Spin-wave propagation in a microstructured magnonic crystal

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Transmission of microwave spin waves through a microstructured magnonic crystal in the form of a permalloy waveguide of a periodically varying width was studied experimentally and theoretically. The spin wave characteristics were measured by spatially-resolved Brillouin light scattering microscopy. A rejection frequency band was clearly observed. The band gap frequency was controlled by the applied magnetic field. The measured spin-wave intensity as a function of frequency and propagation distance is in good agreement with a model calculation.

Magnonic crystals (MCs) operate with spin waves (SW) in the microwave frequency range and are the magnetic counterpart of photonic and sonic crystals. The greatest success in MC making has been achieved with yttrium-iron-garnet (YIG) film based structures due to the extremely small magnetic loss and the incompatibility of the YIG film growing process with modern CMOS technology inhibit their wide practical use. Applications in microelectronics require downscaling to sub-micron sizes and a replacement of YIG films by thin ferromagnetic metallic layers.

Previous studies of metal film based microstructured magnonic crystals (micro-MCs) were mostly focused on their thermal SW spectrum, or were purely theoretical. Here we report on the experimental observation and characterization of spin-wave propagation in a metal micro-MC.

To ensure SW propagation the crystal was fabricated as a SW-waveguide made from a permalloy (Py) stripe with a periodically varying width. This concept was suggested in theoretical works done in the group of S. K. Kim and are magnetic counterpart of photonic and sonic crystals. The greatest success in MC making has been achieved with yttrium-iron-garnet (YIG) film based structures due to the extremely small magnetic loss. However, comparatively large sizes of these devices (hundreds of microns) and the incompatibility of the YIG film growing process with modern CMOS technology inhibit their wide practical use. Applications in microelectronics require downscaling to sub-micron sizes and a replacement of YIG films by thin ferromagnetic metallic layers.

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Electron beam lithography, molecular beam epitaxy, and lift-off process were used to fabricate the magnonic crystal in the form of a notched permalloy stripe on thermally oxidized Si(001) substrate (see Fig. 1). The width of the 40 nm thick Py (Ni81Fe19) stripe varies periodically between \( w_0 = 2.5 \mu m \) and \( w_1 = 1.5 \mu m \). The length of the 2.5 \( \mu m \)-wide sections is 0.75 \( \mu m \) and the length of the 1.5 \( \mu m \)-wide sections (“notches”) is 0.25 \( \mu m \). This forms a magnonic crystal with a lattice constant \( a = 1 \mu m \). As a reference a second waveguide with a uniform \( w_0 = 2.5 \mu m \) width was also patterned on the same substrate 6 \( \mu m \) apart from the magnonic crystal (see Fig. 1).

Spin waves are excited by the microwave Oersted field created by a 500 nm thick and \( w_a = 1 \mu m \)-wide copper antenna, which is placed across the both Permalloy waveguides (see Fig. 1). In order to detect spin waves the space-resolved Brillouin light scattering microscopy is used: a focused laser beam probes spin waves with...
The calculated dispersion for the lowest (fundamental) width mode of a $w_0 = 2.5 \, \mu m$-wide uniform waveguide is shown in Fig. 2(a) as solid line. For comparison, in this panel we also show the dispersion for a 1.5 $\mu m$-wide uniform waveguide which corresponds to the narrow sections of the magnonic crystal. The calculation was carried out by numerically solving the integro-differential equation derived in Ref. [13]. Note, that this calculation takes into consideration the inhomogeneity of the internal static magnetic field and the static magnetization which is also responsible for the bell-shaped transverse profile of the fundamental mode (see, the inset in Fig. 2).

The experimentally measured SW intensity for the reference waveguide is shown in Fig. 2(b) (dotted line) as a function of the applied microwave frequency. The maximum intensity corresponds to spin waves with wavenumbers slightly larger than $k = 0$ because of the highest excitation efficiency and the highest SW group velocity. With increasing frequency (and increasing spin-wave wavenumber, respectively) the excitation efficiency drops [16]. For the used antenna it gets close to zero above 11 GHz. A weak oscillatory intensity variation with frequency can be understood as beating of the fundamental width mode with the third one, which is also excited by the antenna but less efficiently [15, 17].

Solid line in Fig. 2(b) shows the measured SW intensity for the magnonic crystal. A pronounced rejection band (where spin waves are not allowed to propagate) is clearly observed for frequencies close to 8 GHz. One can see that the rejection frequency is slightly shifted down with respect to the frequency expected from the simple Bragg analysis of the SW dispersion for the uniform 2.5 $\mu m$-wide waveguide ($k_{\text{rej}} = \pi / a = 3.14 \, \text{rad} / \mu m$). We suppose that this is due to inhomogeneity of the internal magnetic field within the crystal. The decrease in the internal field between the opposite notches shifts the dispersion curve downwards in frequency. As a result the condition $k_{\text{rej}} = \pi / a$ is fulfilled for a smaller frequency value. It is worth noting that the rigorously calculated SW intensity, which is also shown in Fig. 2(b), is in good agreement with the experiment. The second rejection band $k_{\text{rej2}} = 2 \pi / a = 6.28 \, \text{rad} / \mu m$ is visible in Fig. 2(b) as well. However, it is not well pronounced because $k_{\text{rej2}}$ coincides with the edge of the antenna excitation band $k_{\text{max}} = 2 \pi / w = 6.28 \, \text{rad} / \mu m$.

Scattering of spin waves from an array of notches on a stripe waveguide is described by an equation similar to Eq. (5) in Ref. [18]:

$$\hat{\chi}(\mathbf{r}) \mathbf{h}_d(\mathbf{r}) = \int_\mathcal{S} \hat{G}_{\text{exc}}(\mathbf{r} - \mathbf{r'}) \hat{\nu}(\mathbf{r'}) \mathbf{h}_d(\mathbf{r'}) d^2 \mathbf{r'} = \mathbf{m}_0(\mathbf{r}), \quad (1)$$

where $\mathbf{h}_d$ is the total dynamic dipole field of the incident and the scattered spin waves, $\hat{\nu}(\mathbf{r}) = (\hat{\chi}_0(\mathbf{r})^{-1} \hat{\chi}(\mathbf{r}) - \hat{I})$, $\hat{\chi}$ is the microwave magnetic permeability tensor which is position dependent through the nonuniformity of the internal static magnetic field and the static magnetization, $\hat{\chi}_0$ is its value for the respective uniform waveguide of the width $w_0$, $G_{\text{exc}}$ is the Green’s function of excitation of waves in this waveguide, $\mathbf{m}_0$ is the amplitude of the spin wave with a wavenumber $k$ incident on the notch array, and $\hat{I}$ is the identity tensor. This equation allows an analytical solution in the First Born Approximation (FBA) [5, 18]. From this analytic solution it can be shown that the depth of the rejection minima is proportional to the total dipole energy $E$ of the incident spin wave contained in the waveguide cross-section which is cut out by the notches (shaded area in the inset in Fig. 2). Figuratively, part of the spin-wave energy incident on a pair of notches is reflected because the SW width profile does not fit into the narrow waveguide section. The reflection grows faster than linearly with the notch depth, as $E$ grows with the size of the dashed area in the inset. In particular, one may expect a negligible rejection when the notch depth is smaller than the size of the demagnetized area at the edge of the uniform waveguide. This assumption is confirmed by our measurements on a different micro-MC having 250 nm-deep notches.

To get a closer insight into the wave scattering mechanisms we performed a simulation based on a phenomenological approach from [2, 19]. For this purpose we consider the micro-MC as a periodic sequence of sections of regular transmission lines with different prop-
agitation constants (different \(k\)-values) for the same carrier frequency. The rejection coefficient at the junction of wider-to-narrower waveguide can then be written as \(\Gamma_{0-1} = (k_1 - k_0)/(k_1 + k_0) + \Gamma'\), where \(k_0\) and \(k_1\) are the wavenumbers for \(w_0\)-wide and \(w_1\)-wide waveguide sections, respectively \[19\]. As it was mentioned above, the spin wave is scattered back not only due to the difference in \(k\), which is accounted by first summand \(\Gamma_{0-1}\), but also because its initial transverse profile does not fit into the width \(w_1\). To account for this additional reflection mechanism we phenomenologically introduce \(\Gamma'\). The rejection coefficient for the waveguide junction narrower-to-wider contains only one term \(\Gamma_{1-0} = -(k_1 - k_0)/(k_1 + k_0)\).

The theoretical dependence of the SW intensity on the applied frequency is shown in Fig. 2(b) with a dashed line. It was calculated as \((F(k_0)/|T_{11}|)^2\), where \(F(k_0) \propto \sin(k_0 \cdot w/2)/k_0\) is the efficiency of the antenna excitation. \(T_{11}\) is the element (1,1) of the MC transmission matrix \([\mathbf{2, 19}]\) which includes \(\Gamma_{1-0}, \Gamma_{0-1}\), and the experimentally measured spatial SW damping corresponding to a Gilbert damping parameter \(\alpha \approx 0.007\) \[20\]. This best fit is obtained for \(\Gamma' = 0.12\). It means that 12 percent of incident beam energy is reflected back due to the geometrical mismatch between the waveguide sections. We should also emphasize that the reflection caused by the change of the SW wavenumbers is of the same order.

The experimentally measured transmission characteristic for the micro-MC is shown in Fig. 3(a) for different bias magnetic fields. Good agreement between the theory and the experiment is seen. The first rejection band is clearly visible for all the fields higher than 150 Oe. This value corresponds to the minimum field one has to apply in order to saturate the magnonic crystal. One also sees that variation of the applied bias magnetic field in the range from 150 Oe to 700 Oe makes it possible to control the band gap frequency in the range from 6.5 to 9 GHz.

Figure 3(b) shows the SW intensity for both the magnonic crystal and the reference waveguide as a function of the spin-wave propagation distance \((x = 0\) corresponds to the edge of the antenna) \[21\]. The intensity was measured in the middle of the stripes along their longitudinal axes. The oscillations of the SW intensities with \(x\) can be interpreted as the spatial beating of different waveguide width modes \[15\]. The dependence obtained in the transmission band of the micro-MC is very similar to the one from the reference waveguide. This fact proves the ability of practically undisturbed SW propagation in the metal waveguide with strongly damaged edges. At the same time spin waves in the band gap undergo pronounced resonant scattering. It results in an intensity which is ten times smaller than that for the reference sample after passing eight periods of the structure.

In conclusion, a micro-sized magnonic crystal operational at microwave frequencies has been fabricated in the form of a notched permalloy waveguide. Formation of pronounced magnonic band gaps was observed. They are seen as considerable decrease in SW transmission caused by the resonant backscattering from a periodical lattice. The band gap frequency can be tuned in the range from 6.5 to 9 GHz by varying the applied magnetic field.

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[21] The data for $x < 2 \mu m$ were removed from the picture because magnetization dynamics in this area is predominantly not a propagating wave but represents a near antenna field.