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Nonreciprocity engineering in magnetostatic spin waves

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ABSTRACT

Magnetostatic surface spin waves (MSSW) excited from a coplanar waveguide antenna travel in different directions with different amplitudes. This effect, called nonreciprocity of MSSW, has been investigated by micromagnetic simulations. The ratio of amplitude of two counter propagating spin waves, the nonreciprocity parameter κ, is obtained for different ferromagnetic materials, such as NiFe (Py), CoFeAl, yttrium iron garnet (YIG), and GaMnAs. A device schematic has been proposed in which κ can be tuned to a large value by varying simple geometrical parameters of the device.

1. Introduction

Spin waves are eigen-disturbances in magnetic moments propagating within a magnetic material, such as a ferromagnet, ferrimagnet, or antiferromagnet, via exchange or magnetostatic interactions. Based on the directions of the spin wave propagation ($\vec{k}$) relative to the static magnetization ($\vec{M}$), there are three well known modes of magnetostatic spin waves: (1) magnetostatic surface waves (MSSW), (2) backward volume mode (BVM), and (3) forward volume mode (FVM) [1–5]. In MSSW and BVM, both $\vec{k}$ and $\vec{M}$ lie in the film plane. $\vec{k}$ is perpendicular to $\vec{M}$ in MSSW, but parallel in BVM. In FVM, $\vec{k}$ is in the plane of magnetic film, whereas $\vec{M}$ points out of the film plane.

Spin waves are a subject of great interest because of their potential applications in novel information transfer devices [6–10]. Spin waves are also useful in phase matching of spin torque oscillators [11], and in the enhancement of the spin pumping effect [12]. A recent demonstration of interference-mediated modulation of spin waves offers a new method of engineering spin wave intensity for communication and logic [13,14]. The tunability of the refractive index and frequency of spin waves over a large range offers an opportunity for technological applications of magnonics [15]. Logic gates based on spin waves have been proposed and experimentally demonstrated [16].

The phenomenon of nonreciprocal wave propagation provides an additional means of controlling the flow of signal and power in the fields of microwave, photonics, and the recently growing areas of magnonics. Nonreciprocity in spin waves is quantified by the parameter κ, defined as the ratio of amplitudes of counter-propagating spin waves. In magnonic circuits, a large value of κ is essential for the realization of logic circuits, interconnects, and switches. In YIG, the κ is higher compared to conventional metallic ferromagnets such as Py, however, YIG films are not compatible with silicon-based microfabrication technology. In this work, we address the origin of spin wave nonreciprocity in thin films, and evaluate the value of κ in different materials, such as NiFe (Py), CoFeAl, yttrium iron garnet (YIG), and GaMnAs by means of micromagnetic simulations. The results show that κ decreases as the saturation magnetization of the material increases, thus explaining a higher value of κ in YIG as compared to Py. The κ is also shown to increase as the applied bias field increases. In addition, a device geometry for engineering a large value of κ is proposed.

2. Simulation methods

In this study, micromagnetic simulations based on the Object Oriented MicroMagnetic Framework (OOMMF) [17] are used to investigate the nonreciprocity of spin waves. Simulations are done with a 50 nm × 120 μm × 50 nm cell size on a cuboidal sample of dimensions 300 μm × 120 μm × 50 nm. To excite the spin waves, a pulse field is applied to the sample via a waveguide located at the centre of the sample as shown in Fig. 1(a). The waveguide has a width of 2 μm and a thickness of 200 nm, and is separated from the sample by a 50 nm thick insulator. The temporal profile of the pulse is a sinc function with a frequency of 100 GHz, and its spatial profile

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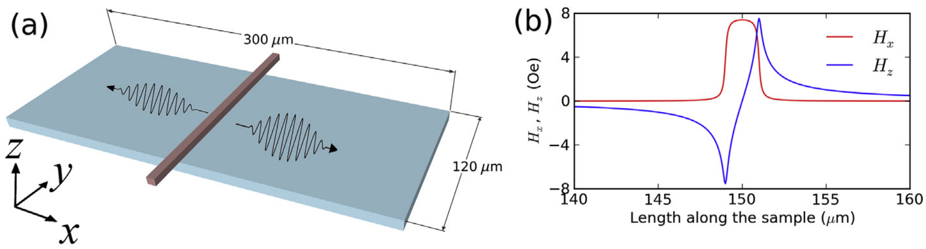

Fig. 1. (a) The device geometry used in the simulations. (b) The magnetic field distribution due to *rf* current through the waveguide.

is given by the Karlqvist equations [18]. The reason for using a sinc pulse of 100 GHz is that, in the frequency domain, this pulse has a uniform distribution over 0–15 GHz. A bias field (H_b) of 100 Oe is applied along the *y*-direction. The amplitude of the magnetic field pulse is shown in Fig. 1(b). It must be noted that we have used 1D simulations, with only one cell each in the *y*- and *z*-directions. Since the spin waves in our geometry travel in the *x*-direction, 1D simulations are sufficient to capture the phenomena. In order to confirm this, simulations were also carried out with a cell size of 50 nm × 500 nm × 10 nm, and identical results to those for a larger cell (50 nm × 120 μm × 50 nm) were obtained.

3. Results and discussion

Fig. 2(a–c) shows the magnetization oscillation as a function of time for different modes of spin waves in Py, namely MSSW, BVM, and FVM, respectively, monitored at two different locations (±10 μm away from the centre of spin wave excitation source). The material parameters used for Py are as follows: the Gilbert damping constant $\alpha = 0.01$, the saturation magnetization $M_s = 860 \times 10^3$ A/m, and the exchange stiffness $A = 1.3 \times 10^{-11}$ J/m. Fig. 2(d) shows the magnetic field-dependent frequencies of the different modes of spin waves. It is worth noting that a phase difference of π is observed in the BVM as shown in Fig. 2(b) [19], and the FVM is excited only for bias fields higher than that required to saturate $\overrightarrow{M}$ in the out-of-plane direction of the film in Fig. 2(d). The bias field-dependence of frequency for the MSSW and BVM is very similar as shown in Fig. 2(d). It can be seen from the dispersion relations of MSSW $\omega^2 = \gamma^2\mu_0^2[H_{\mathrm{eff}}(H_{\mathrm{eff}}+M_s)+M_s^2(1-e^{-2kd})/4]$, and that of BVM $\omega^2 = \gamma^2\mu_0^2[H_{\mathrm{eff}}(H_{\mathrm{eff}}+M_s((1-e^{-kd})/kd))]$, that for small kd, both of these equations reduce to $\omega^2 \approx \gamma^2\mu_0^2[H_{\mathrm{eff}}(H_{\mathrm{eff}}+M_s)]$. Here, H_{eff} is the effective field experienced by the magnetic moments, which includes the magnetic anisotropy field, exchange field, and external dc field.

From Fig. 2(a–c), it is clear that the amplitude of precession is different for MSSW travelling in the $+\overrightarrow{k}$ and $-\overrightarrow{k}$ directions. This effect is called nonreciprocity of spin waves [19–21], and is quantified by κ, which is defined as the ratio of amplitudes of counter propagating spin wave packets. In this study, we have used the amplitudes of spin waves at distances of +10 μm and −10 μm from

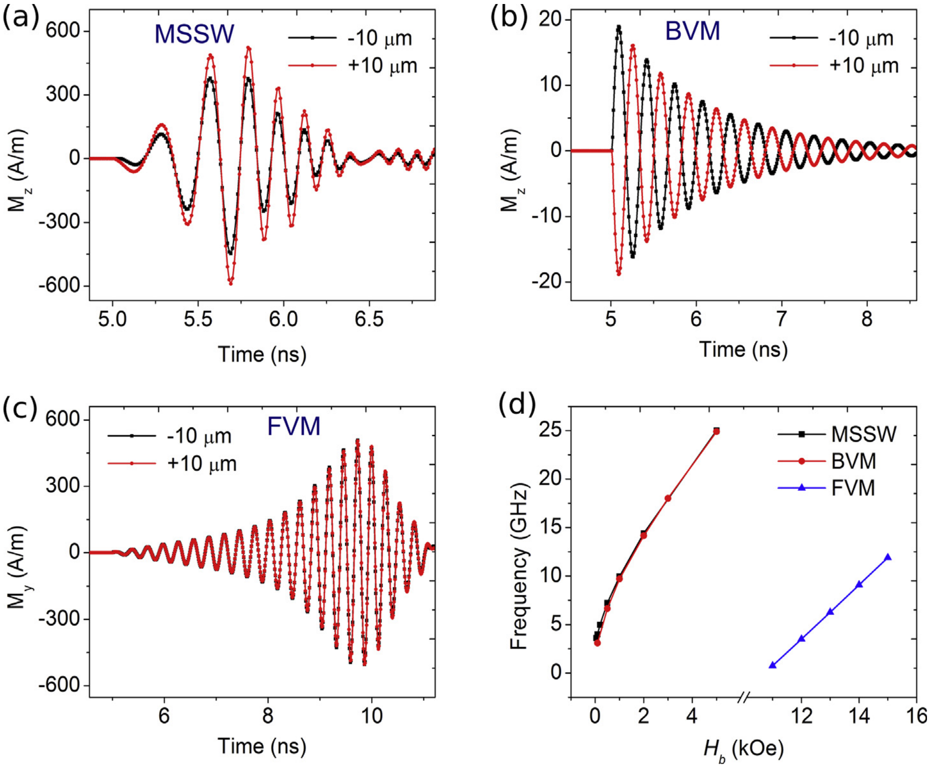

Fig. 2. Different modes of spin waves. The amplitude of oscillation as a function of time in magnetostatic surface mode (a), backward volume mode (b), and forward volume mode (c). (d) The frequency of different spin wave modes as a function of magnetic field.