined by the magnitude of \( H_x \), the exchange length, and the Gilbert dissipation constant of the waveguide material. Also, for \( L < L_{opt} \) the wave number \( k \) of the excited spin wave can be controlled by the variation of \( H_x \) (\( k \) decreases with the increase of \( H_x \)), while for \( L > L_{opt} \) the wave number \( k \) is fully determined by the contact length \( L \) (\( k \sim 1/L \)), similar to the case of an unrestricted two-dimensional FL.\(^7\)

II. ANALYTICAL MODEL

The core of the device geometry under investigation is a trilayer structure composed of an extended thick magnetic layer, also referred to as “pinned layer” (PL), a nonmagnetic spacer, and a thin magnetic layer (FL) in the form of a thin, quasi-one-dimensional waveguide (prism) elongated along
The first term on the right-hand side of Eq. (1) represents the conservative precessional torque. The second term on the right-hand side of Eq. (1) is the magnetic damping torque written in the traditional Gilbert form ($\alpha_G$ is the damping constant) of the FL material. The last term is the Slonczewski spin-transfer torque that is proportional to the bias current $I$. The function $\Theta(L/2 - |x|)$ describes the spatial distribution of the current across the nanocontact area (of the length $L$). The coefficient $\beta$ characterizing the strength of the spin-transfer torque is related to the dimensionless spin-polarization efficiency $\varepsilon$ ($0 < \varepsilon < 1$) by the expression $\beta = \varepsilon g \mu_B / 2eM_0 W d_{FL}$, where $g$ is the spectroscopic Landé factor, $\mu_B$ is the Bohr magneton, $e$ is the absolute value of the electron charge, $d_{FL}$ is the FL thickness, and $W$ is the waveguide width (along the $y$ axis). In this formulation, the coefficient $\beta$ is independent of the nanocontact length $L$. The unit vector $p$ defines the spin-polarization direction, which coincides with the equilibrium direction of the FL magnetization. In our analysis, we assume that the directions of the static magnetization of the two layers are parallel to each other. In the first approximation, the misalignment of equilibrium magnetization orientations in the two layers leads simply to the reduction of the effective spin-polarization efficiency, i.e., to the scaling of the critical current. Since we are considering normal-to-plane bias fields, we thus assumed that $p = z$.

Introducing the dimensionless complex variable $a$,

$$a = \frac{M_x - i M_y}{\sqrt{2M_0(M_0 + M_z)}},$$

proportional to the amplitude of the magnetization precession in the FL (where $M_i$, with $i = x, y, z$, are the Cartesian projections of the FL magnetization vector $M$), we can rewrite Eq. (1) in the following form (for the details of the derivation, see Ref. 23):

$$\frac{\partial a}{\partial t} = i \left( \omega_0 - D \frac{\partial^2}{\partial x^2} \right) a - \Gamma a + \Theta(L/2 - |x|) \frac{\beta I}{L} a,$$

where $\omega_0$ is the ferromagnetic resonance (FMR) frequency in the perpendicularly magnetized (along the $z$ axis in Fig. 1) thin FL ($d_{FL} \ll W$), namely

$$\omega_0 = \gamma(H_z - 4\pi M_0),$$

and where $D = \gamma^2 4\pi M_0 \lambda_{ex}^2$ is the dispersion coefficient of the exchange-dominated spin waves excited in the nanocontact, $\lambda_{ex} = \sqrt{\gamma^2 A_2 M_0^2}$, $A$ is the exchange constant, and $\Gamma = \alpha_G \omega_0$ is the FMR linewidth proportional to the FL Gilbert damping constant $\alpha_G$. Only the terms linear in the spin wave amplitude $a$ were retained in Eq. (3): the nonlinear corrections, which can also be obtained using ansatz Eq. (2), do not influence the threshold of spin wave generation and do not change the profile or frequency of the excited mode at the threshold. Eq. (3) correctly describes spin wave dynamics only when $H_z > 4\pi M_0$ and the saturated state of the waveguide is stable; below, we restrict our analysis to this case.
The stationary solution of Eq. (3) at the threshold of the current-induced spin wave generation can be found in the form
\[
a(t,x) = e^{-i \omega t}
\begin{cases}
\cos(\kappa x), & |x| < L/2 \\
\cos(\kappa (L/2)) e^{i k(|x| - L/2)}, & |x| > L/2
\end{cases}
\]
where \(\kappa\) and \(k\) are the complex wave numbers of the spin wave modes excited inside and outside the current-carrying nanocontact region and \(\omega\) is the frequency of the excited spin waves. The imaginary parts of the wave numbers \(\kappa\) and \(k\) describe the energy loss or gain of the excited spin wave mode. Using the condition of continuity for the variable spin wave amplitude \(a(t,x)\) at the boundaries of the nanocontact region, we can obtain the following system of equations defining the complex spin wave numbers \(\kappa\) and \(k\), the frequency \(\omega_e\) of the excited spin wave, and the threshold current \(I_{th}\) at which the current-induced spin wave excitation starts in the nanocontact:
\[
\omega_e = \omega_0 + D \kappa^2 - i \left( \Gamma - \frac{\beta I_{th}}{L} \right), \quad (6a)
\]
\[
\omega_e = \omega_0 + D k^2 - i \Gamma, \quad (6b)
\]
\[
\kappa \tan(\kappa (L/2)) = -i k. \quad (6c)
\]
The preceding system of equations cannot be solved analytically in a general case, but if we introduce the characteristic length scale \(\ell_c\) of the problem as
\[
\ell_c = \sqrt{\frac{4D}{\Gamma}} = \frac{2\alpha_G}{\sqrt{\alpha_G} \sqrt{(H_c/4\pi M_0) - 1}}, \quad (7)
\]
and the characteristic current \(I_c\) as
\[
I_c = \frac{\Gamma}{\beta} \ell_c, \quad (8)
\]
it is possible to find approximate analytical solutions of the problem in two limiting cases.

In the limiting case of a “long” nanocontact \(L \gg \ell_c\), when the spin wave propagation is dominated by the Gilbert losses, the approximate solution of Eq. (6) has the form
\[
I_{th} = I_c \frac{L}{\ell_c}, \quad k = \frac{\pi}{L}, \quad \omega_e = \omega_0 + D \left( \frac{\pi}{L} \right)^2. \quad (9)
\]
In the opposite limiting case of a “short” \(L \ll \ell_c\) nanocontact, when the spin wave propagation is dominated by the propagation losses, the approximate solution of Eq. (6) has the form
\[
I_{th} = I_c \left( \frac{3}{4} \right)^{1/3},
\]
\[
k = \left( \frac{6}{L \ell_c^2} \right)^{1/3} = \frac{1}{(L \ell_c^2)^{1/3}} \left[ \frac{3\alpha_G}{2} \left( \frac{H_c}{4\pi M_0} - 1 \right) \right]^{1/3}, \quad (10)
\]
\[
\omega_e = \omega_0 + D \left( \frac{6}{L \ell_c^2} \right)^{2/3}.
\]
It is clear from the expressions for critical current in Eqs. (9) and (10) that there should be an optimum value of the nanocontact length \(L_{opt} \sim \ell_c\) at which the critical current has the minimum value \(I_{th}^{\text{min}} \sim I_c\). The exact values of \(L_{opt}\) and \(I_{th}^{\text{min}}\) can be found from numerical solution of Eq. (6):
\[
L_{opt} \approx 0.52 \ell_c, \quad (11)
\]
\[
I_{th}^{\text{min}} \approx 1.48 I_c. \quad (12)
\]
The typical values of \(\ell_c\) lie in the range of 50–100 nm for applied fields \(H_e \sim 2\) times higher than the saturation field \(4\pi M_0\).

It is also clear from the expressions in Eqs. (9) and (10) for the wave number \(k\) of the spin wave mode propagating from the nanocontact that for a “long” contact [Eq. (9)], the wave number is totally determined by the nanocontact size \(L\). In contrast, for a “short” contact [Eq. (10)], it is possible to control the value of \(k\) by variation of the external bias magnetic field \(H_e\). This latter regime is qualitatively different from the case of nanocontact radiation of spin waves in a two-dimensional FL and could be used to enhance the group velocity of spin waves propagating in a waveguide, thus improving the possibility of mutual synchronization of several generating nanocontacts connected to the same FL waveguide.\[^{19}\]

### III. MICROMAGNETIC MODEL

To check the above-presented approximate analytical results, we performed the numerical study of the spin-torque-induced excitation and propagation of spin waves in a magnetic waveguide by means of finite-difference micromagnetic scheme,\[^{12,20,21,24,25}\] which integrates, in the time domain, the Landau-Lifshitz-Gilbert-Slonczewski equation of motion in Eq. (1). In our numerical study, we used the following parameters of the nanocontact device (Fig. 1): exchange constant \(A_{ex} = 1.4 \times 10^{-6} \text{ erg/cm}\), saturation magnetization \(4\pi M_0 = 8 \text{ kG}\), lateral sizes of the PL \(L_T \times L_T = 3 \times 3 \mu\text{m}\) and thickness \(d_{PL} = 70 \text{ nm}\), lateral sizes of the FL \(L_T \times W = 3 \mu\text{m} \times 69 \text{ nm}\) and thickness \(d_{FL} = 3 \text{ nm}\) (the corresponding integration cell is a cube with a side of 3 nm), Gilbert damping constant \(\alpha_G = 0.02\), and spin-torque efficiency \(\varepsilon = 0.3\). It was assumed that the current-carrying region has a fixed width \(W = 69 \text{ nm}\) along the \(y\) axis, while the \(x\) dimension (nanocontact length \(L\)) is varied. The current density was assumed to be uniform within the \(W \times L\) area and zero outside. The strength of the external bias magnetic field \(H_e\) was varied in the range \((8–20) \text{ kOe}\).

### IV. COMPARISON BETWEEN MICROMAGNETIC AND ANALYTIC RESULTS AND DISCUSSION

In the course of our micromagnetic study, we first calculated the dependences of the bias current \(I_{bi}\) and the spin wave frequency \(f_{s} = \omega_{s}/2\pi\), both computed at the threshold of spin wave generation, as functions of the external bias magnetic field \(H_e\) for the nanocontact of the length \(L = 69 \text{ nm}\). The results of these micromagnetic calculations are presented in Figs. 2(a) and 2(b) as dots. In the same figures we present the results of numerical solution of the analytical model Eq. (6) as solid lines.

As we can see from Fig. 2, the dependences of the analytically calculated threshold current and generated frequency on the bias field have the same form as the micromagnetically calculated ones but are shifted to the right by \(\sim 0.2 \text{ T}\). This shift is explained by the finite sizes of the magnetic waveguide in
FIG. 2. (Color online) Dependence of the (a) current $I_{th}$ and (b) generation frequency $f_g = \omega_g/2\pi$, computed at the threshold, on the magnitude of the bias magnetic field $H_e$. Dots show the numerical simulation; the solid line shows the analytic theory from Eq. (6).

The simulations, which leads to finite demagnetization factors of the waveguide. As a result, the FMR frequency (and, respectively, Gilbert damping, which determines threshold current) is not described by the simple Eq. (4) but has a more complicated form [see Eq. (14)], which can be approximated by the shift of the bias field.

In addition, the linear slope $\partial f_g / \partial H_e \approx 27.4 \text{ GHz/T}$ of the micromagnetically calculated curve $f_g = f(H_e)$ presented in Fig. 2(b) agrees quite well with the value of the gyromagnetic ratio $\gamma$ for electron spin, which follows from Eqs. (13) and (14).

Then, we calculated the dependence of the generation frequency $f_g = \omega_g/2\pi$ on the applied bias current at the fixed magnitude of the bias magnetic field $H_e = 10$ kOe and fixed nanocontact length $L = 69$ nm from the micromagnetic simulations in Eq. (1) and from the numerical solution of the model Eq. (3). The results of these calculations are presented in Fig. 3. It is clear that the generation frequency increases with current, like it should in the case of a perpendicular magnetization of the FL, and demonstrates nonlinear behavior at larger current magnitudes. Micromagnetic results (dots) show that the excitation of spin waves by direct current exhibits no hysteresis. It is also clear from Fig. 3 that micromagnetic results (dots) reproduce well the results of the numerical solution of the model Eq. (3) (solid line).

The micromagnetically calculated generation frequency $f_g$ can be well described by the classical expression for the frequency of exchange-dominated spin waves:

$$\omega_g = \omega_{\text{FMR}} + DK_{\text{num}}^2,$$

where $\omega_{\text{FMR}}$ is the FMR frequency of the perpendicularly magnetized FL waveguide (taken as a rectangular prism) and $K_{\text{num}} = 2\pi/\lambda_{\text{num}}$ is the numerically calculated wave number (where $\lambda_{\text{num}}$ is the wavelength of the generated spin wave). The FMR frequency in the waveguide $\omega_{\text{FMR}} \approx \omega_0$ is computed from the expression [see Eq. (2) in Ref. 26]

$$\omega_0 = \gamma \sqrt{(H_e + (N_{xx} - N_{zz})4\pi M_0)(H_e + (N_{yy} - N_{zz})4\pi M_0)},$$

where $N_{ii} (i = x, y, z)$ are the demagnetizing factors of a rectangular prism. The numerical values of the prism demagnetization factors $N_{xx} = 0.0014$ and $N_{yy} = 0.0638$ are much smaller than that of $N_{zz} = 0.9348$, so Eq. (14) gives a result $f_{\text{op}} = \omega_{\text{op}}/2\pi = 7.76 \text{ GHz}$ that is close numerically to the result obtained from the simple approximate expression in Eq. (4).

Also, for each value of the bias direct current $I$, we determine from the micromagnetic simulations the wave number $k_{\text{num}}$ of a spin wave excited in the waveguide nanocontact. Then, using these values in Eq. (13), we get the frequencies of generated spin waves that agree well (the difference is <300 MHz) with the frequencies obtained from both the micromagnetic simulations and the numerical solution of the model Eq. (3).

Our micromagnetic simulations also allow us to determine the spatial profile of the excited spin wave mode and to confirm

FIG. 3. (Color online) Dependence of the generated frequency $f_g = \omega_g/2\pi$ on the applied current $I$ at the fixed value of the bias magnetic field of $H_e = 10$ kOe and fixed length $L = 69$ nm of the nanocontact. Dots show the micromagnetic simulation; the solid line shows the numerical solution of the model Eq. (3).
the propagating character of this mode. For example, the micromagnetically simulated profile of the spin-wave power $P$ (proportional to the square of the envelope amplitude $A$ ($P \sim A^2$) of the $y$ component of the normalized magnetization) as a function of the distance $r$ from the nanocontact center is shown in Fig. 4 by dots.

It is clear from Fig. 4 (and in particular from the log-scale inset) that the normalized power of the excited spin wave mode exhibits an exponential decay. This is well described by the expression $P(r)/P_0 = (A/A_0)^2 = \exp(-2r/\rho)$, where the characteristic spin wave “propagation distance” $\rho$ (distance at which the spin wave amplitude $A$ reduces $e$ times), characterizing the spin wave propagation losses in the FL waveguide, is determined from the comparison with the micromagnetic results to be $\rho = 455$ nm (Fig. 4). The propagation distance $\rho$ can be also approximately calculated quasi-analytically, assuming that it is equal to the ratio between the spin wave group velocity $v_g$ and the effective damping rate $\Gamma$ and determining the spin wave number $k_{\text{num}}$ from micromagnetic simulations:

$$\rho = \frac{v_g}{\Gamma} = \frac{\partial \omega_g/\partial k}{\alpha_G \omega_g} = \frac{2D k_{\text{num}}}{\alpha_G \omega_{0p} + D k_{\text{num}}^2}. \quad (15)$$

Using the analytical expression $D = g/4\pi M_0^2 \lambda_{\text{ex}}^2 = 7740 \text{GHz} \cdot \text{nm}^2$ for the exchange stiffness, Eq. (14) for the FMR frequency $\omega_{0p}/2\pi = 10.5$ GHz, the nominal value $\alpha_G = 0.02$ for the Gilbert damping constant, and the micromagnetically calculated value of the spin-wave number ($A = 4 \text{ mA}$) $k_{\text{num}} = 0.042 \text{ nm}^{-1}$ ($\lambda_{\text{num}} = 150$ nm), we obtain the value $\rho = 490$ nm, which turns out to be in reasonably good agreement with the above-presented micromagnetic results.

The most interesting and nontrivial result obtained in our micromagnetic simulations performed for the quasi-one-dimensional waveguide geometry is the confirmation of the nonmonotonic dependence of the threshold current $I_{\text{th}}$ on the nanocontact length $L$ for a fixed value of the bias magnetic field ($H_b = 10$ kOe). It follows from the above-developed analytic theory in Eqs. (6)–(12) that the dependence of the bias current $I_{\text{th}}$ on the nanocontact length $L$ should have a minimum value $I_{\text{th}}^{\text{min}} \sim I_c$ near the point where $L \approx \ell_c$ [Eqs. (11) and (12)] and qualitatively different behavior of $I_{\text{th}}$ below and above this point [Eqs. (9) and (10)]. All these conclusions of the analytic theory were fully confirmed in our micromagnetic simulations, the results of which are presented in Fig. 5.

Indeed, Fig. 5 demonstrates a pronounced minimum in the threshold current at the nanocontact length $L = 102$ nm, which is close to the analytically predicted value $L_{\text{opt}} \approx 105$ nm following from Eq. (7). Also the micromagnetically calculated behavior of the threshold current in the regions $L < L_{\text{opt}}$ and $L > L_{\text{opt}}$ agrees remarkably well with the analytic predictions in Eqs. (10) and (9), respectively (see dashed lines in Fig. 5).

There is another nontrivial feature of the considered quasi-one-dimensional geometry of the FL (Fig. 1). In contrast with the case of a finite-radius nanocontact in a two-dimensional FL, where the wavelength of the spin wave excited at the threshold is determined exclusively by the nanocontact radius $R_c$ ($\lambda_{\text{ex}} \sim 4.5 R_c$), in the case of a short ($L < L_{\text{opt}}$) nanocontact in a waveguide, the wavelength $\lambda$ (or the wave number $k$) of the excited spin wave can be also controlled by varying the strength of the bias magnetic field $H_b$ [Eq. (10)]. This interesting feature analytically predicted in Eq. (10) provides an additional degree of freedom to manipulate the properties of the excited spin waves. This theoretical prediction is also confirmed in our micromagnetic simulations (Fig. 6) performed for a “short” ($L < L_{\text{opt}}$) nanocontact of the length $L = 69$ nm. It is clear from Fig. 6 that the micromagnetically calculated wavelength of the spin wave excited at the threshold (dots in Fig. 6) can be reduced 2 times when the bias magnetic field $H_b$ is increased from 10 to 20 kOe. The analytic result from Eq. (10) (shown as a solid line in Fig. 6) is in reasonably good agreement with the simulation results.
V. CONCLUSIONS

Our analytic and micromagnetic study of the spin-transfer-driven excitation of spin wave modes in a quasi-one-dimensional magnetic waveguide demonstrated two new features of this geometry in comparison with the traditional two-dimensional nanocontact geometry: (i) the dependence of the threshold bias current on the nanocontact length is nonmonotonous and has a minimum defined by Eqs. (11) and (12) and (ii) for "short" \( L < L_{\text{eq}} \) nanocontacts, it is possible to control the wavelength of the radiated spin wave by varying the magnitude of the bias magnetic field. This last feature might be important for the experimental study of the spin wave propagation in magnetic waveguides, because by the variation of the bias field, the spin wavelength could be brought to the region \( \lambda > 300 \) nm, where the wave process is accessible for the observation by the microfocus Brillouin light scattering. The same feature might also be useful for the development of the synchronized linear arrays of nanocontact STNOs, because by variation of the wavelength, we can also vary the spin wave group velocity [and therefore the spin wave propagation distance \( \rho \); see Eq. (15)]. That way, by varying the bias magnetic field \( H_{\text{c}} \), it would be possible to vary the effective coupling between the nanocontact STNO and thus influence the synchronization properties of the linear STNO array.

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