Current-Induced Modulation of Magnetostatic Forward Volume Mode

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The excitation of the spin-waves (SWs) is a ubiquitous in a magnetic system [1]. The considerable interest is revived due to the intensive works owing to elucidate the underlying physics such as not only dispersion, reflection, tunneling, and current-induced Doppler shift but also microscopic relaxation mechanism of the SWs [2]. Now, it is possible to use the SWs for delivering the signal information, which a several designs for the device application such as SW bus interconnect [3], and logic device [4] are proposed. However, significant challenging issue, which the SW amplitude is substantially decayed within a few micrometers, should be overcome for the practical application. From our previous work, the SW attenuation can be modulated by injecting an electric current through a magnetic nanowire as propagating waveguide of the SW [5]. In particular, the amplitude is even amplified above the critical current density (u_c), which is typically a few 10^8 A/cm^2. In this study, we found that the uc is reduced by less than 100 (m/s) for the magnetostatic forward volume (MSFVM), since the excited frequency of MSFVM is sub-GHz range.

To perform the micromagnetic simuilation, we use the phenomenological Landau-Lifshitz-Gilbert equation including spin toruqe (ST) terms (Eq. (1)),

$$\partial \boldsymbol{m}/\partial t = -\gamma \boldsymbol{m}\times H_{\mathrm{eff}} + \alpha \boldsymbol{m}\times \partial \boldsymbol{m}/\partial t + u\cdot\nabla - \beta\,[u\cdot(\boldsymbol{m}\times\nabla)]\boldsymbol{m} \quad (1)$$

where γ is the gyromagnetic ratio (= 1.76×10^7 s^{-1}Oe^{-1}), $\boldsymbol{m}$ is the local magnetization, $\boldsymbol{H}_{\mathrm{eff}}$ is the effective magnetic field, α is the Gilbert damping constant. $\boldsymbol{u}=u_0\boldsymbol{x}$, u_0 (=$Pj_e\mu_B/eM$S) represents the magnitude of the adiabatic ST, P is the spin polarization, j_e is the electric current density, μ_B is the Bohr magneton, M_S is the saturation magnetization. β is the ratio of non-adiabatic ST to the adiabatic one. Fig. 1(a) shows the modeling system. The waveguide is the rectangular strip of $Ni_{80}Fe_{20}$. The dimension is 20 µm long, 3.5 µm wide, and 2 nm thick with the unit cell of 4 × 3500 × 2 nm^3. Standard material parameters were used; 700 emu/cm^3 for M_S, 0.01 for α, 1.3×10^{-6} erg/cm for the exchange constant (A_{ex}). The crystalline anisotropy constant and the temperature were assumed to be zero.

We apply an external magnetic field (0.88T) exceeding the shape anisotropy ($N_Z M_S$=0.878T) to align the magnetization along the z-axis. The Oersted field (H_{Oe}) induced by flowing current through the antenna locally excites the magnetization, the so-called MSFVM were generated. Inset shows the induced H_{Oe} calculated by using Biot-Savart law assuming a spatially uniform current on the antenna. The excited frequency of the MSFVM is determined by the frequency of the ac current on the antenna. dc current is injected to the Py waveguide.

Fig. 1(b) shows the spatial variation of the MSFVM for f_{SW} = 1 GHz, and their FFT spectra is shown in fig. 1(c). From the excited region, the SWs propagate both temporally and spatially, and the amplitude decays exponentially. Therefore, SWs can be considered as a plane wave, $\boldsymbol{m}=\boldsymbol{x}+\boldsymbol{m}_0\exp[i(\omega t+kx)]\exp(-x/\Lambda)$ with ω (=$f_{sw}/2\pi$) is the frequency, k is the wave vector, and Λ is the characteristic attenuation length of the SWs.

Fig. 1(d) shows the inverse characteristic attenuation length (Λ^{-1}) as a function of u_0 for several β. Λ^{-1} decreases with increasing u_0, which means that the amplitude of the SWs less decays with increasing dc current density. Also, Λ^{-1} decrease with increasing β. Above the critical value of uc = 90 (48) m/s for β = 3α (5α), it is shown that the sign of Λ^{-1} is change, which means that the SWs spatially amplified.

In summary, we numerically show that MSFVM is modulated by injecting spin current along the waveguide. Comparing with the cases of DESWs (300m/s) [5], it is found that MSFVM has low u_c (48m/s for β=5α). However, it is still high for the practical application. Note that the magnitude of β is still highly controversial [8], if β > 5α, uc can be less than 10^8 A/cm^2.

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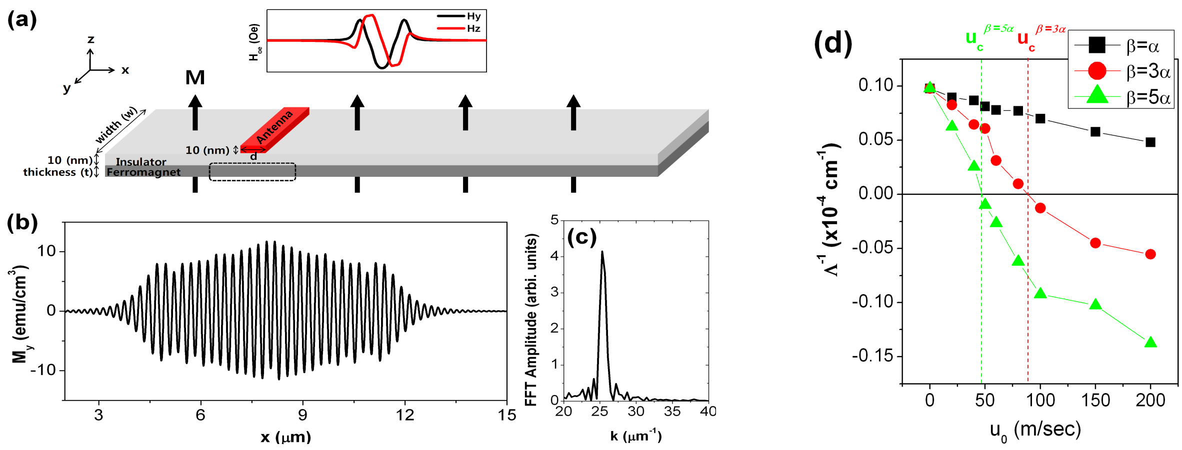

Fig. 1. (a) Schematic view of the modeling system. Inset shows the Oersted field profile induced by flowing current on the antenna. dc current flows along the ferromagnetic strip.(b) The spatial variation of the magnetization, and (c) their FFT analysis for f_{sw} = 1.0 GHz. (d) Inverse characteristic attenuation length (Λ^{-1}) of the SW (f_{sw}=0.3 GHz) as a function of u0 for several cases of β.