Novel Non-Reciprocal Microwave Spin Wave and Magneto-Elastic Wave Devices for On-Chip Signal Processing

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***Abstract*—The discovery of interfacial Dzyaloshinskii-Moriya interaction (DMI) enables development of novel ultra-compact non-reciprocal devices for microwave signal processing. Such devices are based on control of spin waves and magneto-elastic waves by electric field and addition of ultra-thin layers of heavy metals to the devices. Here we discuss recent advances in the development of such systems, which can be used for implementation of on-chip non-reciprocal microwave devices.**

***Keywords*—magnonics, microwave magnetics, magnetic films, microwave devices, magnetoelasticity.**

I. Introduction

Non-reciprocal microwave devices based on ferrites have been used as lumped elements in microwave circuits for over half a century. These devices employ the unique advantage offered by magnetic materials, namely broken time reversal symmetry, to enable non-reciprocal microwave signal propagation when combined with inversion symmetry breaking. Low-insertion-loss isolators, circulators and directional couplers based on ferrites have been widely used. The disadvantage of these devices is that they require bias magnetic field provided by permanent magnets and thus are bulky. There is no direct pathway for scaling these devices to microscopic dimensions needed for integrated microwave circuits.

However, magnetic materials can be potentially used in integrated microwave circuits in the form of thin films. In such thin films, transmission of microwave signals can be carried by spin waves and magneto-elastic waves instead of the conventional electromagnetic waves. This offers additional advantages for device scalability as the wavelength of such waves can be much smaller than that of electromagnetic waves of the same frequency. Thin films also offer unique ways of inducing non-reciprocity for microwave signal propagation via design of non-reciprocal frequency-momentum dispersion relations of spin waves and magneto-elastic waves. Recent discoveries of interfacial Dzyaloshinskii-Moriya interaction (iDMI) and spin flexoelectric interaction (SFI) are the two novel ways of creating spin wave non-reciprocity [1]. The iDMI arises from antisymmetric indirect exchange coupling between two spins of a ferromagnetic (FM) material mediated by atoms of an adjacent nonmagnetic material (NM) the FM/NM interface. The SFI arises from inversion symmetry breaking in a FM induced by application of an electric field. The iDMI and SFI can be imprinted onto acoustic waves via magneto-elastic coupling of FM with non-reciprocal spin wave dispersion to acoustic waves in a proximate films. This approach allows one to take advantage of low decay rate of acoustic waves [2] and enables non-reciprocal microwave devices with low insertion loss.

II. Nonreciprocal Surface Acoustic Wave Devices

Surface acoustic wave (SAW) in high-quality piezoelectric single crystals is widely used in microwave devices such as filters and sensors. SAWs exhibit low propagation losses at frequencies ranging from a MHz to several GHz. SAWs can be excited with a very high efficiency, and the insertion losses of SAW devices can be just a few dB [2]. The wavelength of SAWs are several orders of magnitude smaller than those of electromagnetic waves of the same frequency, thus allowing a miniaturization of SAW signal processing devices compared to their electromagnetic counterparts. One disadvantage of SAW devices is their reciprocity. We propose to solve this problem via coupling of SAWs to spin waves in a FM film with non-reciprocal spin wave dispersion induced by iDMI. Figure 1 shows schematic of a multilayer used for nonreciprocal SAW. A standard SAW piezoelectric crystal such as $LiNbO_3$ is used as a substrate for hosting SAWs. On top of this substrate, a magneto-elastic FM film (e.g. Ni) is deposited. The FM film is covered by a heavy metal layer such as Pt to induce iDMI and create non-reciprocal spin wave dispersion in Ni. The magneto-elastic

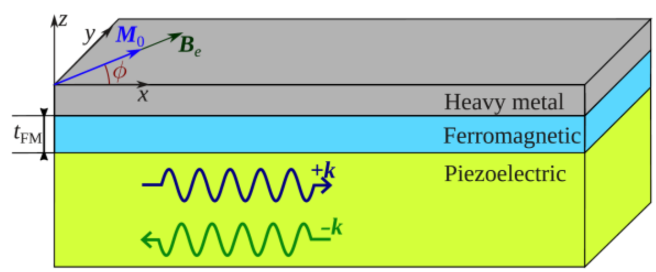

Fig. 1. A layout of a multilayer for generation of non-reciprocal SAW: a piezoelectric substrate covered by a ferromagnetic–heavy-metal bilayer.

coupling at the Ni/$LiNbO_3$ interface transfers the spin wave dispersion non-reciprocity to the SAW dispersion [3].

We developed a theory of SAW in the structure shown in Fig. 1 and found that interaction between SAW and spin waves (SWs) leads to opening spectral gaps (hybridization gap) in the SAW dispersion relation near crossing points of spin wave spectra and SAW spectra [4]. Figure 2a shows that SW dispersion has a non-zero gap at zero wave vector k_x induced by external magnetic field, while SAW dispersion is gapless. This leads to crossing of the SW and SAW dispersion at non-zero values of k_x. Near such crossing points, the interaction between SW and SAW is resonantly enhanced leading to opening a gap in the spectra near this crossing point as illustrated in Fig. 2b. Because the SW dispersion is non-reciprocal due to iDMI, the gaps for the forward and backward propagating waves are found at different frequencies, as shown in Fig. 2b. This implies the possibility of a SAW that can only propagate in one direction but not the other. Indeed, a SAW with a particular value of the wave vector determined by periodicity of the interdigital transducer (IDT) antenna can be excited in this structure. The wave vector can be chosen such that for one direction of the wave vector, the frequency of excitation fall within the hybridization gap while for the opposite direction of the wave vector it is well outside of the gap. Since only evanescent wave can be excited within the gap, purely unidirectional propagating waves will be excited by such a transducer. Furthermore, at this particular frequency and wave vector, the effective magneto-elastic medium of our multilayer supports propagation of waves in only one direction. Therefore, this medium can be employed for building circulators, isolators and directional couplers based on the non-reciprocal properties of the media itself.

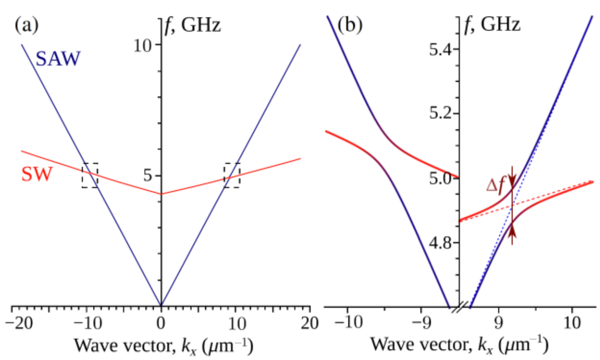

Fig. 2. (a) Spectra of SAWs in the $LiNbO_3$/Ni/Pt multilayer that, away from the points of wave hybridization, look like independent crossing spectra of the SAW and the SWs, respectively. (b) Close-up of the spectra near the hybridization points [marked by dashed rectangles in (a)], where the magneto-elastic band gaps are clearly seen. The Ni layer thickness is 10 nm, the magnetization angle is in the sample plane at 45° with respect to the SAW propagation direction, and in-pane magnetic field is 41 mT.

Using our theory [4], we calculated the optimal material parameters and magnetic field biasing condition to maximize the medium non-reciprocity. Our calculations reveal the optimal thickness of the FM Ni layer is 9 nm, while the optimal direction of the applied magnetic field is in the plane of the sample at 45° with respect to the SAW propagation direction. Figure 3 shows the S matrix parameters calculated for such an optimized structure. It is clear that in narrow frequency band, very strong unidirectional isolation is achieved. Indeed, in a frequency band around central frequency of 5.095 GHz, the difference between S_{12} and S_{21} parameters exceeds 45 dB. Therefore, such a structure can act as a unidirectional valve for microwave signal propagation, from which isolators and circulators can be constructed. We also note that this structure is very compact with the distance between the transmitter and receiver IDT antennae of just 0.25 mm, suitable for on-chip integrated non-reciprocal microwave devices.

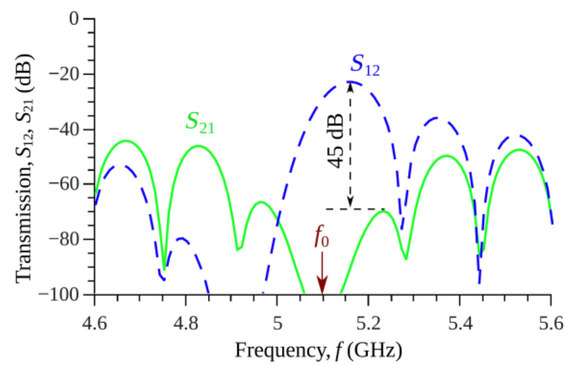

Fig. 3. Transmission characteristics of a SAW in the $LiNbO_3$/Ni/Pt medium for the opposite directions of wave propagation [S_{12} (the dashed line) and S_{21} (the solid line)]. The thickness of the Ni layer is 9 nm, the distance between the IDT transmitter and receiver antennae is 0.25 mm, the optimal operation frequency is 5.095 GHz, the number of IDT fingers is 30, and the bias magnetic field of 45 mT is applied 45° with respect to the SAW propagation direction.

III. Nonreciprocal Spin Waves in Thin Films of Yttrium Iron Garnet

An alternative approach to non-reciprocal on-chip microwave media is to use SWs in FM films with low magnetic dissipation (low Gilbert damping parameter). Yttrium iron garnet (YIG) is a ferromagnetic insulator material that has the lowest known Gilbert damping parameter. Until recently, YIG was not available in ultrathin (down to a few nm) thin film form. However, recent improvements in the ultrathin YIG film growth techniques have enabled growth of such films with high crystalline quality and low Gilbert damping parameter [5]. Therefore, if significant iDMI can be induced in such ultrathin YIG films, SWs in these films can be used for building ultra-compact non-reciprocal microwave devices.

Here we report measurements of SW non-reciprocity in ultrathin YIG films grown either directly on a gadolinium gallium garnet (GGG) substrate or on a GGG substrate covered with thin Pt layer. Quite surprisingly, we observe significant spin wave non-reciprocity and iDMI in both of these systems, with a stronger iDMI in the GGG/Pt/YIG system [6]. This implies that development of integrated non-reciprocal microwave devices based on ultrathin YIG films is possible. Figure 4 shows a scanning electron micrograph (SEM) of a device for measuring spin wave non-reciprocity in a GGG/YIG(40 nm) film. The device consists of two coplanar strips (CPS) microwave antenna (receiver and transmitter antennae) patterned on top of the film using e-beam lithography. The small dimensions of the CPS antennae allow us to probe propagation of SWs with their wavelength down to 400 nm.

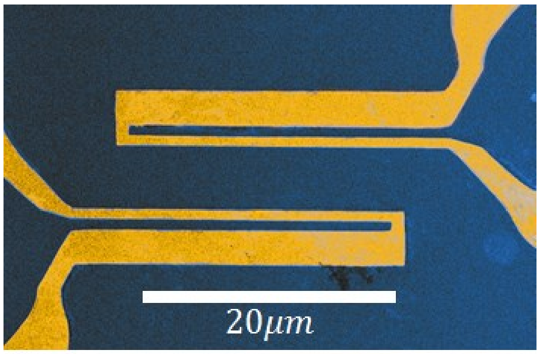

Fig. 4. Colorized SEM image of transmitter and receiver coplanar strip microwave antennae patterned on top of a GGG/YIG(40 nm) film for measurements of spin wave propagation in the YIG film.

We employ a microwave network analyzer to make measurements of spin wave propagation in the device shown in Fig. 4. Figure 5 shows the S matrix parameters measured in this device as a function of microwave frequency and magnetic field applied in the plane of the film perpendicular to the direction of SW propagation (Damon-Eshbach or DE geometry [7]). The S_{12} and S_{21} parameters show clear oscillatory dependence on frequency and magnetic field, demonstrating that the signal between the two CPS antennae is carried by spin waves in the YIG films.

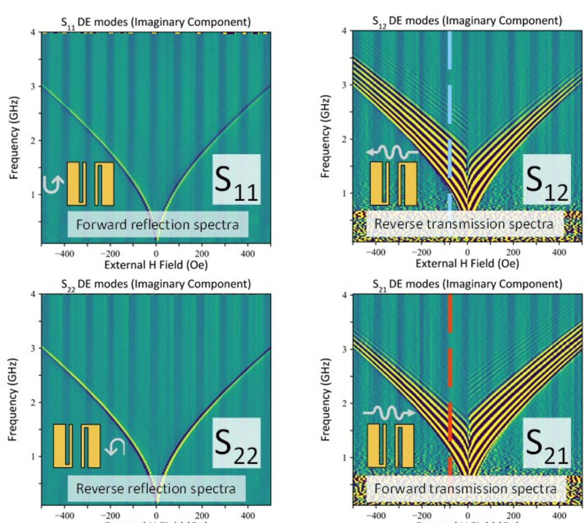

Fig. 5. S matrix parameters measured for the device in Fig. 4 as a function of frequency and magnetic field applied in the plane of the film perpendicular to the spin wave propagation direction.

Further inspection of the data in Fig. 5 reveals that the values of S_{12} and S_{21} parameters at a given field are not the same and remain different upon the magnetic field reversal. This indicates that spin wave propagation in this device is non-reciprocal. This non-reciprocity is further revealed by examining the dependence of S_{12} and S_{21} parameter on frequency at a fixed value of magnetic field as shown in Fig. 6. The clear difference in the oscillation frequency of the two traces reveals non-reciprocity of the SW propagation in this YIG film [8].

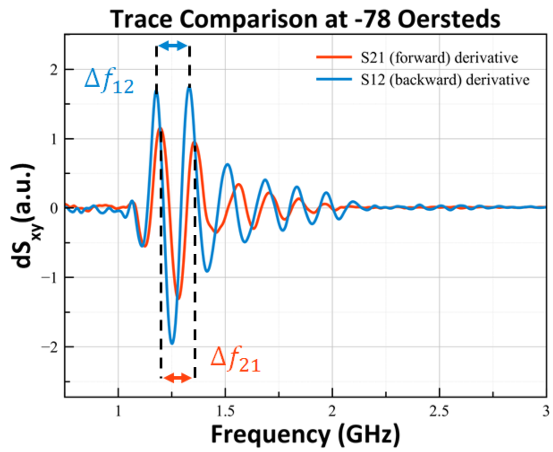

Fig. 6. Comparison of S_{12} and S_{21} parameters at one particular value of the magnetic field for the GGG/YIG system. Different frequency of the S parameter oscillations for the two traces reveals non-reciprocity of the spin wave dispersion relation in YIG.

Analysis of the frequency difference between neighbouring peaks in Fig. 6 give us group velocities for forward and backward propagating SWs. This analysis gives forward and backward propagating group velocities of 699 m/s and 725 m/s, respectively. This means that a 4% non-reciprocity in SW group velocities is present in this film. We attribute this surprising non-reciprocity to iDMI at the interface between GGG and YIG.

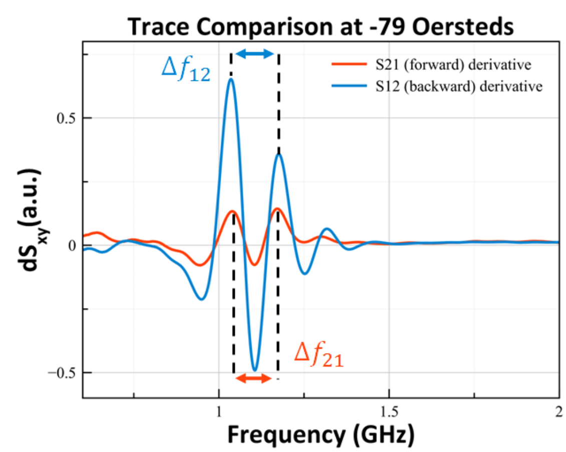

Fig. 7. Comparison of S_{12} and S_{21} parameters at one particular value of the magnetic field for the GGG/Pt/YIG system. Different frequency of the S parameter oscillations for the two traces reveals non-reciprocity of the spin wave dispersion relation in YIG.

To test the hypothesis of the interfacial origin of the non-reciprocity, we insert a Pt metal between the GGG substrate and the YIG film. Figure 7 shows comparison of the S_{12} and S_{21} parameters for the GGG/Pt/YIG device as a function of frequency measured for a fixed value of the magnetic field. The non-reciprocity of SW propagation of this device is apparent as well. Analysis of the data reveals that group velocities of the forward and backward propagating spin waves are 775 m/s and 822 m/s, respectively. This is a 6% difference between group velocities of the forward and backward propagating spin waves. We thus conclude that the Pt insertion layer enhances the non-reciprocity of the SW dispersion of the ultrathin YIG film. This is consistent with our hypothesis of the iDMI origin of the observed non-reciprocity. Indeed, Pt is a heavier element than Gd and Ga, and thus has stronger spin-orbit interaction that is ultimately responsible for iDMI.

Our results demonstrate that ultrathin YIG films support propagation of non-reciprocal spin waves and thus can serve as propagation medium for non-reciprocal on-chip microwave devices based on spin waves. Furthermore, we show that the degree of non-reciprocity of spin waves in ultrathin YIG films can be enhanced by interfacing this film with a heavy-element non-magnetic film.

IV. Conclusions

We show that interfacial Dzyaloshinskii-Moriya interaction can be efficiently used to induce non-reciprocity of both spin waves in thin magnetic films with low damping and surface acoustic waves. Both of these approaches to generating non-reciprocal wave medium for propagation of GHz-frequency excitations in thin films hold significant promise for development of integrated on-chip non-reciprocal microwave devices such as isolators, circulators and directional couplers.

Acknowledgment

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References

[1] F. Hellman *et al.*, “Interface-induced phenomena in magnetism,” *Rev. Mod. Phys.*, vol. 89, p. 025006, 2017.
[2] A. A. Oliner, Ed., *Acoustic Surface Waves*. Berlin Heidelberg: Springer-Verlag, 1978.
[3] R. Sasaki, Y. Nii, Y. Iguchi, and Y. Onose, “Nonreciprocal propagation of surface acoustic wave in $Ni/LiNbO_3$” *Phys. Rev. B*, vol. 95, no. 2, p. 020407, Jan. 2017.
[4] R. Verba, I. Lisenkov, I. Krivorotov, V. Tiberkevich, and A. Slavin, “Nonreciprocal Surface Acoustic Waves in Multilayers with Magnetoelastic and Interfacial Dzyaloshinskii-Moriya Interactions,” *Phys. Rev. Applied*, vol. 9, no. 6, p. 064014, Jun. 2018.
[5] L. Soumah *et al.*, “Ultra-low damping insulating magnetic thin films get perpendicular,” *Nature Communications*, vol. 9, no. 1, pp. 1–6, Aug. 2018.
[6] M. Evelt *et al.*, “Spin Hall-induced auto-oscillations in ultrathin YIG grown on Pt,” *Scientific Reports*, vol. 8, no. 1, p. 1269, Jan. 2018.
[7] R. W. Damon and J. R. Eshbach, “Magnetostatic modes of a ferromagnet slab,” *Journal of Physics and Chemistry of Solids*, vol. 19, no. 3, pp. 308–320, May 1961.
[8] H. Maier-Flaig *et al.*, “Note: Derivative divide, a method for the analysis of broadband ferromagnetic resonance in the frequency domain,” *Rev Sci Instrum*, vol. 89, no. 7, p. 076101, Jul. 2018.