Nanostripe of subwavelength width as a switchable semitransparent mirror for spin waves in a magnonic crystal

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Spin wave transmission experiments are performed on a one-dimensional magnonic crystal (MC) where an injection pad for domain walls reverses the magnetization of selected nanostripes independently from the otherwise saturated MC. The MC consists of a periodic array of 255-nm-wide permalloy nanostripes with an edge-to-edge separation of 45 nm. In the experiment and simulations, we find that a single nanostripe with antiparallel magnetization performing opposite spin precession reduces significantly the transmission of long-wavelength spin waves. Our findings allow for the implementation and current-controlled operation of magnonic devices such as spin-wave-based logic on the nanoscale.

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I. INTRODUCTION

The control of amplitudes and phases of propagating spin waves (SWs) is of special interest for magneto-logics using SWs. Different local inhomogeneities of magnetic properties have been explored, such as a geometric defect, an interface, the core polarization in nanomagnet chains, and a local magnetic field creating a potential barrier at which reflection, transmission, and tunneling of SWs occurred. Recently, it has been shown that one-dimensional (1D) magnonic crystals (MCs) consisting of interacting nanostripes allow for artificially tailored SW band structures that depend on the magnetic state. For further advancements in magnonics, one aims at controlling spin waves with individual nanoscopic magnets. In this paper, we report the control of SW propagation across a 1D array of 255-nm-wide permalloy (Ni80Fe20) nanostripes [Figs. 1(a) and 1(b)] using a deep-subwavelength magnetic element. We find a significantly reduced transmission signal when we selectively reverse one of the nanostripes in the otherwise saturated MC. Micromagnetic simulations show that a single antiparallel nanomagnet reflects the nanostripes in the otherwise saturated MC. Micromagnetic simulations were performed using the commercial software MICROMAGUS using standard parameters for permalloy. By a magnetic force microscope (MFM). Micromagnetic simulations were performed using the commercial software MICROMAGUS using standard parameters for permalloy.

II. EXPERIMENTAL TECHNIQUES AND MICROMAGNETIC SIMULATIONS

The array of collinear nanostripes was structured by electron beam lithography and subsequent liftoff processing of 40-nm-thick permalloy (Py) on a GaAs substrate. The effects reported here were observed on different 1D MCs. In the following, we focus on a sample with period \( p = 300 \) nm, where the edge-to-edge separation (air gap width \( h \)) was 45 nm and the length of the wires amounted to about 300 \( \mu m \). Here, two selected nanostripes were attached intentionally to an injection pad (IP) for domain walls in order to control their magnetic state independently from the remaining MC [Figs. 1(a) and 1(b)]. On top of 8-nm-thick Al2O3, coplanar waveguides (CPWs) were integrated by electron beam lithography, evaporation of Cr and Au, and liftoff processing. The widths of the signal and ground lines were 2.0 \( \mu m \). The separation between ground and signal lines was 1.3 \( \mu m \). The distance between CPW1 and CPW2 amounted to \( s_{21} = 16.5 \mu m \) [Fig. 1(b)]. In between them, there were the two nanostripes attached to the IP covered by CPW3. By a vector network analyzer (VNA) we applied an rf electromagnetic wave to one of the CPWs. The magnetic rf field \( \mathbf{h}_r \) excited the magnetization \( \mathbf{M} \) of nearby nanostripes via the torque \( \tau = d \mathbf{M}/dt \propto -\mathbf{M} \times \mathbf{h}_r \) (t is the time) as extracted from the Landau-Lifshitz equation. Using the VNA we measured scattering parameters \( S_{ij} \) as the real and imaginary part of \( S_{ij} \), respectively, as the magnitude. The quantity \( a_{ij} \) reflects the susceptibility. Magnetic states of nanostripes were investigated by a magnetic force microscope (MFM). Micromagnetic simulations were performed using the commercial software MICROMAGUS using standard parameters for permalloy.

We simulated propagating spin waves after a pulsed excitation following Ref. 3.

III. EXPERIMENTAL DATA AND SIMULATION RESULTS

A. Broadband spin wave spectroscopy

SW resonances (dark) measured separately on the 1D MC via CPW1 and injection pad via CPW3 are shown in Figs. 1(c) and 1(d), respectively. First a saturation field of \( \mu_0 H_{sat} = +100 \) mT was applied. Then \( H \) was decreased in...
CPW1 and CPW3 detecting the MC and the IP, respectively. The signal strength varies abruptly at (i) Mag(\(H_{sw1}\)) and (j) Mag(\(H^{*}\)) of the MC and IP differ by about 2 GHz due to an injection pad (IP). (c) Propagation attenuation Mag(\(\delta f / 2\)) in Fig. 1(g), i.e., the signal transmitted between CPW1 and CPW2 in the x direction, a branch is seen at the same field-dependent eigenfrequencies as in Figs. 1(e) and 1(f). The transmission signal does not show abrupt changes either in frequency \(\delta f\) or in signal strength. In Figs. 1(h) and 1(i), Mag(\(\alpha_{11}\)) and Mag(\(\alpha_{22}\)) are shown for \(\mu_0H_{ML} = -5\) mT. The branches are identical to Figs. 1(e) and 1(f), respectively. The transmission signal Mag(\(\alpha_{21}\)) in Fig. 1(j) displays however an abrupt change of signal strength at \(\mu_0H^{*} = 7.5\) mT. For \(\mu_0H < 7.5\) mT (\(\mu_0H > 7.5\) mT) the detected signal is weak (strong). This observation is attributed to a field-induced variation of the magnetic state \(M(r)\) specifically between CPW1 and CPW2. The antiparallel \(M\) of a nanostripe attached to the IP will be substantiated later by the MFM. We label the relevant state as “ferromagnetically ordered state with a magnetic defect (FMO").”

We now study in detail the propagation properties of spin waves below and above \(H^{*}\) for the FMO and FMO* states. Figure 2(a) shows a direct comparison of Im(\(\alpha_{21}\)) taken at \(\mu_0H = 7.0\) mT for FMO and FMO*. Both states show a transmission signal near the eigenfrequency \(f = 5.5\) GHz. The signals differ considerably in shape and amplitude though they are taken at the same field \(H\) and \(\mu_0H_{ML}\) is varied by only 1 mT [cf. Figs. 1(e) to 1(j)]. In the FMO state, the curve contains a clearly oscillatory part which is known to indicate spin wave propagation between emitter and detector. In the FMO* state, the oscillatory contribution is weaker. We now subtract the two curves to reduce the background. The phase-shifted oscillatory behaviors of Im(\(\Delta\)) = Im(\(\alpha_{21}\))\((\text{FMO}) - \text{Im}(\alpha_{21})(\text{FMO*})\) (line) and Re(\(\Delta\)) = Re(\(\alpha_{21}\))\((\text{FMO}) - \text{Re}(\alpha_{21})(\text{FMO*})\) (dotted) in Fig. 2(b) indicate a VNA-measured SW propagation signal in an ideal way. Following the subtraction, the transmission of SWs is reduced for the FMO* compared to the FMO state. The group velocity extracted from \(\delta f / \delta g\) amounts to \(g = \delta f / \delta g = 4.6\) km/s. In Fig. 2(c), the field-dependent propagation attenuation Mag(\(\alpha_{21}\))/Mag(\(\alpha_{11}\)) is shown. For the FMO state, Mag(\(\alpha_{21}\))/Mag(\(\alpha_{11}\)) (open diamonds) decreases for increasing...
revolved nanostripe was attached to the IP. We did not detect
the white color for both nanostripes at the same time for
$H_{sw} < H_{ML} < 0$. There might have been a pinning potential
along the second nanostripe attached to the injection pad
preventing this particular nanostripe from a full reversal at
such small $|H_{ML}| < |H_{sw}|$. The FMO$^*$ state is thus argued to
contain a single magnetic nanostripe of opposite $\bf{M}$.

C. Simulated spin wave propagation

In Figs. 3(b) to 3(d) we depict the outcome of the micro-
magnetic simulations. We simulated an array consisting of 256
nanostripes with a period $p = 300$ nm and a length of 4.8 $\mu$m
each. The length was smaller than in the experiment due to
restrictions existing with nowadays computational power. On
the vertical axis of Fig. 3(b) from top to bottom we follow the
temporal evolution of the dynamical magnetization $m(x,z,t)$
for nanostripes after application of a field pulse at $t = 0$. We
depict the components $m_x$ (left) and $m_z$ (right). The $x$ axis
shows the distance $D$ measured to both sides from the excited
nanostripes located at $D = 0$. We observe spin-wave packets
as they move to both sides of the 1D MC (highlighted by two
arrows). The black and white contrast of the ringing pattern
illustrates negative and positive spin-precessional amplitudes,
respectively. To achieve a large signal-to-noise ratio up to
$|D| = 4 \mu$m and thereby illustrate the underlying physics
clearly we provoked a large $v_p$ by considering a small air
gap width of $\eta = 9$ nm in the simulation.\textsuperscript{25}

In Fig. 3(c), simulation data for the FMO$^*$ state are dis-
dplayed for $H = 0$ where at $D = -1.9$ $\mu$m a single nanostripe
with an antiparallel magnetization $\bf{M}$ is included. At this
magnetic defect (MD), a SW (solid arrow) splits into a reflected
(dashed arrow) and transmitted wave (dotted arrow) that expe-
riences a reduced amplitude consistent with our experimental
observation. We now subtract the simulated traces for FMO
and FMO$^*$ providing $\Delta m_x$ and $\Delta m_z$ in Fig. 3(d). For $\Delta m_x$
only the transmitted and reflected SW beams are visible. The
spin-precessional amplitudes suggest efficient SW reflection at
the single magnetic nanoelement (about 50%). The MD shows
a ringing pattern being in-phase with the spin waves. For $\Delta m_z$
in Fig. 3(d), the incoming SW is visible for about $-2 \mu$m
$< D < 2 \mu$m. This is attributed to the dipolar interaction of
nearby nanostripes with the MD modifying their ellipticity $\frac{m_z}{m_x}$. Strikingly, for $\Delta m_z$ the ringing of the MD is $\pi$-phase-shifted
with respect to the neighboring MC.

IV. DISCUSSION

To analyze in detail the spin-precessional motion we subdivide $\bf{M}$ of a nanostripe into a static component $M_y$
collinear with the $y$ axis and a dynamic component $m$
precessing in the $x,z$ plane according to $\bf{M} = M_y + m_{x,z}$
($m_{x,z} \ll M_y$). Excitation of neighboring stripes is provoked by dynamic demagnetizing fields $h_d(r)$,
\[ h_d(r) = \nabla \times \nabla \times B(\mathbf{r}) m(\mathbf{r}) d\mathbf{r}, \]
where $\nabla$ is the tensorial magnetostrictive Green’s function and
$r, r', r''$ are position vectors inside and outside the nanostripes
of volume $V$. For the FMO state all nanostripes have $+M_y$, and
neighboring nanostripes precess in unison in a right-handed
manner around the $+y$ direction. Following $\tau \propto -M_x h_y$, a
strong in-plane component $+h_{x,y}$ deflects neighboring stripes

B. Magnetic force microscopy

For each MFM data set the MC was first saturated at large
$\mu_0 H_{sat}$ of about $+100$ mT. The field was passed through
zero reaching $\mu_0 H_{ML} < 0$ and then gradually increased.
The MFM images were taken at $H = 0$. Reference MFM
images with $\mu_0 H_{sat} \approx +100$ mT ($\mu_0 H_{sat} \approx -100$ mT) and
$\mu_0 H_{ML} = 0$ provided all black (white) contrast at a given end
of the nanostripes (not shown). Applying $H_{sw} < H_{ML} < 0$,
we detected the reversal of one nanostripe (white) in Fig. 3(a)
(bottom graph).\textsuperscript{24} Comparing with the topography image
taken with the MFM (top graph), we substantiated that the

FIG. 3. (Color online) (a) MFM image for the two nanostripes
connected to the injection pad as indicated. Every second nanostripe
is intentionally a little bit longer. The topography (top) and the
stray-field contrast (bottom) are shown. Dark (light) contrast indicates
a magnetization $\bf{M}$ (arrow) in $+y$ direction ($-y$ direction). One
nanostripe with injection pad is found in a reversed state (white
end) for $\mu_0 H_{sat} < \mu_0 H_{ML} < 0$. (b) Simulated in-plane $m_x$ and
out-of-plane $m_z$ component of $m(x,z,t)$ for the FMO state at $H = 0$.
Spin waves propagate in both directions (solid arrows). (c) $m_x$ and $m_z$
for FMO* with one nanostripe of antiparallel $\bf{M}$ at $-1.9$ $\mu$m (vertical
arrows). A reflected (dashed arrow) and transmitted (dotted arrow)
wave is seen. $m_x$ ($m_z$) of the MD oscillates in-phase (out-of-phase)
with the MC. (d) Difference between (b) and (c) highlighting the
MD-induced effects.

$H$ starting from a value of about 0.03. Strikingly for the FMO$^*$
state, $\text{Mag}(a_{z1})/\text{Mag}(a_{z1})$ (open squares) starts at a low level
of 0.02 and exhibits an abrupt jump to larger values at $H^*$.
For $H > H^*$, $\text{Mag}(a_{z1})/\text{Mag}(a_{z1})$ of FMO* recovers the values
of the FMO state perfectly. Note that $\text{Mag}(a_{z1})/\text{Mag}(a_{z1})$
measured in the opposite propagation direction [open upward
(FMO) and downward (FMO*) triangles] is found at very
small values for both magnetic states due to the nonreciprocal
SW excitation.\textsuperscript{10,23} The discrepancy between FMO and FMO$^*$
states can thus not be resolved with the same signal-to-noise
ratio. In the following we first investigate the magnetic state $\bf{M}(r)$
of the MC by an MFM and second perform micromagnetic simulations.

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in the same manner for $\lambda \gg p$, such that their dynamic components $m$ point, e.g., into the $-z$ direction at the same time. Consequently, $h_{\text{dc}}$ is large and the same for neighboring stripes. In contrast, in the FMO state $M$ of the MD exhibits $-M_z$ and performs a left-handed precession under excitation of $+h_{\text{dc}}$. Following Ref. 7, the component $m_{\text{MD},x}$ of mode $n = 0$ can still be in-phase with the MC for $\lambda \gg p$, but $m_{\text{MD}}$ precesses towards the $-z$ direction while neighboring unit cells of the MC precess towards the $+z$ direction. Therefore, the MD experiences a partly compensated demagnetization field and different $\tau$ compared to the FMO state. This difference provokes a mismatched "wave impedance" for the SW leading to partial reflection and reduced transmission at the subwavelength-wide magnet ($w/\lambda \approx 0.02$–0.03). Note that the “wave impedance mismatch” is due to the counterprecessing $m_{\text{MD}}$ of a single nanomagnet in contrast to the local inhomogeneities exploiting a SW band structure mismatch so far.23,35 The magnonic crystal with periodic nanopatterning is key to provoke the observed type of elastic scattering. In further simulations we have considered different numbers $q$ of selectively reversed nanostrings (we tested $q = 1, 2, 3, 4$). The reflected SW intensity did not depend crucially on $q$ suggesting an "interfacial" rather than a "bulklike" effect. The discovered semitransparent SW mirror is far reaching. It has been shown that $M$ of a stripe can be reversed by a biasing current which moves back and forth an existing domain wall.26

By integration of leads, a three-terminal 1D MC with emitter and detector antennas can be created where a central nanostripe is controlled by current pulses.27 Then, the transmitted SWs can be switched between high and low signal levels consistent with transistor applications in digital electronics. Using two of the mirrors in series, spin wave cavities in MCs become switchable.

**V. CONCLUSIONS**

In conclusion, we studied spin wave propagation in 1D MCs with a reprogrammable magnetic defect. The spin wave was partially reflected at the single subwavelength nanostripe with antiparallel magnetization due to out-of-phase precession. Such a semitransparent mirror can be switched on and off by the magnetic history or a current offering spin wave control on the nanoscale.

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$H_{\text{init}}$ therefore did not agree perfectly between the two setups. $H_{\text{sw1}}$ is extracted at the MFM from the reversal of nanostripes not connected to the IP.

Though $\eta$ differs between simulation and experiment, extracted velocities $v_g$ are found to be nearly the same. Unintentional edge roughness in the real nanostripes might be the reason. Roughness is known to reduce the demagnetization effect and thereby enhances spin-precessional amplitudes right at the geometrical edges provoking a large $v_g$ via enhanced dipolar coupling.
