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Study of Surface Character of Micrometer-Scale Dipole-Exchange Spin Waves in an Yttrium Iron Garnet Film

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We demonstrate that micrometer-scale spin waves can be excited in a thin film of the ferrimagnetic material yttrium iron garnet (YIG) using patterned, multi-element antennas. The magnitude of the dynamic magnetic field generated by such antennas decays exponentially along the thickness direction, and this leads to an enhanced coupling to modes having a surface-like character as opposed to a more sinusoidal bulk-like character. We have used this property to identify spin waves having a mixed bulk/surface character.

***Index Terms*— Dipole-exchange spin wave, hybridization, multi-element antenna, surface mode.**

I. Introduction

SPIN waves propagating in a ferromagnetic slab were first studied by Damon and Eshbach [1] where they identified two classes of modes: bulk like and surface like. One of the bulk-like modes is the so-called backward volume (BV) mode, where the name arises from the property that the group velocity is negative at long wavelengths; the surface mode, which has a positive group velocity, is now commonly referred to as the Damon–Eshbach (DE) mode. Damon and Eshbach's treatment neglected the effects of exchange and was limited to in-plane external fields in the magnetostatic limit ($\nabla \times \mathbf{H} = 0$). DeWames and Wolfram [2] and Wolfram and DeWames [3] extended the magnetostatic theory to include the exchange interaction; they argued that there will be modes that involve an admixture of bulk and surface character in the region where both the dipole–dipole and exchange interactions are important. In particular, some of the exchange split modes (originally having a bulk character) acquire a surface character in the region where their dispersion relations cross, which leads to mode repulsion and hybridization. Recently, Kreisel *et al.* [4], Arias [5], and Li *et al.* [6] obtained similar results.

Exciting spin waves in the region where both dipole and exchange interactions are important is experimentally challenging since the associated wavelengths are of order a micrometer. To address this problem, we pattern antennas which consist of array parallel strips separated by distance d. When the underlying system supports a spin wave having a frequency matching that of an applied microwave signal and a wavelength λ matching antenna spacing d, resonant absorption can occur. Theoretical treatments involving this approach have been given elsewhere [7], [8].

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II. Sample Fabrication

The material used in these experiments is yttrium iron garnet (YIG) which is a ferrimagnet that is well-known for its low magnetic damping. The YIG film was grown epitaxially on a (111) gadolinium gallium garnet substrate and was obtained from MTI Corporation, Richmond, CA, USA. We patterned multi-element antennas directly on the free surface of our YIG sample using electron beam lithography. Fig. 1 shows an SEM image of the multi-element antenna. The antenna can be viewed as a ladder having 1/2 mm-long rungs with a width and spacing of 500 nm; the distance between each rung (the period) is then 1 μm which corresponds to the wavelength of the spin waves that can be excited by the antenna. The individual elements consist of 100 nm of Au over 5 nm of Ti. The YIG layer has a thickness of 2.843$\pm$0.002 μm, as measured with an M-2000 ellipsometer (J. A. Woollam Corp.); hence, the thickness and the period of antenna are of the same order of magnitude.

III. Experimental Measurement Techniques

Fig. 2 shows a schematic of the measurement apparatus. We used a fixed microwave frequency and swept the magnitude of the static magnetic field. The microwave source was an HP 8360 signal generator; the applied power was 25 dBm, and measurements were carried out in the range from 4 to 8 GHz. The generator output was applied to the antenna through a

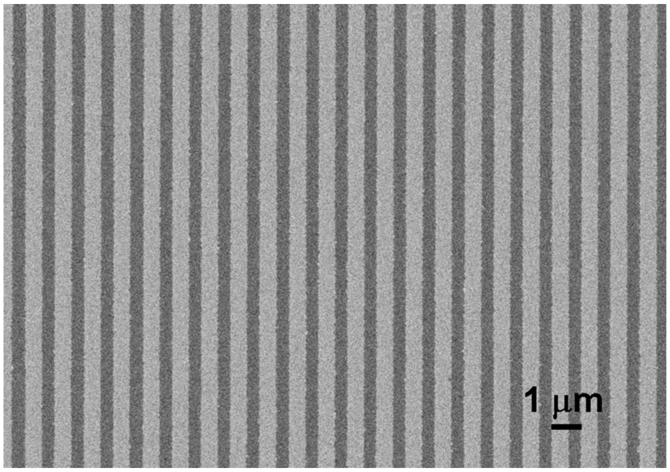

Fig. 1. SEM image of the multi-element antenna which has 1 μm period. Light parts: gold. Dark parts: YIG.

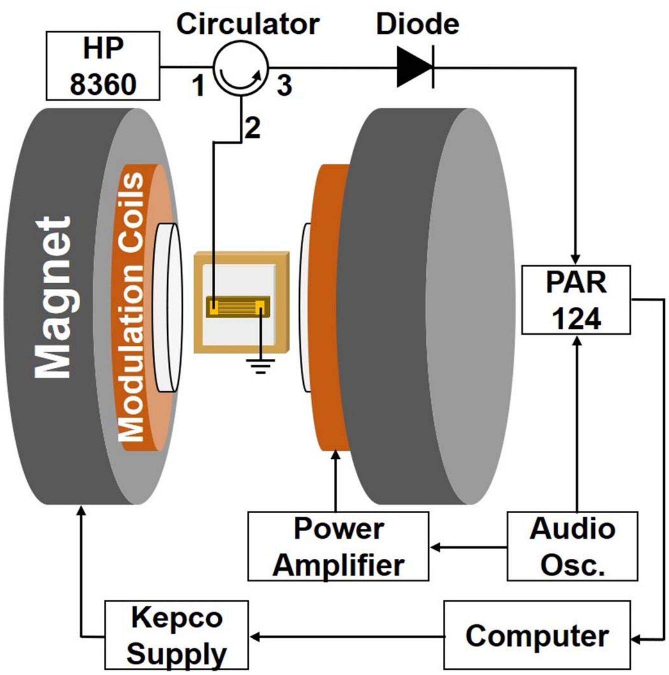

Fig. 2. Schematic of the measurement system. A 200 μm-thick glass coverslip forms a gap between the YIG film and the Cu plate on the sample holder which avoids any effects of a conducting surface.

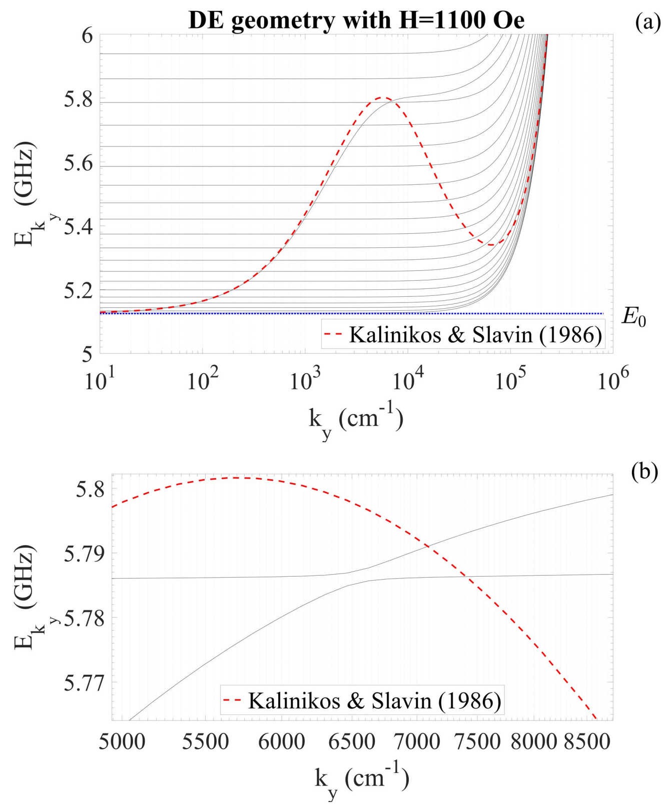

Fig. 3. Numerical calculation of the dispersion in the DE geometry at $H = 1100$ Oe, $E_0(\approx 5.12$ GHz) indicates FMR frequency. (a) Wide range of wave vectors. (b) Expanded view around $f = 5.8$ GHz. Dashed line: model dispersion of surface modes as given by Kalinikos and Slavin [9].

circulator (from port 1 to port 2). The reflected microwave signal from the sample went back through the circulator (from port 2 to port 3) to a diode detector, the output of which was applied to a lock-in amplifier (PAR 124); the lock-in output was then recorded with a computer. The reference signal applied to the lock-in was also amplified and applied to a pair of modulation coils surrounding the magnet pole pieces, resulting in an ac component in the detected microwave signal that is proportional to the derivative of the microwave absorption versus magnetic field.

The antenna structure generates a spatially periodic microwave field with components perpendicular to the film and parallel to the propagation direction. To determine the spatial behavior along the film normal, we adopt a magnetostatic model wherein the magnetostatic potential must satisfy Poission's equation; the general form of the potential is then given by

$$\phi(y, z) = \sum_n \phi_{0n} \cos(k_n y) e^{-k_n z} \tag{1}$$

where z is the thickness direction of the YIG sample, $k_n = 2\pi n/d$, and d is the period of the antenna (1 μm). The microwave magnetic field is then given by $\mathbf{H}_\mu = \nabla\phi$ so that the field decays exponentially along the thickness direction with a characteristic decay length that is also governed by the period of the antenna.

IV. Numerical Calculations of the Dispersion

Numerical calculations based on the microscopic Hamiltonian of Kreisel *et al.* [4] were performed with various parameters. Fig. 3 shows the numerical results for dispersion in the DE geometry (where the in-plane component of the wave vector is directed perpendicular to the applied magnetic field) for a magnetic field of 1100 Oe. The primary features exhibited here are a family of initially flat exchange split bulk modes together with the single DE mode which "cuts through" the bulk modes and, to varying degrees, hybridizes with them. The mode repulsion associated with the hybridization can be seen in Fig. 3(b). Two modes are

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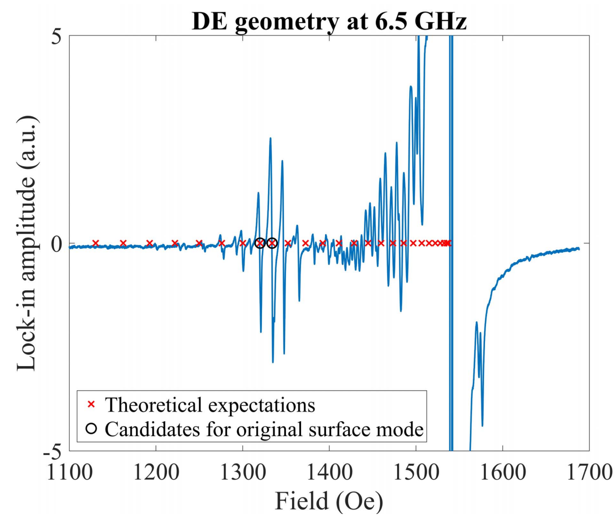

Fig. 4. Measured data in the DE geometry at 6.5 GHz along with theoretical mode positions. Points denoted by X show various bulk modes with $\lambda = 1\ \mu$m, whereas the circles indicate two modes that strongly couple to the DE surface wave. The oscillations lying adjacent to the FMR resonance (off scale) correspond to long wavelength standing waves induced by the antenna.

seen to approach each other, but ultimately repel leading to an anti-crossing. This is because the exchange interaction acts as a perturbation that couples them [2], [5], [6]. Further calculations show that at our wavelength of 1 μm, the surface wave intersects the 19th, 18th, and 16th exchange split bulk modes (as counted from the FMR frequency) at magnetic fields of 1100, 1400, and 1960 Oe.

We have also calculated the dispersion in the BV geometry (where the in-plane component of wave vector is parallel to the applied field) for a field of 1960 Oe. These latter calculations show that spectrum has a minimum in this geometry with a wavelength of 1.003 μm, which is close to our antenna period (1 μm); note that the wavelength of the minimum is insensitive to magnitude of the applied static field so that the wavelength of the minimum at $H = 1100$ Oe is also about 1 μm. The minimum occurs in a region where the negative dispersion (caused by magnetostatic effects) is compensated by the positive dispersion (arising from exchange). The lowest lying mode in the BV geometry is accompanied by a family of higher lying exchange split modes. Measurements and calculations associated with this geometry will be reported elsewhere.

V. Results and Discussion

Fig. 4 shows the measured data together with the theoretically expected mode positions ($\times$) at the wavelength of our antenna. Also indicated are "candidate" positions of bulk modes ($\circ$) with which the original surface mode might most strongly hybridize; the latter corresponds to the 18th and 19th bulk modes (again as measured from the FMR frequency), as estimated from the numerical calculations for $H = 1100$ Oe shown in Fig. 3. Note that the experimental data clearly show enhanced responses for these two modes.

There are two possible explanations for the enhanced responses. First, the admixture of surface character into the

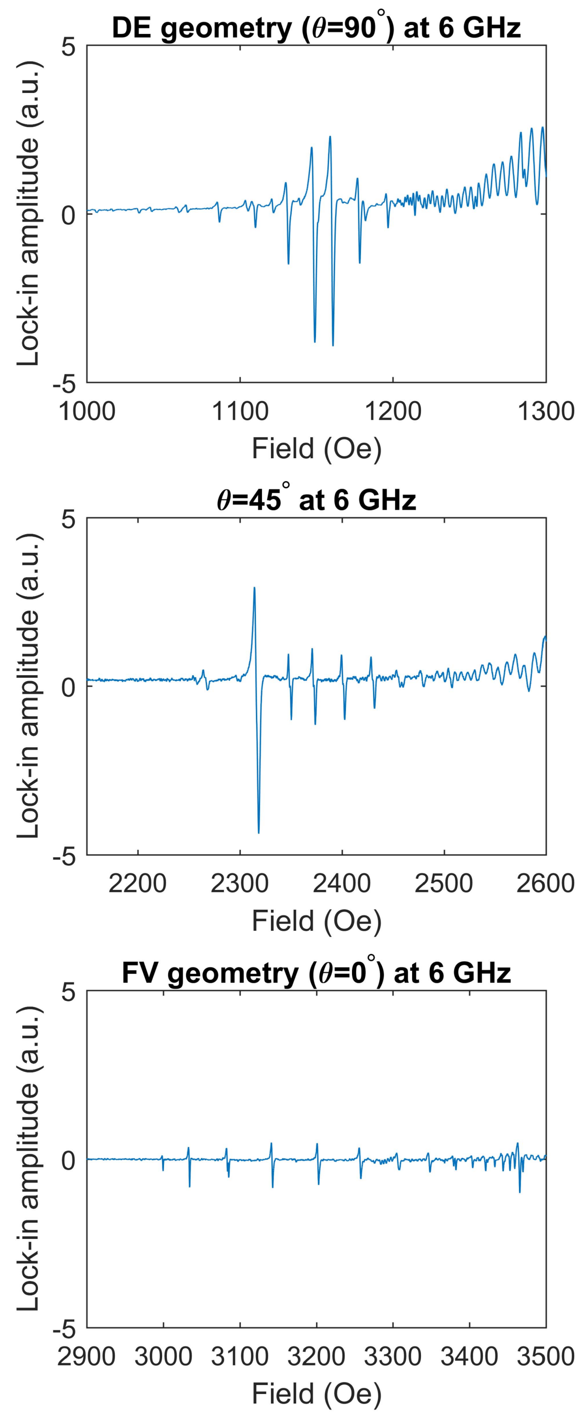

Fig. 5. Measured data at three different field angles lying in the DE–FV plane.

bulk modes is large, and the second, the vertical oscillatory period of the spin wave is comparable to the characteristic length of the field generated by antenna along the thickness direction. We can rule out the second possibility on the basis of the following: the perpendicular component of wavenumber of nth exchange split modes is given approximately by $k_z = \pi n/s$, where s is the thickness of the YIG film. Since the period of antenna is 1 μm and the thickness of the YIG film is about 2.8 μm, the wavelength of the third exchange mode corresponds approximately to the antenna spacing. Hence, the antenna decay length is much larger than the period of higher lying modes, e.g., the 18th mode. Therefore, we conclude that the enhanced coupling arises from a strong admixture of the DE surface mode with the corresponding bulk modes.

Fig. 5 shows the measured data for the magnetic field at three different internal field angles lying in the plane containing $\mathbf{n}$ and $\mathbf{n} \times \mathbf{k}$ where $\mathbf{n}$ is the film normal and $\mathbf{k}$ is the in-plane wave vector; $\theta = 0$ corresponds to the forward volume (FV) geometry. The amplitude of FMR signal (which is off scale to the right in Fig. 5) has been set to be equal for all three field angles so that we can directly compare the amplitude of exchange split modes. We note that the strength of the response is the smallest in the FV geometry, and it is well-known that here the propagating branch is bulk like (as opposed to surface like in the DE geometry). Therefore, we can conclude that large response in the DE geometry actually arises from an interaction between the surface mode and the exchange split modes.

VI. Conclusion

We patterned a multi-element ladder antenna consisting of equally spaced rungs on a YIG film to excite spin waves which have the wavelength defined by the period of the antenna. This wavelength corresponds to a region of propagation where both dipole and exchange interactions are important. From the solution of the magnetostatic equation, we find that the time-varying magnetic field generated by the antenna exponentially decays along the film normal so that it can strongly couple to spin waves having a similar character. We have observed large coupling to certain exchange split modes that lie near the intersection with the DE surface mode. We also confirmed that a large response does not occur between the bulk FV mode and the exchange split bulk modes. This suggests that further characterization of the surface character of various modes can be probed by measuring the spectrum for out-of-plane fields.

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