Enhancing or Suppressing Microwave Magnetic Loss via Spin-Transfer Torque Effect

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Abstract

Based on micromagnetic simulation results, it is found that due to the misalignment between the magnetic moment vector direction at both ends of a single nanowire and the direction of the polarized current density (J), the spin-transfer torque (STT) of electrons can only act on the magnetic moments at both ends of the nanowire. By increasing the spin polarization (P) of the polarized current, the microwave magnetic loss at 18 GHz in the microwave magnetic spectrum of this simplified model can be significantly suppressed, while it is found that the magnitude of the natural resonance frequency corresponding to the microwave loss is not affected by STT. Under the effect of STT, a negative imaginary part of permeability is also achievable. Additionally, simulation results show that by increasing the β value in the non-adiabatic effect term of the STT effect, the microwave magnetic loss at 18 GHz can be significantly enhanced. Based on the influence of different torque origins in the STT effect on the effective damping constant (e) of the magnetization precession process, the above results can be reasonably explained: adiabatic torque can reduce the e value, thereby suppressing the magnitude of microwave magnetic loss; non-adiabatic torque can increase the e value, thereby enhancing microwave magnetic loss. Our research results demonstrate an innovative method for actively tuning microwave magnetic loss.

Full Text

Preamble

Suppress or Enhance Microwave Magnetic Losses by Spin Transfer Torque Effect

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Author Contribution Statements: HAN proposed the research ideas, designed the simulation details, analyzed the data, and prepared the entire manuscript.

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Abstract

Using micromagnetics simulations, we demonstrate that spin transfer torques (STT) from electrons are exerted only on magnetic moments at the two ends of a single nanowire where they are misaligned with the direction of the polarized current density (J). By increasing the polarization rate (P) of the current, microwave magnetic losses at 18 GHz can be significantly suppressed in this simplified model. We also find that the natural resonance frequency cannot be altered by the STT effect, and that negative imaginary parts of permeability become feasible under STT. Conversely, the results show that microwave magnetic losses at 18 GHz can be enhanced by increasing the β value in the non-adiabatic term. This behavior is well understood through changes in the effective damping constant ( ) arising from different contributing torques of the STT effect.

The adiabatic torque of STT decreases the value and therefore suppresses microwave magnetic losses, while the non-adiabatic torque of STT increases the value and enhances the losses. Without employing any metamaterials, these results demonstrate an active and innovative approach to controlling microwave magnetic losses and developing magnetic gain media.

Keywords: spin transfer torque; permeability; micromagnetics; magnetic losses; magnetic gain medium

1. Introduction

Electromagnetic composites with ferromagnetic inclusions (such as flakes, microwires, and nanowires) are currently under extensive investigation due to their significance in modern electronics and military applications [1-2]. Ferromagnetic nanowire arrays, as advanced functional materials with strong shape anisotropy, find numerous applications including acoustic sensors [3], perpendicular magnetic recording media [4], electromagnetic wave absorbers, and self-biased electromagnetic devices [5]. These nanowires are typically deposited into anodic aluminum oxide (AAO) templates to create periodically ordered arrays. To mitigate electromagnetic wave pollution, absorbing layers have been fabricated containing randomly oriented magnetic nanowires [4], where larger dielectric losses (’ ‘>0) and/or magnetic losses (’ ‘>0) are required for specific operating frequency bands. However, for many applications, periodically ordered ferromagnetic nanowires are necessary. In our previous work, we measured the frequency-dependent permittivity and permeability of periodically ordered Fe nanowire arrays [7]. For microwave magnetic devices such as circulators or isolators, lower magnetic loss (’’ $→$0) is preferable.

Traditional approaches to suppressing or enhancing microwave magnetic losses rely on finding magnetic materials with specific crystalline structures and proper microstructures [8-10]. These methods are passive because once materials are selected, it becomes impossible to control magnetic losses during device operation. Beyond naturally synthesized materials, so-called metamaterials are designed to tune high-frequency permittivity and permeability to manipulate electromagnetic wave propagation. Negative real parts of permittivity (’ <0) and/or permeability (’ <0) are often achieved in artificial structures such as split-ring resonators (SRR). As shown in Fig. 1 [Figure 1: see original paper], electromagnetic media can be classified into four types based on the signs of the real parts of permittivity and permeability. Notably, in the third quadrant where both real parts are negative, the medium is termed a left-handed material, exhibiting exotic properties like negative refraction, amplification of evanescent waves, reversed Doppler effect, and reversed Cherenkov radiation [11-12]. However, the imaginary parts of permittivity and permeability for metamaterials have rarely been studied, despite their importance for electromagnetic fundamentals and engineering applications such as electromagnetic wave absorbing materials.

In this contribution, we propose an innovative approach to actively control the imaginary parts of permeability without using any metamaterials. Using a simplified model with only a single iron (Fe) nanowire, we theoretically demonstrate how to actively suppress or enhance the high-frequency magnetic losses of ferromagnetic materials through the spin transfer torque (STT) effect. These results provide a valuable pathway for actively adjusting microwave magnetic losses for specific applications.

Fig. 1 Classification of electromagnetic materials with ’’ > 0 and ’’ > 0

2. Simulation Details

In this work, we employ micromagnetics based on continuum theory to simulate the high-frequency permeability of Fe nanowires. This approach describes magnetization processes on a length scale large enough to replace atomic magnetic moments with a continuous function of position, yet small enough to resolve transitions between magnetic domains. We utilize the widely used micromagnetics simulation software “OOMMF” (Object-Oriented Micromagnetic Framework) [13]. To study the dynamic response of magnetization to external excitation, micromagnetics simulations are performed by solving the Landau-Lifshitz-Gilbert (LLG) equation. When the spin transfer torque effect is included, the LLG equation is modified as follows [14,15]:

-(1)

where H_{eff} is the effective magnetic field comprising exchange interaction, magnetic anisotropy field, applied external magnetic field, and demagnetization field. α is the Gilbert damping constant for the dynamic precession of magnetization (M) without STT, set to 0.01 for all simulations. γ is the Gilbert gyromagnetic ratio (2.21×10^5 m/A • s).

On the right side of Eq. 1, the third term describes the adiabatic effect of spin transfer torque, while the last term represents the non-adiabatic contribution, which accounts for the impact of current-induced Joule heating on the dynamical behavior of M. β is the non-adiabatic parameter. According to the physical model in Equation (1), vector u is a velocity related to moving electrons defined as:

-(2)

where _B is the Bohr magneton, P is the polarization rate of current (P = (I↑-I↓)/(I↑+I↓)), g is the Landé factor, e is the electron charge, and J is the density of polarized current, which will be varied to study its impact on magnetic losses.

The physical parameters for pure iron (Fe) nanowires in the micromagnetics simulation are: magnetocrystalline anisotropy constant K_1 = 4.8$×10^{4}$ J/m^3, exchange stiffness constant A = 2.1$×10^{-11}$ J/m, and saturation magnetization M_s = 1.7$×10^{6}$ A/m. The unit cell size for discretizing the nanowire is set to 2 nm × 1.25 nm × 1.25 nm, which is smaller than the critical exchange length (3.4 nm for Fe) [16]. The geometric dimensions (Length × Diameter, L×D) of an isolated Fe nanowire are set to 100 nm (L) × 10 nm (D).

To obtain the frequency-dependent permeability of the Fe nanowire, we first establish an initial equilibrium state of magnetic moments without an applied magnetic field, where the orientation of magnetic moments results solely from minimizing the total free energy. Then, a pulsed magnetic field (h(t) = 1000 exp(-10^9t), with t in seconds and h in A/m) is applied perpendicular to the nanowire length (x-axis) to excite the magnetization away from equilibrium. Finally, the dynamic responses of magnetization as a function of time are recorded and transformed into the frequency domain using fast Fourier transform (FFT). Based on the following definitions, the permeability spectra are obtained:

-(3)
-(4)
-(5)

3.1 Suppress Microwave Magnetic Losses

To understand the origins of microwave magnetic loss peaks, the equilibrium states of magnetization vectors along the nanowire are required and shown in

Fig. 2 [Figure 2: see original paper]. The current density J flows along the nanowire length, while the pulsed magnetic field is applied along the y-axis. Clearly, M vectors at the two ends of the nanowire are misaligned with those in other regions, indicating they experience different effective magnetic fields.

To illustrate our concept of suppressing microwave magnetic losses via the STT effect, we simulated the frequency-dependent permeability (~ f) of a single Fe nanowire. For this purpose, J was set to 13$×10^{11}$ A/m^{2}, β to 0.01, and P was varied to study the effect of spin polarization rate. With the dimensions of our single nanowire model, only a small polarized current (approximately 1 mA) is required to achieve such a large J value. First, the ~ f spectrum without STT effect is shown in Fig. 3a [Figure 3: see original paper].

Two significant magnetic loss peaks are observed at 18 GHz and 31 GHz. Assuming the 18 GHz peak is the target for suppression, we note that the simulated natural resonance peak (f__r) at 31 GHz is often called the "bulk mode" [17,18] and is attributed to the natural resonance phenomenon of M oriented perfectly along the nanowire length direction. Our f__r value for the "bulk mode" is calculated as 31.49 GHz according to the following equations [19]:

-(6)
-(7)
-(8)
2012ssKNM =Δ,102„ksssKHKKKM ==
-(9)

where K__s is the shape anisotropy constant, and H__k and H__s are the anisotropy fields related to K_1 and K__s, respectively. In our case, H__k and H__s are aligned in the same direction. ΔN is the demagnetization factor difference between the x-axis direction (N__x=0) and y-axis direction (N__y=0.5). The calculated resonance frequency closely matches the simulated bulk mode peak frequency (31 GHz, see Fig. 3). The other peak at 18 GHz is termed the "edge mode" and lacks a direct calculation formula. This edge mode resonance is believed to originate from magnetizations at both nanowire ends that are misaligned with the bulk mode magnetizations, as shown in Fig. 2.

For the natural resonance mechanism without STT, the precession cone angle ( ) of magnetization continuously decreases due to microwave magnetic losses, as illustrated in Fig. 3c. The decay of M__y,z(t) components shown in Fig. 3b indicates that angle is decreasing. Therefore, a positive ' ' value denotes magnetic loss and continuously decreasing . According to STT theory, when spin-polarized current flows through a region of ferromagnetic material with non-uniformly oriented magnetic moments, the spin angular momentum of electrons can be transferred to the magnetizations (M), exerting a torque on M [20,21]. In our case, since magnetic moments at both nanowire ends are not uniformly oriented, the impact of STT on the ~ f spectra should only be observed for the magnetic loss peak of these zones, as shown in Fig. 4 [Figure 4: see original paper].

Clearly, increasing the polarization rate of current (P) gradually suppresses the magnetic loss at this frequency. When P is 0.3, 0.4, and 0.5, the maximum ’’ values are 15.50, 11.64, and 4.66, respectively. Notably, when P reaches 0.7, the positive loss peak at 18 GHz almost disappears. These results demonstrate that the STT effect can be employed to suppress microwave magnetic losses. Additionally, the STT effect does not impact the magnetic permeability of the "bulk mode" at 31 GHz, which corresponds to the zone where J and M are aligned in the same direction. Furthermore, when the STT effect is sufficiently strong, the torque transferred from spin increases the precession cone angle of magnetization, meaning the energy transferred from the polarized current surpasses the energy losses due to normal natural resonance. Consequently, this results in negative ”values (see Fig. 4d), which is commonly considered impossible for normal natural resonance. This phenomenon is fundamentally different from metamaterials, where only negative ’ is possible and ’’ is always positive [22]. It should be noted that some previous papers reported negative ’’ values in naturally synthesized materials, but we believe those results were due to measurement errors without convincing physical origins. According to electromagnetic theory, conventional passive materials cannot have negative imaginary parts of permeability (or permittivity) because this violates the causality principle and energy conservation. The "causality" principle means that any negative ’’ resembling negative dissipation must be legitimized by an external energy source; otherwise it violates the Kramers-Kronig relations and falls into a physically forbidden zone. In our case, external energy is pumped into the system, enabling negative ’’ and providing an active method to control permeability without metamaterials. A medium with ’ <0 and ’’ <0 is called a "gain-magnetic double-negative metamaterial."

Based on Equation 2, increasing the J value has the same effect as increasing the P value. The impact of J value on permeability spectra was reported in our previous paper [23], where the total free energy of the magnetic system varied when polarized electrons transferred angular momentum to the magnetizations. The additional energy is transported through the following chain: electric field energy drives the polarized current to flow → polarized current transfers spin angular momentum to M → the precession cone angle of M changes due to the transferred torque (torque = Δ(angular momentum)/Δt). Therefore, a polarized current with larger P value requires a smaller critical J value (J_c) to completely suppress unwanted microwave magnetic losses. If the system has larger Gilbert damping torque for the precession, as depicted in Fig. 3c, a larger J_c will be required for a larger STT torque.

To understand how the STT effect influences magnetic losses, we compared the precession behaviors of the magnetization component (M_z) for cases with and without STT effect, as shown in Fig. 5 [Figure 5: see original paper]. Before excitation by the pulsed magnetic field or STT, the M_z component is zero (=0). For cases with STT effect, the amplitude of M_z is much larger, indicating precession starting with a larger due to additional torque from STT (see Fig. 3c). The precession without STT effect decays much faster to the initial equilibrium state (M_z = 0) due to energy dissipation. We propose that under STT effect, the normal precession damping behavior is modified by an effective value : = + _{stt}, where _{stt} is the damping term due to STT (adiabatic and non-adiabatic) effects. _{stt} can be positive or negative depending on the STT torque direction. In our case shown in Fig. 4, _{stt} should be negative because the STT torque opposes the Gilbert damping torque (see Fig. 3c). As P increases, the STT effect becomes stronger and _{stt} becomes more negative, causing to decrease and eventually become negative. Since microwave magnetic loss due to natural resonance is positively correlated with , the magnetic losses are suppressed as decreases, as shown in Fig. 4. When P is 0.7, the STT torque is strong enough to enlarge , inferred from the increasing M_z component after 0.8 ns (see Fig. 5b). With increasing , more energy is transferred to M, and is logically inferred to be negative, explaining the observed negative '' values.

3.2 Enhance Microwave Magnetic Losses

Many applications require large microwave magnetic losses to dissipate electromagnetic wave energy. For instance, to counteract electromagnetic wave pollution, ferromagnetic (or ferrimagnetic) materials are widely used to absorb unwanted electromagnetic energy in specific frequency bands via natural resonance. Again assuming we want to dissipate electromagnetic wave energy at 18 GHz (as shown in Fig. 3a), we aim to enhance magnetic losses around this frequency. Here we demonstrate how to accomplish this goal.

We set P = 0.5 and J = 8$×10^{11}$ A/m^2, varying β to study its effect on magnetic losses. According to STT theory, β is a parameter related to the "non-adiabatic torque" of STT, thought to stem from "momentum transfer" or "spin-flip scattering" [15,28,29]. Despite debates about its origins, experiments have shown that this non-adiabatic torque can drive domain wall motion [30,31], and the magnitude of β has been found experimentally to be comparable to the Gilbert damping constant α [32,33]. Therefore, it is rational and worthwhile to investigate how to enhance microwave magnetic losses via STT effect. Our results are shown in Fig. 7 [Figure 7: see original paper].

The magnetic loss peaks are significantly enhanced. When β is 0.01, 0.5, and 0.8, the maximum '' values are 15.28, 28.26, and 35.95, respectively. As before, the non-adiabatic torque has no effect on other resonance peaks, providing an approach to manipulate specific microwave magnetic losses without affecting device operating frequencies. We compared the precession behaviors for different β values, as illustrated in Fig. 8 [Figure 8: see original paper]. Larger β values produce faster damping. After 1 ns, M_z(t) for $\beta = 0.01$ still oscillates with large amplitude, while for $\beta = 0.5$ it has already been significantly damped. This indicates that the torque due to the Joule heating effect of the non-adiabatic term in Eq. 1 tends to assist M_z components in returning to their initial equilibrium states.

It can be inferred that increasing β gives rise to a positive _{stt}, leading to a larger effective damping constant ( ) and consequently enhanced microwave magnetic losses.

Finally, both STT torques cannot influence the natural resonance frequency (f_r), as shown in Fig. 4 and Fig. 7. According to Equation 8, this is expected: f_r depends only on the effective magnetic field (H_e) acting on M. Additionally, a minor resonance peak (“s” peak) appears in Fig. 4a. Since it is also unaffected by STT like the bulk resonance frequency, it originates from magnetizations perfectly aligned with current J, but with a larger local effective magnetic field than that of magnetizations related to the bulk mode. The local H_e is inhomogeneous along the entire nanowire and strongly determines the number of resonance peaks observed in the permeability spectra [34,35].

4. Conclusions

This paper uses a simplified model of an isolated Fe nanowire to demonstrate the feasibility of suppressing and enhancing microwave magnetic losses via the STT effect. The results are understood through changes in the effective damping constant ( ) arising from different STT contributions: adiabatic torque decreases and suppresses magnetic losses, while non-adiabatic torque increases and enhances losses. The abnormal negative ’’ phenomenon is also well explained. These results demonstrate an innovative approach to actively controlling microwave magnetic losses.

CRediT Authorship Contribution Statement

Mangui Han: Writing -review & editing, Writing -original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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