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Citation: Journal of Applied Physics 118, 163904 (2015); doi: 10.1063/1.4934519
View online: http://dx.doi.org/10.1063/1.4934519
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/118/16?ver=pdfcov
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Dispersion and spin wave “tunneling” in nanostructured magnetostatic spin waveguides

Dispersion in magnetostatic CoTaZr spin waveguides
Spin wave scattering and interference in ferromagnetic cross

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(Received 20 August 2015; accepted 10 October 2015; published online 22 October 2015)

Magnetostatic spin wave scattering and interference across a CoTaZr ferromagnetic spin wave waveguide cross junction were investigated experimentally and by micromagnetic simulations. It is observed that the phase of the scattered waves is dependent on the wavelength, geometry of the junction, and scattering direction. It is found that destructive and constructive interference of the spin waves generates switching characteristics modulated by the input phase of the spin waves. Micromagnetic simulations are used to analyze experimental data and simulate the spin wave scattering and interference. © 2015 AIP Publishing LLC.

I. INTRODUCTION

Micro- and nano-structured ferromagnetic films are widely used in magnetic memory, sensors, microwave electronics, and more exotic magnetic logic applications.1–13 Spin wave modes and ferromagnetic resonance in these structures are used in microwave delay lines, tunable filters, and attenuators. Spin wave based logic devices rely on traveling spin wave modes and local magnetostatic spin wave modes to perform logic operations. Lithographically patterned ferromagnetic films support shape defined spin wave modes quantized with the structure dimensions. Stripes and wires of various geometries, magnonic arrays, and three dimensional tubular structures have been intensively studied. Quantized spin wave modes,14–19 spin wave "tunneling,"20–23 current induced Doppler shifts,24,25 spin torque spin wave excitation,26,27 magnon Bose-Einstein condensation,28 and various nonlinear effects29–32 have been observed in these structures. Spin wave interference was studied both numerically and experimentally.11,33–41 Mach-Zehnder type interferometer was proposed for use in the spin wave logic devices.10,11 A recent work investigating magnetostatic surface spin waves turning a corner demonstrated the importance of magnetization orientation for the spin waves to propagate along the curved spin-wave waveguides.42,43 The spin wave does not propagate in a bent waveguide subjected to uniform external magnetic field used to ensure uniform magnetization due to the mode mismatch. A local magnetization disorder (induced by another spin wave directly.

This phenomenon has potential use in a spin wave logic device45 and magnonic holographic memory/data processing device.46 The cross is formed by two metallic ferromagnetic spin-wave waveguides intersecting at a right angle. Configurational anisotropy defines the magnetization within the cross. Micromagnetic simulations show that at zero external magnetic fields ferromagnetic cross has four possible ground states with axially magnetized arms and the center magnetized at a 45° angle with respect to the arms. As the cross dimensions are increased, a more complex magnetization alignment containing multiple domains within each arm is formed. The magnetization state similar to the one observed in a nano-scale cross can be achieved by applying an external biasing magnetic field. The center of the cross thus acts as a local magnetization disorder for the spin waves traveling in vertical or horizontal arms of the cross. A wave excited in one of the cross arms scatters into the other three arms due to the matching between local spin wave modes of the cross center and traveling modes in the cross arms. The wave phase shifts gained in the cross center are different for different scattering directions. As a result, when two waves are simultaneously excited in neighboring arms, a non-zero amplitude output wave is observed at least in one output arm of the cross for any input wave phase shifts. By changing the phase of one of the input waves, the output wave can be switched between the two cross output arms. This phenomenon has potential use in a spin wave logic device in which a spin wave propagation can be controlled by another spin wave directly.

II. EXPERIMENTAL APPROACH

A ferromagnetic Co90Zr5Ta5 cross junction was lithographically fabricated using the following fabrication flow (see Fig. 1). A 200 nm thick amorphous ferromagnetic Co90Zr5Ta5 film was sputtered onto a Si/SiO2 substrate. A saturation magnetization of $M_s = 955 \text{emu/cm}^3$ and a coercive field $H_c \approx 2 \text{Oe}$ were measured on the unpatterned Co90Zr5Ta5 film using a vibrating sample magnetometer. Using lithographic techniques, the film was selectively etched to define the ferromagnetic cross with 4 μm wide and 12 μm long arms. The patterned ferromagnetic film was then
covered with a 100 nm thick insulating SiO$_2$ layer. 100 nm thick aluminum coupling loops were lithographically formed by short-circuiting the ends of a pair of coplanar waveguides positioned over the cross arms. The structure was covered with another 200 nm thick SiO$_2$ insulating layer. 2 $\mu$m long ferromagnetic tubes were formed by etching holes down to the bottom magnetic layer and subsequently patterning another layer of Co$_{90}$Ta$_{5}$Zr$_{5}$ on top. Tubes thus formed at ends of the cross junction arms formed a closed magnetic circuit and served for enhanced coupling between microwaves and spin waves. More details about these tube couplers can be found in the literature.\textsuperscript{37} Magnetostatic spin waves were excited and detected by coupling loops formed by the short-circuited ends of coplanar waveguides (Fig. 1(a)). High frequency currents in the signal line of the coplanar waveguide produced magnetic fields inside the tube couplers that effectively excite the backward volume magnetostatic spin wave (BVMSW) modes. Four port transmission S-parameters were measured by the Agilent 5240PNA vector network analyzer (VNA). Four ports of the VNA were used to excite and detect spin waves in the corresponding four ports of the ferromagnetic cross (see Fig. 1(b) for port number convention used in this work).

The spin wave interference was measured as follows. A continuous wave (CW) signal at a frequency $f_0$ was used to continuously generate spin waves at the port 1. Measurements of $S_{31}$ and $S_{41}$ were carried out in time domain while continuously feeding a CW signal in the port 2 at a constant frequency $f_1 = f_0 + df$. The frequency offset $df$ provided a linear evolution of the phase shift in time and was chosen to provide the desired phase shift over the duration of the measurement (typically $2\pi$ radians phase shift per 10 s).

Time evolution of the spin wave amplitude (beats) was converted to the phase dependent amplitude for which a single period of the beat observed corresponds to the phase shift of $2\pi$ rad. Spin wave transmission and interference measurements carried out at zero and 2.5 kOe magnetic fields served as a reference used to subtract the electromagnetic and expose magnetostatic coupling between the spin wave excitation and detection points.

Spin wave excitation/detection efficiency is strongly dependent on the relative alignment of the local magnetization and the current flow in coplanar waveguides. In order to achieve the same coupling for all 4 ports, a biasing magnetic field was applied at 45° to the horizontal and vertical cross arms.

**III. RESULTS AND DISCUSSION**

Spin wave scattering as a function of external biasing magnetic field applied at 45° angle was measured. Spin waves were excited at the port 1 and detected at ports 2–4. Results of $|S_{21}|(f, H)$ and $|S_{31}|(f, H)$ measurements are shown in Figure 2. At low magnetic fields $|H| < 50$ Oe, an irreproducible spin wave transmission spectrum is detected in $|S_{31}|$, while no spin wave transmission is detected in $|S_{41}|$. As the field is varied in the range $50 < H < 120$ Oe, a weak spin wave transmission peak is observed for both $|S_{21}|$ and $|S_{31}|$ at $f \sim 7.5$–8.5 GHz. Starting at biasing fields $H > 200$ Oe, a well pronounced spin wave transmission peak is observed with its frequency increasing as the magnetic field is increased. At $H > 500$ Oe, additional peaks in the transmission spectrum are observed. The magnetization disorder of the cross arms is responsible for the absence of spin wave transmission at low magnetic fields. As the field is increased, magnetization alignment is defined by both the cross configurational anisotropy and external magnetic field.

Micromagnetic simulations were used to reveal the cross magnetization alignment at different biasing magnetic fields using the LLG micromagnetic simulator.\textsuperscript{38} The following simulation parameters were used: zero crystalline anisotropy, exchange stiffness $A = 1.050 \times 10^6$ erg/cm$^3$, and mesh size 10 nm. A hysteresis curve simulation for the CoTaZr cross (200 nm thick, arm widths 4 $\mu$m, and $M_s = 960$ emu/cm$^3$) was carried out. An external magnetic field $H_{15}$ was applied at a 45° angle with respect to the cross arms. Results of the simulations are shown in Fig. 3. In the absence of an external magnetic field, the cross exhibits a non-uniform magnetization. As the biasing field is increased to 100 Oe, the cross maintains a complex multi-domain structure (Fig. 3(c)). We attribute this to the absence of spin wave transmission at this field range. At 100 < $|H_{15}| < 500$ Oe, arms of the cross magnetize axially, while the center is magnetized along the biasing field direction (Fig. 3(b)). This magnetization configuration is similar to the ground state of the nano-scale
Such magnetization alignment should result in the BVMSW modes propagating along the cross arms, which were measured in spin wave transmission experiments. At higher magnetic fields, the cross magnetization saturates along the field direction. A complex spectrum of spin waves propagating at 45° to the magnetization orientation is observed.

Spin wave attenuation in the studied structure was referenced to the attenuation in previously studied stripe waveguides of the same cross section. Spin wave transmission measured at the outputs of the cross is approximately 2 \((S_{31})\) and 3.5 \((S_{21})\) times smaller than measured in a plain ferromagnetic stripe with the same separation of tubular couplers. We attribute that to the poor coupling between the spin wave modes in the cross arms and its center.

Magnetic field \(H_{45} = 230\) Oe, large enough to ensure an axial cross arm magnetization, was used to study the two wave interference. The results of the magnetization alignment simulations for this field value are shown in Fig. 3(b). Spin waves were excited using the CW microwave signal with frequency \(f_0 = 8\) GHz corresponding to the maximum in the spin wave transmission spectrum at that field. Results of the spin wave interference measurements are shown in Fig. 4. We observed a typical interference pattern: spin wave amplitude oscillations in both horizontal (port 3) and vertical (port 4) output arms of the cross as the phase offset between the input spin waves changed in the range from 0 to 12π. Remarkably, the input wave phase offsets \(\phi_{d31}\) and \(\phi_{d41}\) resulting in the destructive interference (or \(\phi_{c31}\) and \(\phi_{c41}\) for constructive interference) are different for \(S_{31}\) and \(S_{41}\). We define the phase shift for the forward, left, and right scattered waves as \(\phi_0\), \(\phi_90\), and \(\phi_{180}\) correspondingly. The condition for the constructive interference is then

\[
\phi_0 = 0, 90, 180°
\]

FIG. 2. Frequency and biasing field dependence of \(|S_{21}|\) (left) and \(|S_{31}|\) (right) scattering parameters measured on the fabricated structure.

FIG. 3. Results of micromagnetic simulations. Hysteresis curve (a); schematic of magnetization alignment at \(-200\) Oe (b); and other magnetic field values (c). Numbers indicate the magnetic field in Oe.
satisfied when $\varphi_{c31} = \varphi_{0} - \varphi_{00}$ and $\varphi_{c41} = -\varphi_{0} + \varphi_{00}$ (similar expressions can be obtained for destructive interference). Differences in phases satisfying the constructive interference conditions in ports 3 and 4 imply spin wave gain different phase shifts when scattering into the two neighboring and opposite arms of the cross.

Phase shifts gained by scattered waves at the center of the cross junction were investigated numerically using micromagnetic simulations. Spin waves were excited by applying an oscillating local magnetic field perpendicular to the static magnetization orientation with 10 Oe amplitude at port 1. Phase shifts of the waves scattered in the ports 2, 3, and 4 were measured at the same distance from the center of the cross. The wavelength of the spin waves was varied from 1.5$a$ to 6$a$, where $a$ is the width of the cross arm. Results of these simulations are shown in Figure 5. The wave scattered into the arm 3 (scattered forward, at 0° angle) was used as a reference. By subtracting the reference phase, the distance-dependent phase shift was eliminated thus exposing the phase shift gained at the cross center relative to the wave scattered into the arm 3. The waves scattered into arms 2 and 4 gain equal (within the error of simulations) phase shifts that are different from the phase shift of the spin wave scattered into the arm 3: $\varphi_{0} - \varphi_{00} \neq \varphi_{0}$ ($\varphi_{00} = -0.125\pi$ for the geometry of the simulated and fabricated structure). Plot of the phase shift measured in the arms 2 and 4 as a function of the wave vector (Fig. 5(a)) can be fitted with a straight line with non-zero slope equal to $a/2$—waveguide half-width. This result suggests that the horizontal wave travels $a/2$ longer distance within the cross junction center as it scatters. Symmetric spin wave scattering in the center of the cross is defined by local magnetization oscillation modes supported by the junction center area. The local magnetization oscillations in the cross center are phase-locked to the incoming spin wave. Almost a circular wave front is formed inside of the cross center (Fig. 5(c)). As it propagates through the cross center, the BVMSW uniform mode in both vertical and horizontal cross arms is excited. The outgoing waves are also phase-locked to the spin wave modes of the cross center. Ongoing waves in the arm 3 are about one half of the wavelength behind in phase relative to the waves scattered into vertical output arms; due to the longer distance, the circular wave phase front travels in the cross center. Mode-matching in the cross arms and its center results in the spin wave transmission/scattering. This is different from the process of a spin wave “turning a corner” described by Vogt et al.,42 where the mode mismatch stopped spin wave propagation. Also no conversion between MSSW and BVMSW modes is happening in contrast to the spin wave propagation in the T-junction, investigated by Sadovnikov et al.44

In order to evaluate the importance of the cross center in the spin wave scattering process, spin wave scattering simulations were carried out with the “empty” cross, in which the square central region was absent. Results of these simulations are shown in Fig. 5(b). The waves gain equal phase shifts as they scatter into arms 3 and 4. The wave scattered into the arm 2 (upward) is 180° behind in phase. Dipolar coupling of the cross arms ensures the spin wave excitation in the output arms of the cross. Oscillating magnetic moments at the right end of the arm 1 generate magnetic fields that are 180° out of phase in the neighboring ends of arms 2 and 4. An “empty” center of the cross causes no phase shifts to the wave traveling through it. That explains “out of phase” spin wave scattering in the arms 2 and 4 and “in phase” spin wave scattering into the arms 3 and 4.

Results of micromagnetic simulations of the spin wave interference are shown in Figure 6. Following the interference experiment, the initial phase $\varphi_{0}$ of the wave excited in the arm 2 varied in the range 0–10\pi radians, while the phase of the wave excited in the arm 1 kept constant. The
amplitude of the spin waves at the arms 3 and 4 was measured. Results of these simulations are in good agreement with experimental data (Fig. 4).

As mentioned above, the waves scattered at +90° and −90° angle directions (upward and downward corresponding) gain the same phase shift (φ0 = φ00 = φ06), therefore the conditions for the constructive interference can be written as

\[ \phi_{c31} = + (\phi_0 - \phi_00), \quad \phi_{c41} = - (\phi_0 - \phi_06). \]

For these spin wave phases, the constructive interference will happen in either arm 3 or arm 4, but not in both arms simultaneously. Constructive interference conditions obtained from the experiment are \((0.41 \pm 0.02)\pi\) for arm 3 and 
\((-0.41 \pm 0.05)\pi\) for arm 4 with periodicity of 2π, which is the same as 0.42π obtained from micromagnetic simulations. The values of the phase offset of the wave scattered from arm 1 into the arm 3 were estimated to be \(\phi_0 = 0.295\pi\). Based on the results of spin wave scattering micromagnetic simulations, we estimate the spin wavelength of 3.4 μm which is in good agreement with the wavelength value obtained from the spin wave dispersion measured in scattering experiments.

In contrast to reported spin wave interferometers, a non-zero amplitude spin wave is generated at all input wave phase differences thus resulting in no information loss. By changing the phase of the spin wave in port 2 while keeping the other input wave phase constant, the output can be switched to either port 3 or 4 resulting in one spin wave controlling propagation of the other spin wave—spin wave routing. This phenomenon can be used in the spin wave logic device that we proposed recently.45

IV. SUMMARY

In summary, scattering and interference of the backward volume magnetostatic spin waves were measured and simulated in the ferromagnetic cross. Scattered spin waves gain different phase offsets when scattered at 0° and ±90° angles. The spin wave modes excited in the cross center define the phase shift of the waves scattered into the opposite arms.


