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The phase accumulation and antenna near field of microscopic propagating spin wave devices

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We studied phase accumulation by the highly non-reciprocal magnetostatic surface spin waves in thin Permalloy microstrips excited and received by microscopic coplanar antennae. We find that the experimentally measured characteristic length of the near field of the antenna is smaller than the total width of the coplanar. This is confirmed by our numerical simulations. Consequently, the distance over which the spin wave accumulates its phase while travelling between the input and output antennae coincides with the distance between the antennae symmetry axes with good accuracy. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4863078>]

In the past decade, the study of spin wave (SW) propagation in metallic ferromagnetic media has attracted attention due to potential applications in magnonics.^{1–9} In a Propagating Spin Wave Spectroscopy (PSWS) experiment of nanometer-range thickness large-magnetic-moment metallic ferromagnetic films, micrometer-sized spin wave antennae (SWA) are patterned over the ferromagnetic material. Microwave current in emitting (input) SWA generates an ac magnetic field, which drives SW in the underlying ferromagnetic layer. The propagating SWs are detected using a second (detection or output) SWA patterned at some distance from the input antenna. This device actually represents a SW delay line or a phase shifter.¹⁰ For design of these devices, it is important to accurately predict the microwave phase shift ϕ they insert. ϕ is determined by the SW wave number k and the (effective) distance between the input and the output antenna (“propagation distance”) x_{eff} , where $\phi = kx_{eff}$.

Excitation and reception of SW signal in low-loss low-saturation magnetization yttrium iron garnet (YIG) films with micron-range thicknesses were the subject of research in the previous decades.¹¹ SWs in YIG films propagate distances of a few millimetres. To excite and detect them, microstrip SWA are used, and these are quite compact. The distances between SWs are much larger than the typical width of the microstrip SWA (50 μm)¹² and thus x_{eff} is equal to the physical distance between the antennae.

For the metallic ferromagnetic films, coplanar SWAs are more suitable¹² since they naturally ensure microwave impedance matching for SWA of micron and submicron range sizes typical for these devices. Due to the larger relative widths of the coplanar SWA and larger propagation losses in the metallic films, the distance between the antennae is always comparable to the width of SWA (see, e.g., Fig. 1(c) from Ref. 2). Therefore, the definition of x_{eff} for the metallic-film based devices should include a correction term originating from the finite width of SWA. The correct definition of x_{eff} is important for all applications, which exploit the phase accumulation by travelling SW. Besides the phase

shifters and delay lines, these are also logic devices.^{6,8} Furthermore, in experiments, the SW dispersion is often determined from the phase interference pattern recorded at the output antenna; this is determined by x_{eff} . In the following, we will determine x_{eff} based on our experiments and numerical simulations.

The parameter which is responsible for the magnitude of the correction is the spatial extent x_{near} of the near field of the antenna and we will relate x_{eff} to x_{near} . Dipole-dominated long-wavelength SW are slow electromagnetic waves with a dominating magnetic field component. Therefore, the characteristics of electromagnetic wave radiation by usual radio or TV antennae should be applicable to SWA. It is known that the field of an antenna separates into two regions (with continuous transition region in between): near-field and far-field.^{13–15}

In the experiment where the second antenna is used to detect the SW signal, it is impossible to measure the near field directly. However, one can measure x_{eff} as the ratio $x_{eff} = \frac{\phi}{k}$. (We define ϕ as the phase difference of the microwave signals at the input port of the input antenna and the output port of the output antenna.) Let x_0 be the distance between the *symmetry axes* of the central conductors of the two antennae (Fig. 1(a)). Then, it is convenient to define x_{near} as

$$x_{near} = \frac{x_0 - x_{eff}}{2}. \quad (1)$$

Note that the factor $1/2$ in Eq. (1) originates from accounting for the near fields of both emitting and detection SWA, and that we assume both antennae to be identical (i.e., x_{near} is defined for a single antenna). Also note that x_{near} actually gives the co-ordinate of the right-hand boundary of the near field of the *input* antenna (Fig. 1(b)).

To measure x_{near} , we designed a PSWS experiment as follows. A series of Permalloy microstrips were patterned onto silicon wafer substrates using standard photolithography techniques. The narrowest and widest microstrips are 2 and 100 μm , respectively. All the microstrips have the same length at 200 μm . Three different Permalloy film thicknesses

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FIG. 1. (a) Diagram illustrating the experiment, showing dimensions and field lines. The antennae separation gap, stripe width, and stripe thickness are labelled x_0 , y , and z , respectively. The applied dc field H is in-plane and parallel to y . Microwave current $i(\omega)$ in the left-hand antenna generates a non-uniform excitation field $h(\omega, x, z)$, which in turn drives spin waves, $m(\omega, k)$. 1 denotes the Permalloy stripe, 2 is the 30 nm thick Al_2O_3 insulating layer, and 3 is the receiving antenna (the similar structure to the right is the output antenna). (b) Enlarged view of the antenna cross-section. The origin $x = 0$ of the frame of reference coincides with the symmetry axis of the input antenna.

were fabricated: 55 nm, 80 nm, and 110 nm. The microstripes were overlaid with gold coplanar SWA (Fig. 1(b)); the conductor widths and separation gaps are $1.5 \mu\text{m}$, and the thickness is 200 nm. The SWA were short-circuited at their ends. The SWA were $200 \mu\text{m}$ long. This length is much smaller than the microwave wavelengths used; therefore, the effects of propagation of the electromagnetic wave *along* the antenna are negligible. The distances x_0 between the emitting and receiving antennae were varied from 12 to $110 \mu\text{m}$. To make an impedance-matched transition to a standard coaxial line, far away from the Permalloy microstripes, the width of coplanar lines (CPW) gradually become larger and terminates at $100 \mu\text{m}$ sized contact pads to accommodate connection with a coaxial line via a submillimetre coplanar probe. The probes represent the input and output ports of the devices. The CPW geometrical proportions were maintained throughout to ensure impedance matching throughout. A 30 nm thick aluminum oxide spacer was deposited between the overlaying gold antennae and underlying Permalloy microstripes to ensure no direct contact between the two conducting layers.

We used the inductive method of excitation and detection of SW.^{2,16–18} An external dc magnetic field H was applied in-plane and perpendicular to the long axis of the microstripes. Magnetostatic surface spin waves (MSSW) are excited in this orientation. For each device, microwave power at 10 dBm (at the output port of the generator) and frequency of 10 GHz was fed through one SWA. After accounting for cable attenuations, insertion losses, and impedance mismatch, the total microwave current in the SWA is estimated to be 2 mA. Our numerical simulation shows that the maximum magnetization precession angle driven by this current is 2.5° ; this is well below the threshold of Suhl instabilities for Permalloy,¹⁹ thus the measurements were carried out in the linear regime. A second antenna was

connected to a highly sensitive microwave detector and a lock-in method similar to Ref. 20—where one measures the first derivative of the transmitted signal—was used. For data acquisition, the applied magnetic field is swept for particular microwave frequency. The process is repeated for all functioning devices fabricated.

An example transmission data are shown in Fig. 2. The waveform envelope corresponds to the band of available wave numbers k ; this is determined from the spatial Fourier transform of the microwave magnetic field of the CPW antenna.²¹ The oscillations in the waveform are due to interference between the direct electromagnetic cross-talk of the input and output SWA and the transduced SW signal. In the absence of cross-talk, the interference would be absent, and one would only observe a continuous envelope. As explained below, the cross-talk is beneficial; in its absence, one would need to generate the interference artificially.²²

Between the two successive minima of the interference, ϕ varies by 2π . From this, one can extract the SW dispersion using the relationship which relates the difference Δk in k -values between two consecutive minima to x_{eff} .

$$\Delta k = \frac{2\pi}{x_{\text{eff}}}. \quad (2)$$

From Eq. (2) and the value of the field step ΔH corresponding to 2π phase accumulation in the raw trace (see Fig. 2), we derive an expression for extracting x_{near} from the experiment

$$x_0 \Delta H = V' + 2x_{\text{near}} \Delta H, \quad (3)$$

where V' is some constant which scales with the spin wave group velocity.¹⁵

Since for small wave numbers $kz \ll 1$, the pseudo-dispersion law ($H(k)$) for SW is very linear ($\frac{dH(k)}{dk} = \text{const}$), $\Delta H = \frac{dH(k)}{dk} \Delta k$ does not vary with k in the main transmission band of the device. Thus, ΔH is a parameter specific to each particular device. From Eq. (3), one sees that by plotting $x_0 \Delta H$ versus ΔH for various antennae separations x_0 , the slope of the plot gives x_{near} .

Each raw trace of the type in Fig. 2 produces a number of ΔH data whose spread is statistically random. We average

FIG. 2. PSWS transmission data taken at 10 GHz for a 55 nm thick, $100 \mu\text{m}$ wide Permalloy stripe, with antennae symmetry axes separation gap of $30 \mu\text{m}$. Solid lines: experiment. Dashed lines: simulation.

these ΔH data into a single value for each trace. This value is multiplied by the respective x_0 (to produce $x_0\Delta H$) and is plotted against itself for the available stripe widths. The plots are shown in Fig. 3.

The data in Fig. 3 are well-fitted with the linear slopes. The x_{near} values extracted from the plots range from 0.3 to $2.3\ \mu\text{m}$ (Fig. 3), which means that the right-hand edge of the characteristic near field is localized within the $2.25\ \mu\text{m}$ gap from the symmetry axes of the central conductor (Fig. 1(b)). The fact that $x_{near} > 0$ implies that the phase accumulation starts first to the right from the SWA symmetry axis and always below the excitation antenna.

Excitation of MSSW in Permalloy by SWA is highly non-reciprocal (see Refs. 12 and 23 for a simple description of the antenna-induced non-reciprocity). We consider the waves propagating in the direction $x > 0$ of the stronger excitation. The non-reciprocity of MSSW breaks the symmetry of the spatial profile of the excited dynamic magnetization (see Fig. 4). Therefore, a priori one may expect that x_{eff} does not coincide with the distance x_0 (Fig. 1(a)). In order to elucidate these, we carried out numerical simulations using a model from our previous work,¹² now including the efficiency of reception of the SW signal by the second SWA. The simulated transmission characteristics are in good agreement with experiment (Fig. 2). Equation (3) was used to extract x_{near} from the simulation data. The simulated x_{near} is of the order of a few nanometres. However, the vanishing value of the simulated x_{near} does not imply that the near field of SWA does not exist at all.

In Fig. 4, one observes that far from the SWA, the amplitude of the in-plane dynamic magnetization decays exponentially (i.e., linearly on the logarithmic scale) with linear phase accumulation ($\phi' \equiv \frac{\partial\phi}{\partial x} = k = \text{const}(x)$). Both linear

FIG. 3. Plots of $x_0\Delta H$ versus ΔH for each SWA device, at 10 GHz around the vicinity of the SWA dominant wave number. Extracted x_{near} values are displayed next to their respective plots in *italics*. Dimensions are in microns unless otherwise specified.

FIG. 4. Simulated in-plane dynamic magnetization as function of coordinate x . Blue solid line: log magnitude, red dotted line: phase. Grey areas represent the spatial extent of the emitting CPW antenna. The vertical solid line shows the ZPP. Inset: enlarged phase profile, showing the actual and apparent ZPP. Solid lines in the inset: approximation of the phase profile with two linear sections.

dependencies are clear signatures of far-zone behaviour.¹⁵ The non-reciprocity of the SWA is clearly seen in the asymmetry of the amplitudes of the dynamic magnetization on either side of the SWA.

Underneath the SWA, both amplitude and phase of the dynamic magnetization are distorted by the near field of the SWA. This is seen as deviation from the linear laws. In particular, ϕ' varies with x and $\frac{\partial^2\phi}{\partial x^2} > 0$. The point where the slope of the phase profile is zero ($\phi' = 0$) is offset by $0.6\ \mu\text{m}$ to the left of the SWA symmetry axis; we designate $x = -0.6\ \mu\text{m}$ as the “zero phase point” (ZPP).

Recall that x_{near} gives the coordinate for the (apparent) right-hand boundary of the near-field area. Equation (1) may be rewritten as $x_{near} = x_{far} - x_{app}$, where x_{far} is some arbitrary point in the far-field zone of the input SWA and $x_{app} \equiv \left(\int_{x_{ZPP}}^{x_{far}} \phi'(x) dx \right) / k$. For the outlined behavior of $\phi'(x)$, it is possible that x_{far} and x_{app} may coincide, and the right-hand boundary of the near-field area can be occasionally located at $x = 0$, as in our simulation. The inset in Fig. 4 clarifies this argument; $\phi(x)$ may be approximated as two sections of straight lines: one with $\phi'(x) = 0$ located between ZPP and $x = 0$, and the other with $\phi'(x) = k$ for $x \geq 0$. Thus, measurements performed in the far-field region would observe an *apparent* ZPP at $x = 0$ (the wave *apparently* starts to accumulate phase at $x = 0$). The reason x_{near} vanishes is due to shift of the near-field to negative x such that its apparent right-side boundary is at $x = 0$. This shift is due to the strong non-reciprocity of MSSW excitation.

In the experiment, x_{near} is small but not vanishing. We suggest a number of contributions to the difference between the theory and the experiment. First, the experimental x_{near} of approximately $1\ \mu\text{m}$ may be mainly due to the experimental error (which does not exceed 10% of the smallest x_0 for any batch, as follows from Fig. 3). Furthermore, effects which are not included in the model may contribute to the difference. These are the conductivity of Permalloy, the finite thickness of CPW in the z direction (Fig. 1(b)), and the large conductivity of the gold antenna. It is known that the conductivities of the ferromagnetic film²⁴ and the

non-magnetic metal screen²⁵ may modify SW dispersion. In the latter case, the gold SWA may modify the dispersion locally beneath the conductors. It is challenging and beyond the scope of this paper to include these two effects into the theory. If these contributions are indeed non-vanishing, the small positive value of x_{near} found in the experiment will suggest that for the non-reciprocal MSSW, the apparent ZPP is located at $x > 0$, but is significantly shifted to the left with respect to the case of fully reciprocal waves. For the reciprocal waves it can extend over the coordinate range in Fig. 1 occupied by the ground line of the CPW ($2.25 \mu\text{m} < x < 3.75 \mu\text{m}$).¹⁵ There is no way to directly observe the near-field component experimentally in the PSWS experiment. One has to rely on more direct methods, such as space-resolved micro Brillouin light scattering.²⁶

In conclusion, the existence of a finite spin wave antenna near field was probed in a propagating spin wave spectroscopy experiment. We have formulated a method by which the antenna characteristic near-field length may be extracted from the experimental data. We used this method to study phase accumulation by the highly non-reciprocal MSSW in thin Permalloy microstripes. We have also carried out numerical simulations. Our modeling showed that the effective length over which the phase is accumulated by the travelling spin wave equals to the distance between the symmetry axes of the central conductors of the coplanar antennae with high accuracy. The measured effective lengths for all our samples are smaller than predicted by simulations. However, for all experimental data, the extracted half-difference x_{near} between the distance between the symmetry axes and the effective accumulation length is no larger than the distance from the symmetry axis of the antenna to the closest edge of the ground conductor. This result is important for the development of future microwave spin wave devices since the antennae separation gaps x_0 approach the size of the antennae themselves, due to the attenuation length of spin waves in Permalloy being typically in the tens of microns.

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