Nonreciprocal spin wave spectroscopy of thin Ni–Fe stripes

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The authors report on the observation of nonreciprocal spin wave propagation in a thin (~200 nm) patterned Ni–Fe stripe. The spin wave transmission spectrum is measured using a pair of microstrip lines as antennas. The nonreciprocity of surface wave dispersion brought about by an adjacent aluminum ground leads to a nonreciprocal coupling of the antennas. The effects of Ni–Fe film conductivity, thickness, and reflections caused by the lateral confinement of the magnetic stripe are discussed. The nonreciprocity observed in this structure can potentially be used to realize nonreciprocal microwave devices on silicon. © *2007 American Institute of Physics*.
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Patterned micrometer size metallic ferromagnets have recently attracted much attention in view of their potential application in integrated microwave components[1–4] and magnetic recording devices.[5] The dynamic behavior of such elements at high frequencies (or data rates) depends, to a large extent, on the excitation and propagation of spin waves, which are the fundamental excitations of magnetic systems.

The propagation of spin waves of various wavelengths in thin, conducting magnetic films such as Permalloy has been subject to extensive studies (see, e.g., Refs. 6–13). An important characteristic of spin wave propagation in magnetic layers is the possibility of nonreciprocal surface wave propagation. Such effects have been studied extensively in ferrite films,[14–17] and nonreciprocal ferrite-based devices such as microwave isolators and circulators are widely in use today. However, there is little information regarding the nonreciprocal characteristics of spin waves in thin, laterally confined metallic magnetic elements which are currently of increasing technological relevance. Since traditional ferrite-based nonreciprocal devices are not compatible with standard silicon integrated circuit (IC) technology, nonreciprocal behavior in IC-compatible magnetic materials such as Permalloy can be of interest for the on-chip integration of these devices into microwave integrated circuits.

In this work, we report on the observation of nonreciprocal long-wavelength surface waves in patterned Permalloy stripes using the propagating spin wave spectroscopy (PSWS) technique. The latter is based on the transmission and reception of spin waves in a magnetic film by means of two microwave transmission lines (antennas) placed on top of it. Originally employed for ferrites,[17–19] this approach has been extended to metallic films in recent years in the frequency[6,7] and time domains.[8]

The structure (Fig. 1) consists of two microstrip lines placed on top of a magnetic Ni–Fe core. Each microstrip line is short circuited to the ground at one end, resulting in an overall two-port structure. The principle of the experiment is as follows: Spin waves excited by each microstrip propagate on the magnetic film perpendicular to the magnetization direction and are picked up at the other port. For a given magnetization direction, the spin waves propagate on the upper or lower surface of the magnetic film, depending on the direction of propagation. Therefore, the presence of the metallic ground close to one surface of the film causes the dispersion characteristics of the surface waves to be different depending on the propagation direction (Fig. 1).[14] Waves propagating in different directions will thus have different frequency spectra, resulting in a nonreciprocal coupling of the microstrip lines. The experiment is similar to PSWS measurements on thin (~30 nm) Ni–Fe films, recently reported in the literature,[6,7] as well as to the recently proposed idea of spin wave bus interconnections[12] and logic gates.[13] In our case, however, the presence of a ground plane, combined with the use of a thicker magnetic layer (~200 nm), allows for the distinction of spin waves propagating in different directions, leading to the observation of nonreciprocal effects. Moreover, the lateral confinement of the magnetic stripe influences the observed transmission spectrum because of reflections at the film edges.

Magnetic Ni–Fe layers with thicknesses ranging from 50 to 500 nm were sputter deposited using a $Ni_{78}-Fe_{22}$ target. The Al ground and signal lines (antennas) were 2 and

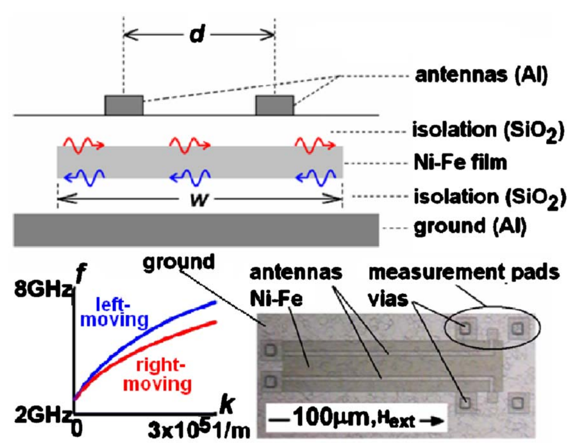

FIG. 1. (Color online) (Top) Schematic cross section of the coupled microstrip structure; two aluminum lines are coupled via surface waves propagating on a Ni–Fe layer. (Bottom left) Due to the presence of a metal ground close to the 200 nm thick Ni–Fe film, surface waves propagating in different directions have different dispersion characteristics, leading to nonreciprocal behavior. The nonreciprocity is enhanced by reducing the 1 μm ground-to-ferromagnet separation. (Bottom right) Top view microphotograph of a sample device, where the aluminum ground (background), rectangular patterned Ni–Fe core, microstrips acting as antennas, measurement pads, and via connections to the ground can be seen.

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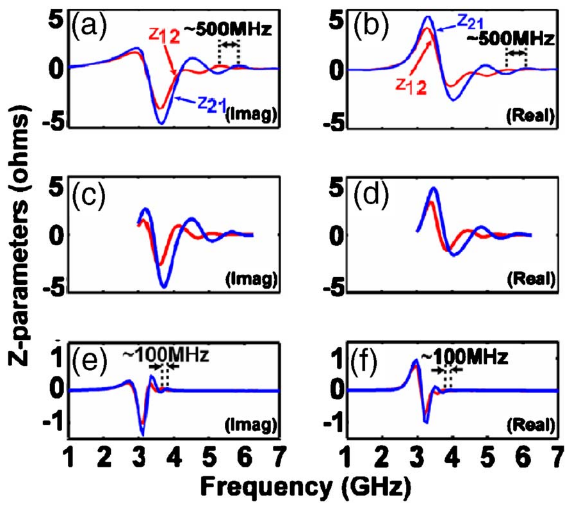

FIG. 2. (Color online) Real and imaginary parts of mutual impedance parameters for 20 μm wide microstrip antennas with 100 μm separation: [(a) and (b)] Z_{12} and Z_{21} for a device with 200 nm thick Ni–Fe film with an external dc field of $\sim$80 Oe applied along the stripe length. There is a frequency split of $\sim$500 MHz at the third peaks between Z_{12} and Z_{21} due to the nonreciprocal dispersion. Reversing the direction of H_{ext} changes the propagation directions on the upper and lower surfaces, swapping the Z_{12} and Z_{21} curves; [(c) and (d)] Simulated Z_{12} and Z_{21} for the same structure using Eq. (1); [(e) and (f)] Measurements for a similar device with a 50 nm thick Ni–Fe film. The nonreciprocity is less pronounced in this case (only $\sim$100 MHz at the third peaks) because of the smaller distance between the Ni–Fe surfaces. Note that the oscillation amplitudes are also closer in this case, indicating a more similar coupling of the antennas to the right- and left-moving surface waves.

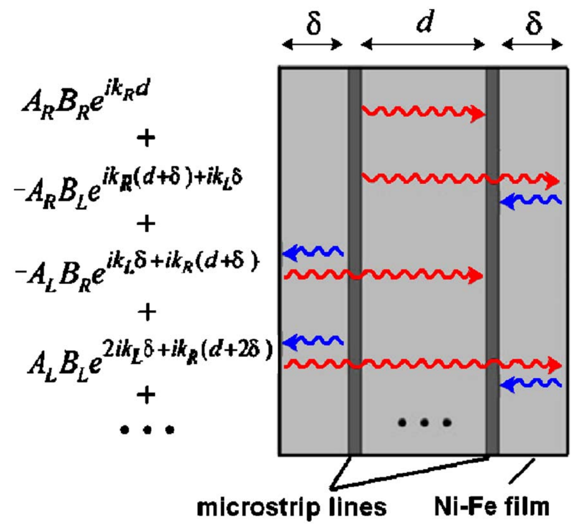

FIG. 3. (Color online) Schematic representation of spin wave reflections from the magnetic stripe edges. Considering all possible propagation paths for surface waves excited at the left antenna and picked up at the other, one can obtain the total voltage induced by the spin waves at the receiving end as a function of d, w, the complex wave numbers k_R and k_L, and the coupling factors A_R, A_L, B_R, and B_L. Note that we have included a phase of π upon each reflection at the edges to account for a total-pinning boundary condition (Refs. 20 and 21).

3 μm thick, respectively, and the SiO_2 isolation layers were 1 μm thick. The edge-to-edge separation of the 20 μm wide antennas was 100 μm. The whole structure was made on a silicon wafer covered with 2 μm thermal oxide. Patterning of the Ni–Fe film into 1 mm long, 240 μm wide stripes was performed by wet chemical etching. Additionally, an external dc field of $H_{ext}=\sim 80$ Oe was applied along the stripes during measurement to magnetize the film.

Two-port scattering parameters were measured on a line-reflect-match-calibrated HP-8510 network analyzer in connection with a Cascade Microtech probe station, and were then transformed to impedance parameters. Real and imaginary parts of the measured mutual impedances Z_{12} and Z_{21} for a device with 200 nm thick Ni–Fe are shown in Figs. 2(a) and 2(b). Oscillations similar to those in Ref. 6 are observed in both components. In our case, however, both the amplitude and the frequency of oscillations depend on the direction of propagation, i.e., which antenna acts as the transmitter and which one as the receiver. This is due to the split in dispersion characteristics of right- and left-moving surface waves in the presence of a metal ground (Fig. 1), but also due to the different coupling strengths of the antennas to each of those waves.

The oscillations in Z_{12} and Z_{21} are caused by the (direction-dependent) phase delay between the transmitted and received signals. However, because of the lateral confinement of the magnetic stripe, one also has to take into account the multiple spin wave reflections at the edges (Fig. 3). For a given frequency ω, let us assume that a current I flowing in the transmitting antenna generates right- and left-moving magnetization waves with the amplitudes $A_R I$ and $A_L I$, respectively. Once a wave reaches the receiving antenna, it induces a voltage equal to the wave amplitude times a coupling coefficient B_R or B_L, depending on the direction of propagation. The mutual impedance between the two microstrip antennas equals V/I, where V is the total induced voltage including all the transmission and (multiple) reflection terms for the spin waves (Fig. 3). It then follows that

$$Z_{21} = e^{ik_R d}[A_R B_R - (A_R B_L + A_L B_R)e^{iK\delta} + A_L B_L e^{2iK\delta}]\sum_{n=0}^{\infty} e^{niKw}, \quad (1)$$

where $K=k_R+k_L$, d is the lateral distance between the antennas, w is the width of the magnetic stripe, and $\delta=(w-d)/2$. The impedance Z_{12} follows by interchanging the subscripts R and L.

We have computed the (frequency-dependent) coupling factors A_R, A_L, B_R, and B_L by solution of Maxwell's equations for a single 20 μm wide line on an infinite Ni–Fe film, in a manner similar to Refs. 19 and 22. The wave numbers k_R and k_L were determined from the dispersion relations for nonreciprocal surface waves on an infinite magnetic film in the vicinity of a metal plane. Note that k_R and k_L contain imaginary terms to account for damping due to film conductivity and magnetic relaxation loss. Values of Z_{12} and Z_{21} computed from Eq. (1) for a 200 nm thick Ni–Fe stripe are given in Figs. 2(c) and 2(d), showing reasonable agreement with the measurements of Figs. 2(a) and 2(b). In reality, the 20 μm wide aluminum lines also cause the wave to be partly reflected,[23,24] affecting the overall frequency spectrum of the impedance parameters, an effect that we did not take into account in the calculation.

For a given structure, the extent of the observable nonreciprocal effect depends, firstly, on the split between the two branches of the associated dispersion diagram (Fig. 1), and secondly, on the spin wave damping in the magnetic film, which tends to smear out the nonreciprocity by widening the coupling peaks. The split between transmission wavelengths in opposite directions can be increased by putting the ground plane closer to one surface, i.e., by reducing the lower isolation layer thickness. It is, in principle, also possible to increase the nonreciprocity by increasing the magnetic film thickness. Measurements on similar structures fabricated on 500 nm thick Ni–Fe films, however, show that the applicability of this option is impeded by the dramatic increase of eddy currents in the conductive Ni–Fe film, which causes the nonreciprocity to almost vanish. Reducing the magnetic film thickness to 50 nm, on the other hand, reduces the frequency splits and weakens the nonreciprocity, as shown in Figs. 2(e) and 2(f). With further reduction of the film thickness, only a slight difference in coupling amplitudes (rather than frequencies) can be observed in different directions, which is due to the different coupling of the antennas with spin waves propagating on upper or lower surfaces of the film, as reported in Ref. 6 for 30 nm thin films.

Measurements on similar devices without an external field reveal that the application of a dc magnetic field increases the spin wave propagation frequencies and causes the magnetization to be more uniform within the Ni–Fe film, leading to an improved distinction of adjacent coupling peaks. Nevertheless, significant nonreciprocal coupling exists even without an external field, a fact which is important for on-chip microwave devices where the application of such a field is usually difficult for practical reasons. Comparison of scattering parameter spectra obtained for devices with 100 and 200 μm antenna separation reveals a transmission drop of $\sim$6 dB/100 μm at $\sim$3.5 GHz due to spin wave damping in the 200 nm Ni–Fe film, which is much higher than the typical loss observed in ferrite films (e.g., $<$1 dB/100 μm in Ref. 25). However, the antenna separation in a practical design can be made much smaller than the 100 μm used in our experiment in order to reduce the insertion loss of the device down to acceptable levels. Such a structure can then be integrated within the multilevel interconnect stack of standard integrated circuit processes, adding steps for magnetic material deposition (e.g., sputtering) and patterning.

In short, it was demonstrated that surface spin waves propagating on a thin patterned Ni–Fe stripe exhibit nonreciprocal behavior. Different frequency spectra were observed for the mutual impedance of antennas in the PSWS experiment for opposite propagation directions. The nonreciprocal behavior strongly depends on the film thickness, as well as on conductive losses in the magnetic layer.

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