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Current-induced modification of spin wave mode interference

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ABSTRACT

We have studied the effect of adiabatic spin-transfer torque on mode interference of spin waves. The mode interference generates amplitude-localized spots at special positions which do not move with time. When applying current, the wavevector of spin wave is modified, resulting in current-dependent displacement of amplitude-localized spots. This current-dependent change in the mode interference may allow to probe current-induced spin wave Doppler shift in space-domain. In favorable situations, it can be used to estimate the intrinsic properties of magnetic materials such as spin polarization.

1. Introduction

The flow of electron through an inhomogeneous magnetization configuration transfers spin-angular momentum; i.e., spin-transfer torque (STT) [1,2]. This STT effect has been studied over a decade due to its rich physics and potential for various applications [3]. To understand the STT physics and to utilize it for device applications, lots of studies have been performed in multilayer structures with current-induced magnetization switching [4–12] and steady precession of magnetization [13–16], and in nanowires with current-induced magnetic domain wall motion [17–22]. It has been reported that spin-transfer also occurs in spin waves, which have the advantages over domain walls because it is less sensitive to local defects [23–29]. It enables to estimate the intrinsic property of STT more accurately.

When spin waves propagate through a confined system, several modes are excited simultaneously. The spin wave modes are quantized in a nanowire [30–32] and the interference of the quantized modes generates spatially localized amplitude patterns [33]. This spatial pattern is caused by locally suppressed amplitude at periodic positions, called amplitude-localized position, which do not move with time. When applying current, STT modifies the wavevector of spin wave, i.e. current-induced spin wave Doppler shift, which causes current-dependent displacement of the amplitude-localized positions. In this work, we study the effect of STT on the mode interference of spin waves through current-dependent displacement of amplitude-localized positions. This paper is organized as follows. In Section 2, we present spin-wave theory for the current-dependent change in the mode interference of spin waves. Section III gives comparisons between theoretical and numerical results. We summarize our work in Section 4.

2. Mode interference of spin waves

When spin wave propagates along a nanowire having a finite width (Fig. 1), the quantized modes of spin wave are excited due to the lateral confinement [30,31]. The lateral confinement provides the quantization condition to the components of spin wavevector k. For the nanowire where the length, width and thickness are along the x-, y-, and z-axis, respectively, the quantization rule forms $k_y = n\pi/L_y$ (n = integer) where L_y is the width of nanowire [32]. That is, an alternating magnetic field at a local position generates several propagating spin wave modes that satisfy the quantization rule, leading to a mode interference [33]. When the alternating magnetic field applied to generate propagating spin waves is spatially uniform, only odd n is allowed and the amplitude of spin waves decreases with increasing n [34]. Thus, we consider the modes of spin wave with $n = 1,3$ only for understanding the mode interference. Indeed, experimentally observed interference pattern of spin wave modes is well reproduced when considering the first two odd modes of spin wave, $n = 1, 3$ [33].

The total spin wave state with the modes of $n = 1, 3$ at a fixed frequency $f = \omega_0/2\pi$ can be written as

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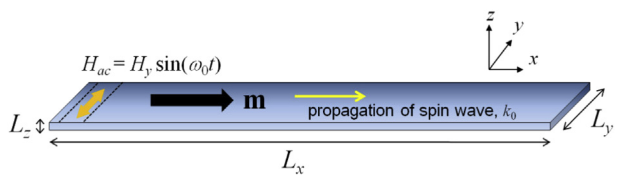

Fig. 1. Schematic of a magnetic nanowire with in-plane magnetization. The length, width, and thickness are L_x, L_y, and L_z, respectively. An alternating magnetic field applied along y-axis with angular frequency of ω_0 generates the spin wave along x-axis with wavevector, k_0.

$$f(x,y,t) = A_1\cos(k_{x1}x - \omega_0 t)\cos(k_{y1}y) + A_3\cos(k_{x3}x - \omega_0 t)\cos(k_{y3}y), \quad (1)$$

where A_n is the amplitude of the mode n, and k_{xn} and k_{yn} are the wave numbers of the mode n along the x- and y-axis, respectively. The wave numbers along the y-axis, k_{y1} and k_{y3}, are determined as π/L_y and $3\pi/L_y$, respectively, from the boundary condition, $f = 0$ at $y = \pm L_y/2$. After some algebra, the above equation is rewritten as,

$$f(x,y,t) = C_1(y)\cos\left(\bar{k}_x x - \omega_0 t\right)\cos\left(\frac{\Delta k_x x}{2}\right) + C_2(y)\sin\left(\bar{k}_x x - \omega_0 t\right)\sin\left(\frac{\Delta k_x x}{2}\right), \quad (2)$$

where $C_1(y) = A_1\cos(k_{y1}y) + A_3\cos(k_{y3}y)$, $C_2(y) = -A_1\cos(k_{y1}y) + A_3\cos(k_{y3}y)$, $\bar{k}_x = (k_{x1} + k_{x3})/2$, and $\Delta k_x = k_{x1} - k_{x3}$. In the above equation, the factors including the time t correspond to propagating waves with a relatively short wavelength $\lambda_s = 2\pi/\bar{k}_x$ whereas the factors without the time t correspond to standing waves with a relatively long wavelength $\lambda_l = 4\pi/\Delta k_x$. Thus, the spin wave state can be described by the product of propagating and standing waves. Fig. 2(a) and (b) depicts two waves described in Eq. (2), with the amplitudes $C_1(y)$ and $C_2(y)$, respectively. In Eq. (2), there is a special position x where the standing wave is zero, that is, either $\cos(\Delta k_x x/2) = 0$ or $\sin(\Delta k_x x/2) = 0$. We define the positions 1 and 2, satisfying $\sin(\Delta k_x x/2) = 0$ and $\cos(\Delta k_x x/2) = 0$, respectively. The spin wave states $f_1(x,y,t)$ and $f_2(x,y,t)$ at the positions 1 and 2 can be written as,

$$f_1(x,y,t) = C_1(y)\cos\left(\bar{k}_x x - \omega_0 t\right), \quad (3)$$

and

$$f_2(x,y,t) = C_2(y)\sin\left(\bar{k}_x x - \omega_0 t\right). \quad (4)$$

At these special positions, the amplitudes are given as $|C_1(y)| = |A_1\cos(k_{y1}y) + A_3\cos(k_{y3}y)|$ and $|C_2(y)| = |A_1\cos(k_{y1}y) - A_3\cos(k_{y3}y)|$, respectively. Describing these amplitudes, one finds the locally suppressed amplitude due to the sum of two cosine functions as shown in Fig. 2(c)–(f). In Fig. 2 for $|C_1(y)|$((c) and (e)) and $|C_2(y)|$((d) and (f)), the black arrows in (e) and (f) mark the locally suppressed amplitude. Especially, we note that for $|C_1(y)|$, the suppressed amplitude at side edges is remarkably small.

In brief summary, at the position 1, the magnetization oscillates with the angular frequency of ω_0 and the amplitude of $|C_1(y)|$ where the amplitude is suppressed at both side edges. Likewise, at the position 2, the magnetization oscillates with the angular frequency of ω_0 and the amplitude of $|C_2(y)|$ where the amplitude is suppressed in the middle of a nanowire width. The positions 1 and 2 appear periodically in the nanowire along the x-axis and the periodicities of position 1 and position 2 are the same as $\Lambda = 2\pi/\Delta k_x$.

For calculating the periodicity Λ, the longitudinal wave numbers k_{x1} and k_{x3} should be defined through the dispersion relation, which can be derived from the Landau–Lifshitz–Gilbert (LLG) equation with the adiabatic STT term as,

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma \mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{m}, \quad (5)$$

where $\mathbf{m} = (m_x, m_y, m_z)$ is the unit vector of magnetization, γ is the gyromagnetic ratio, $\mathbf{H}_{\text{eff}}$ is the effective magnetic field, α is the intrinsic damping constant, $\mathbf{u} = u_0\hat{x}$, $u_0 = \mu_B jP/eM_s$ is the magnitude of adiabatic STT, μ_B is the Bohr magneton, j is the current density, P is the spin polarization, e is the electron charge, and M_s is the saturation magnetization. Here we neglect the nonadiabatic STT term, assuming that its effect is small. We consider the exchange spin wave so that the effective magnetic field $\mathbf{H}_{\text{eff}}$ includes the demagnetization field, the easy axis anisotropy field and the exchange field, i.e. $\mathbf{H}_{\text{eff}} = H_k m_x\hat{x} + D\nabla^2\mathbf{m} - H_d m_z\hat{z}$ where $H_k = (N_y - N_x)M_s$ is the easy axis anisotropy field, $H_d = (N_z - N_y)M_s$ is the demagnetization field, $D = 2A_{ex}/M_s$, A_{ex} is the exchange stiffness constant, and N_x, N_y and N_z are demagnetization factors along the x-, y-, and z-axis, respectively. Then the dispersion relation is readily obtained as

$$\omega_0 = -u_0 k_{x1} + \gamma\sqrt{\left(H_k + Dk_0^2\right)\left(H_d + H_k + Dk_0^2\right)} = -u_0 k_{x3} + \gamma\sqrt{\left(H_k + Dk_0^2\right)\left(H_d + H_k + Dk_0^2\right)}, \quad (6)$$

where $k_0^2 = k_{x1}^2 + k_{y1}^2$ ($k_0^2 = k_{x3}^2 + k_{y3}^2$) for the upper (lower) dispersion relation. From the dispersion relations, one can get analytic forms of k_{x1}, k_{x3}, and Λ, but they are too long to be included here.

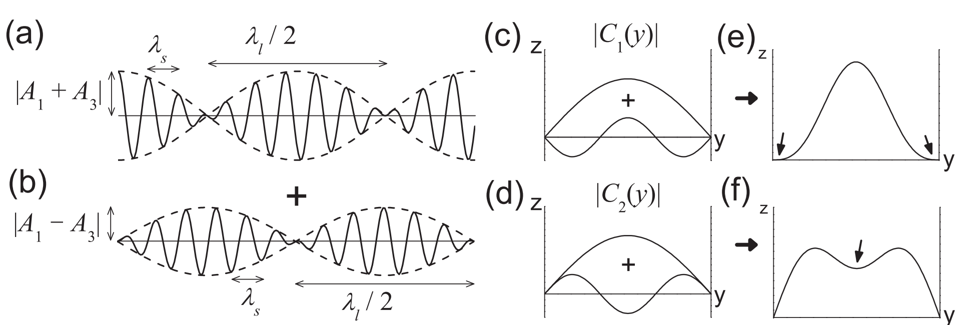

Fig. 2. The spin wave state in Eq. (2) can be described by the sum of two waves shown in (a) and (b). (a) describes $C_1(y)\cos(\bar{k}_x x - \omega_0 t)\cos(\Delta k_x x/2)$ and (b) describes $C_2(y)\sin(\bar{k}_x x - \omega_0 t)\sin(\Delta k_x x/2)$. (a) and (b) include propagating wave with λ_s (solid line) and standing wave with λ_l (dashed line). At position 1 for $|C_1(y)|$, the sum of amplitude of two modes (see (c)) results in the suppressed amplitude at the edge of the nanowire (see (e)). At position 2 for $|C_2(y)|$, sum of amplitude of two modes (see (d)) results in the suppressed amplitude in the middle of the nanowire (see (f)).