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Resonant spin wave excitations in a magnonic crystal cavity

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ABSTRACT

Spin polarized electric current, injected into permalloy (Py) through a nano contact, exerts a torque on the magnetization. The spin waves (SWs) thus excited propagate radially outward. We propose an antidot magnonic crystal (MC) with a three-hole defect (L3) around the nano contact, designed so that the frequency of the excited SWs, lies in the band gap of the MC. L3 thus acts as a resonant SW cavity. The energy in this magnonic crystal cavity can be tapped by an adjacent MC waveguide (MCW). An analysis of the simulated micromagnetic power spectrum, at the output port of the MCW reveals stable SW oscillations. The Q factor of the device, calculated using the decay method, is estimated to be $Q > 10^5$ for an injected spin current density of 7×10^{12} A/m^2.

1. Introduction

Spin waves (SWs) are a collective excitation of magnetic moments in magnetic materials [1]. Various SW devices such as couplers, multiplexers, filters and transistors have been proposed and investigated [2–5]. Magnonic crystals (MCs) have attracted interest since we can tune the SW band gap [6–10]. It was recently reported that MCs can also be used to obtain collimated spin waves [11]. Magnonic crystals (MCs) with defects have also been studied [12–16]. A periodic array of empty holes drilled on a magnetic film substrate forms an antidot MC. These can be prepared using focused ion beam etching, leaving a periodic array of air-holes in the thin film. A line defect in the antidot MC can act as a waveguide that supports SW modes with higher group velocities.

The name spin wave amplification by stimulated emission of radiation (SWASER) was previously suggested [17,18]. More recently researchers have used feedback loops to improve the linewidth of the magnetic oscillations [19,20]. To our knowledge, a magnonic crystal cavity (MCC) based SWASER has thus far not been proposed. In this article, we simulate a nano-contact within a MCC. An electrical current injected into a permalloy (Py) thin film through a nano contact, excites spin waves [21,17,22,23]. An antidot MC with three-hole defects is used to create a cavity around the nano contact. We obtain sustained oscillations within the MCC, accompanied by an increase in SW amplitude. The simulations have been performed using MuMax3 [24].

2. Micromagnetic simulation

The device geometry used in this study is shown in Fig. 1. The material parameters are $M_s = 800 \times 10^3$ A/m for the saturation magnetization, and $A = 13 \times 10^{-12}$ J/m for the exchange stiffness constant. We assumed typical damping of $\alpha = 0.01$ in Py. We considered an antidot MC on a square lattice, on a Py film, with a three-hole defect (L3) [25,26]. A magnonic crystal waveguide (MCW) is formed by creating a line defect as shown in Fig. 1. The L3 cavity and the MCW share the same axis, ensuring better power transfer. A single nano contact was added at the center of the L3 cavity and a spin polarized current was injected into it. The radius of the nano contact is assumed as 20 nm. The thickness of the Py film is assumed as 5 nm. The micromagnetic cell size was taken as $5 \times 5 \times 5$ nm^3 with the in-plane cell dimensions smaller than the exchange length ($l_{ex} = 5.7$ nm for Py). The micromagnetic simulation was run at 0 K. We assumed a damping of $\alpha = 0.01$ throughout the Py, but artificially increased it to $\alpha = 1.0$ over the last 200 nm at the right end of the device. This is shown as an absorbing boundary layer (ABL) in Fig. 1, and serves to avoid reflections from the device edges in our simulations.

We begin by applying a bias magnetic field $\mathbf{B}_0 = 0.5$ T along the y-axis and allow $\mathbf{m}$ to relax to its ground state. We consider a two stage simulation for the relaxation. In the first stage, we set a high damping of $\alpha = 0.4$, obtain an intermediate ground state, and use this as the initial magnetization configuration for the next stage of the simulation where we use $\alpha = 0.01$. This method leads to a faster convergence to the ground state [27].

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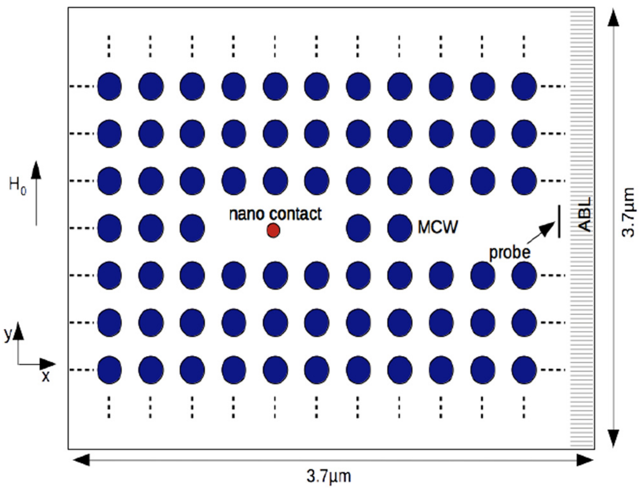

Fig. 1. The MC is formed by antidots of radius 40 nm and lattice constant of 150 nm with L3 cavity and MC waveguide (MCW). The radius of the nano contact is 20 nm, and the full simulation geometry is 3.7 μm × 3.7 μm.

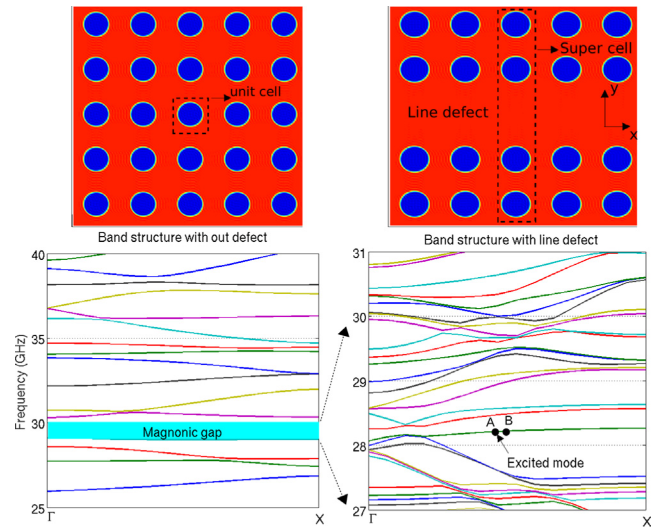

Fig. 2. Band structures along the ΓX direction of the ideal MC (left), and that of the MCW obtained from the supercell method (right). Guided modes of the MCW (right) lie within the band gap of the MC (left). Points A and B represent excitations with different k-vectors, allowing us to achieve cavity mode-matching by slightly tuning the excitation frequency.

3. Design methodology

The design of a MCC based SWASER involves a few parameters, such as the size and separation of the antidots, that can be optimized to yield SWs of a particular frequency.

1. We calculate the band structure of the MC using the plane wave method (PWM) [28].
2. We define a L3 cavity and a MCW on a Py film and place a nano-contact inside the cavity.
3. We estimate the guided modes of the antidot MCW using the supercell plane wave method [29].
4. We adjust the spin current density to excite a SW frequency that will propagate in the MCW.

Finally, we simulate the effect of spin injection into the nano-contact, excite SWs within the L3 cavity, and probe the SW spectrum at the output of the MCW. The spacing of the antidots defines the magnonic bandgap. Within the bandgap, the MCW supports multiple guided modes, but we pick one of these modes by an appropriate selection of the injected spin current density.

The PWM yields the band structure for an antidot MC, with a lattice constant of $a = 150$ nm and radius $r = 40$ nm, as shown in Fig. 2 (left). The band structure of a two-dimensional magnonic crystal with a linear defect, or a MCW, is obtained from the supercell method and is shown in Fig. 2 (right). The band structures for both cases was computed along ΓX (i.e. the direction of propagation of a wave along the MCW). Since the supercell is longer in the y direction, a larger number of reciprocal vectors were required along y for satisfactory convergence. We choose a frequency of 28.3 GHz which is one of the guided modes of the MCW, and lies in the bandgap of the MC. We can achieve cavity mode-matching by tuning the frequency marginally to move the operating point on the dispersion curve, e.g. from point A to point B.

4. Spin wave injection using a nano contact

Now consider a single nano contact on an infinite Py film. The dynamics of magnetization $\mathbf{M}(\mathbf{r}, t)$ of the free magnetic layer under the action of spin-polarized current are described by the LLGS equation

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma[\mathbf{M} \times \mathbf{H}_{\text{eff}}] + \frac{\alpha}{M_s}\left[\mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t}\right] + f(\mathbf{r})\frac{\sigma I}{M_s}[\mathbf{M} \times \mathbf{M} \times \mathbf{p}] \qquad (1)$$

where γ is the gyromagnetic ratio, $\mathbf{H}_{\text{eff}}$ is the effective field and M_s is the saturation magnetization of the free layer. The second term is the phenomenological magnetic damping term and the last term is the Slonczewski spin-transfer torque term, proportional to the bias current I. The function $f(\mathbf{r})$ characterizes the distribution of current across the nano-contact area. In the simplest case of spatially uniform current density, through a nano contact of radius $R_c, f(\mathbf{r}) = 1$ for $r < R_c$ and $f(\mathbf{r}) = 0$ otherwise. The proportionality coefficient [21]

$$\sigma = \frac{\epsilon g \mu}{2eM_s Sd} \qquad (2)$$

where ϵ is the dimensionless spin-polarization efficiency, g is the Landè-factor, μ_B is the Bohr magnetron, e is the absolute value of the electron charge, d is the free layer thickness, and $S = \pi R_c^2$ is the cross-sectional area of the nano-contact. The unit vector $\mathbf{p}$ defining the spin-polarization direction, is parallel to the direction to the in-plane external magnetic field. In our simulations, we used a set of material parameters that is typical for the experiments with current-induced spin wave excitations in in-plane magnetized nano- contacts with a Py free layer [30]. We assume a nano contact of radius $R_c = 20$ nm, a spin polarization efficiency of $\epsilon = 0.25$, a free layer saturation magnetization $\mu M_s = 0.8$ T, free layer thickness $d = 5$ nm, an external magnetic field $\mu H_0 = 0.5$ T, spectroscopic Landè factor $g = 2$, and free layer exchange stiffness constant $A_{ex} = 1.3 \times 10^{-11}$ J/m. The Gilbert damping constant was chosen to be $\alpha = 0.01$. Spin waves are excited in the Py film by injecting current through the nano contact. The current is adjusted to 9 mA, yield a SW excitation at $f = 28.3$ GHz and $k_x = 0.01$ rad/nm. The propagating spin wave excited are axially symmetric with a wave vector $k_c = 1.2/R_c$, and frequency [21,31]

$$\omega_L = \omega_{\text{FMR}} + Dk_c^2, \qquad (3)$$

with $D = (2A_{ex}\gamma/M_s)(\omega_H + \omega_M/2)/\omega_{\text{FMR}}, \omega_M = \gamma\mu_0 M_s, A_{ex}$ is the exchange stiffness, and $\omega_{\text{FMR}} = \sqrt{\omega_H(\omega_H + \omega_M)}$ is the FMR frequency of the film. Simulations were run for a duration of 10 ns, with data saved every 1 ps. A snap shot of the magnetization m_x at $t = 1$ ns is shown in Fig. 3, and we observe energy propagating radially away from the nano contact.

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