Amplification of Spin Waves by Thermal Spin-Transfer Torque

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We observe amplification of spin-wave packets propagating along a film of single-crystal yttrium iron garnet subject to a transverse temperature gradient. The spin waves are excited and detected with standard techniques used in magnetostatic microwave delay lines in the 1–2 GHz frequency range. The amplification is attributed to the action of a thermal spin-transfer torque acting on the magnetization that opposes the relaxation and which is created by spin currents generated through the spin-Seebeck effect. The experimental data are interpreted with a spin-wave model that gives an amplification gain in very good agreement with the data.

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In recent years, there has been an enormous growth of activities in the search for mechanisms to generate and to detect spin currents driven by the very exciting physics involved and potential application in spintronics. The spin Hall effect (SHE) and the inverse SHE have now been established to be efficient means to convert a charge current into a spin current and vice versa [1–8]. Very recently, a more striking phenomenon has been discovered, the spin-Seebeck effect, by which temperature gradients in ferromagnetic metallic or insulating materials create pure spin currents [9–12]. All reported experimental observations of the spin-Seebeck effect rely on the use of the inverse SHE to convert the spin current into a measurable electric current. So they constitute a relatively limited set of information to inspire and test theoretical models [13–18] for the conversion of heat currents into spin currents and for other spin thermoelectric effects in the very challenging field of spin caloritronics.

One important established feature of a spin current is its ability to create spin-transfer torques (STTs) [19] that act on the magnetization and manifest through two main phenomena: magnetization reversal [20] and spin-wave excitation [21,22]. It has been predicted theoretically that temperature gradients can create a thermal spin-transfer torque [23–25], but so far there is scarce experimental evidence of this effect [26]. Spin waves with very low wave numbers, called magnetostatic waves, propagating in thin films of ferromagnetic materials were extensively studied in the 1970s and 1980s motivated by their interesting physical properties and potential applications in microwave signal processing devices [27,28]. Their main advantage over other means such as elastic waves is the control of their characteristics by the intensity of the applied static field. However, the damping of spin waves during propagation in hundreds of nanoseconds, even in very low-loss materials like yttrium iron garnet (YIG), has always been a major difficulty for their practical application. For this reason, considerable effort was devoted to finding ways to amplify spin waves with microwave frequencies. Parametric pumping in YIG with an independent microwave source [29], amplification through the interaction between spin waves and charge carriers [30], and active feedback loops [27] have not proved to be of practical application. In this Letter, we show that spin-wave packets propagating along films of the very low-loss ferrimagnetic insulator YIG can be amplified by thermal gradients applied across the film thickness. The amplification is attributed to the thermal STTs produced by spin currents created through the longitudinal spin-Seebeck effect [11,12].

All experiments were carried out at room temperature with the arrangement shown in Fig. 1. The samples consist of strips 12 mm long and 2 mm wide cut from a wafer with a 28 μm thick single-crystal YIG film grown by liquid phase epitaxy on a 500 μm thick (111) gadolinium gallium garnet (GGG) substrate. Several different schemes

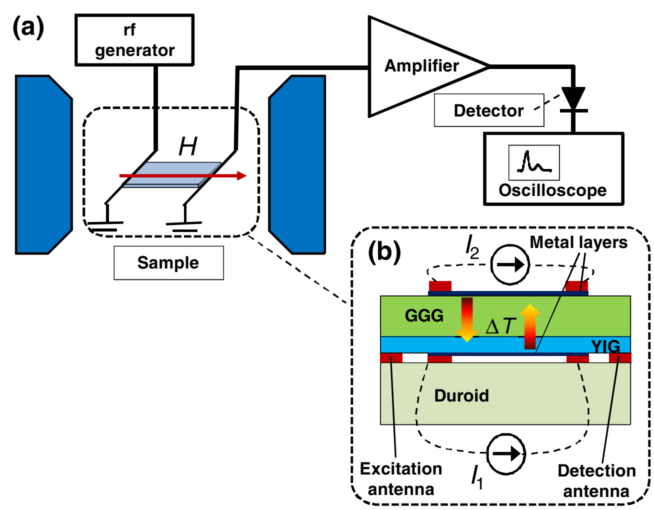

FIG. 1 (color online). (a) Schematics of the apparatus used to observe amplification of spin-wave packets. (b) Illustration of the sample structure with Pt (6 nm) or Mo (3 nm) layers deposited on the surfaces of a YIG/GGG structure and heated by currents I_1 and I_2.

were employed to generate a temperature gradient across the YIG film. We present here the results obtained with the simplest and most efficient scheme, shown in Fig. 1(b), in which the Joule heat is provided by a current through metallic resistive Pt (6 nm thick) or Mo (3 nm) thin layers deposited on either one or both sides of the YIG-film–substrate sample. The YIG film is pressed against four parallel thin Cu strips patterned on a standard microwave microstrip duroid plate. Two strips are at the ends of the film and are used to excite and detect spin waves with microwave frequencies. Two other strips 5 mm apart are use to apply a dc current in the metallic layer on the YIG side. The current for the other metallic layer on the GGG side is applied by external contacts made with silver paint. A thermocouple was used to measure the temperature on the surface of the GGG substrate.

The YIG film is magnetized to saturation by a static magnetic field with intensity H applied in the plane along the long length of the film. The two Cu strips at the ends of the YIG film act as microstrip antennas used to excite and detect spin-wave packets with microwave frequency in a standard configuration employed to study spin waves [27,28]. Microwave radiation pulses with frequency in the range 1–2 GHz, peak power between 1 and 5 mW, duration 50 ns, and repetition rate 10 kHz sent to one of the microstrip antennas excite magnetostatic volume spin-wave packets which propagate in the YIG film. In the absence of the temperature gradient, the structure behaves as a lossy variable delay line [27,28]. The packet propagates with a group velocity determined by the value of the static field H and reaches the other end where it produces a rf pulse in the detection antenna with a delay time that varies with H. The pulse is amplified with a wideband amplifier, detected with a Schottky barrier diode, and observed in a digital oscilloscope.

Figure 2(a) shows the spin-wave frequency $f = \omega/2\pi$ versus wave number k calculated [28] for two values of the magnetic field, for a 28 μm thick YIG film with saturation magnetization $4\pi M = 1.76$ kG and gyromagnetic ratio $\gamma = 2\pi \times 2.8$ GHz/kOe. One can see clearly that as the field increases the dispersion curve shifts upward and the group velocity $v_g = \partial\omega_k/\partial k$ given by the slope of the curve at the operating frequency $f = 1.19$ GHz decreases, resulting in longer time delays. The lines in Fig. 2(b) are typical oscilloscope traces of the detected pulses. The large initial pulse on the left corresponds to the direct electromagnetic transmission between excitation and detection antennas, while the delayed pulse is due to the signal transmitted by the spin-wave packet that has group velocity several orders of magnitude smaller than that of electromagnetic waves. Figures 2(c) and 2(d) show the spin-wave delay time versus H measured at $f = 1.19$ and 1.73 GHz.

The effect of a temperature gradient across the YIG film created by a current I_2 in the Pt layer on the GGG side on the spin-wave pulse with $f = 1.73$ GHz and delay 115 ns is shown by the blue and red lines in Fig. 2(b). The amplitude of the spin-wave pulse increases ninefold as the current I_2 is raised to 30 mA with the current I_1 in the Pt layer on the YIG film kept at zero. Similar results are obtained by passing a current I_1 only in the metallic layer on the YIG side, but lower values of I_1 are necessary to obtain the same gain. Figures 3(a) and 3(b) show the effect on the spin-wave pulse of an increasing current I_1 with $I_2 = 0$. As I_1 increases, the amplitude of the pulse increases rapidly, while the delay time decreases slightly. Pulses which are almost hidden in the noise in the absence of current are amplified with gains greater than 20 by a current of 20 mA. Very strong evidence that the amplification is due to a temperature gradient is provided by the data in Figs. 3(c) and 3(d) showing the behavior of the gain when heating is provided by currents on both sides of the sample. The amplification gain increases with increasing current I_1 reaching $G = 9$ for $I_1 = 20$ mA while $I_2 = 0$ as shown in Fig. 3(c). On the other hand, if the current I_1 is kept fixed at 20 mA and the current I_2 is increased, the gain decreases continuously until amplification ceases at $I_2 = 30$ mA as shown in Fig. 3(d). Thus, when the resistive layers on both sides of the sample are heated, although the heat supplied to the YIG film increases, the temperature gradient decreases and so does the spin-wave amplification.

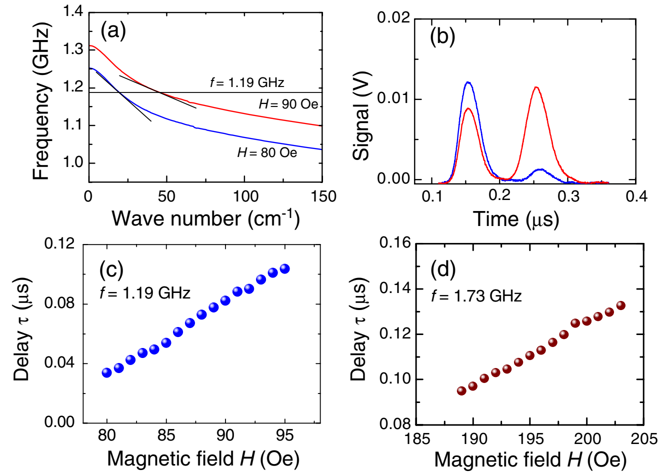

FIG. 2 (color online). (a) Dispersion relation for magnetostatic volume backward waves propagating along the field H on the film plane in a YIG film strip with thickness 28 μm and width 2 mm for two values of the field: $H = 80$ Oe (blue line) and $H = 90$ Oe (red line). (b) Typical oscilloscope traces showing the initial pulse due to the direct coupling between the antennas and the delayed spin-wave pulse with frequency 1.73 GHz and $H = 192$ Oe. The blue trace is obtained with no heating of the sample, while the red trace corresponds to a current $I_2 = 30$ mA on the GGG side and no current on the YIG side $I_1 = 0$. (c), (d) Delay time of the spin-wave pulse versus H measured at $f = 1.19$ and 1.73 GHz.

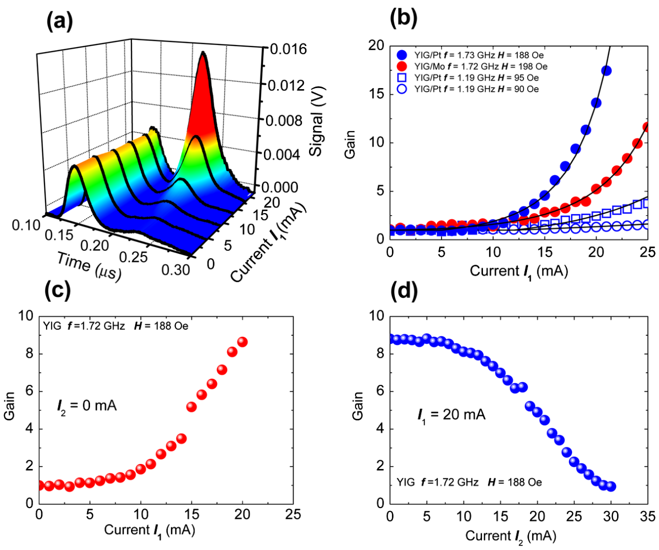

FIG. 3 (color online). (a) Digital oscilloscope traces of the detected pulses showing the amplitude of the spin-wave packet in the YIG/Pt film strip for several values of the dc current I_1 in the Pt layer with $f = 1.73$ GHz and $H = 188$ Oe. (b) Data (symbols) and theoretical fits (solid lines) with Eq. (3) for the amplification gain of spin-wave packets versus current I_1 in YIG/Pt and YIG/Mo with frequencies and field values indicated. (c) Experimental data for the amplification gain versus current intensity I_1 in the Pt layer on the YIG film and no current in the Pt layer on the GGG substrate $I_2 = 0$. (d) Gain measured with fixed $I_1 = 20$ mA and increasing I_2.

One might ask whether the amplification observed with the dc current passing in the Pt layer deposited on the YIG film has any contribution from the SHE, which, as reported in Ref. [6], can produce a STT that excites spin waves in a YIG film. In fact, our experiments were devised to test if the SHE could also be used to amplify spin waves using a 6 nm thick Pt layer deposited on the YIG film since Pt has a large Hall angle [5]. However, three puzzling observations indicated that the amplification mechanism was other than the SHE. The first was the clear reduction in the delay time of the spin-wave pulse with increasing current, an effect that as will be shown later is caused by a reduction in the magnetization due to heating. The other was that no significant changes in the amplification were observed with the reversal of the direction of either current or field, in contrast to the results of spin-wave generation by the SHE [6]. The third and most compelling evidence was that the response time of the change in pulse amplitude with variations in the current was a few seconds, clearly indicating thermal effects. The experiments were repeated with a Mo layer which has a Hall angle much smaller than Pt [5]. The thickness of the Mo layer was 3 nm, half that of the Pt thickness, so that in the two cases the resistances were nearly the same since the resistivity of Mo is close to half that of Pt. As shown in Fig. 3(b), the amplification observed with Mo is comparable to that obtained with Pt when the same frequency is used, a clear demonstration that the spin-wave amplification is not due to the spin Hall effect.

The experimental observations can be explained in terms of a spin-wave model in which the precessing spins are under the action of a thermal STT created by the spin current produced through the longitudinal spin-Seebeck effect observed recently in magnetic insulators [11,12]. The equation that governs the behavior of the propagating spin-wave packet in the temperature gradient is derived in the same way as that obtained for spin waves in a metallic ferromagnetic layer traversed by a spin-polarized current and driven by a STT [31]. We follow Refs. [23,24,26] and consider that the spin current through the YIG film exerts an in-plane torque on the spins $\vec{S}$ proportional to the spin current density produced by the temperature gradient ∇T, across the film, $J_S = \hbar\beta|\nabla T|/A$, where A is the area of the film plane and β is a parameter proportional to the spin-Seebeck coefficient. Note that we use the modulus of the temperature gradient because no change in the amplification was observed with the reversal of the gradient. With the usual transformations from the spin deviation operators into collective magnon creation and destruction operators $c_k^\dagger$ and c_k, respectively, one can write the free-magnon Hamiltonian as $H^{(2)} = \hbar\sum_k \omega_k c_k^\dagger c_k$, where ω_k is the spin-wave frequency. Here we neglect the nonlinear contribution from the four-magnon interactions [31] because the number of magnons involved is very small compared to the number of spins in the YIG film. Using the Heisenberg equation and introducing the contributions from the spin-transfer torque and the relaxation as in Ref. [31], one obtains an equation of motion for c_k in the form

$$\frac{dc_k}{dt} = -i\omega_k c_k - (\eta_k - \beta|\nabla T|)c_k, \quad (1)$$

where η_k is the spin-wave relaxation rate. Assuming that the spin-wave packet is very narrow and considering $t = 0$ the instant when the packet enters the region of the temperature gradient, one obtains from Eq. (1) the equation for the evolution of the spin-wave amplitude:

$$c_k(t) = c_k(0)e^{-i\omega t}e^{-(\eta_k - \beta|\nabla T|)t}, \quad (2)$$

where $c_k(0)$ is the initial amplitude. Equation (2) shows that for $\nabla T = 0$ the spin-wave amplitude decays in time with the relaxation rate resulting in an attenuated transmitted pulse. However, for a nonzero temperature gradient the decay rate is reduced by the action of the thermal STT. If the temperature gradient exceeds a critical value $\nabla T_c = \eta_k/\beta$, the STT overcomes the relaxation rate so that the amplitude of the spin wave increases exponentially as the wave packet propagates in the temperature gradient. Since the diode detector has a square law response at small signals, the amplitude A of the transmitted pulse is proportional to the number of magnons $c_k^* c_k$, and from Eq. (2) one can write the amplification gain as

$$G(\nabla T) = \frac{A(\nabla T)}{A(0)} = e^{a(\nabla T/\nabla T_c)}, \quad (3)$$

where the prefactor in the exponent is $a = 2\eta_k L/v_g$, v_g is the group velocity, and L is the length of the heated region, which is taken to be the distance between the two electrodes shown in Fig. 1(b).

In order to compare the model for the gain with the data, we express the temperature gradient in terms of the heating current I_1 as follows. The heat generated in the resistive layer on the YIG film flows transversely across the thin film and the thick GGG substrate and is radiated by the substrate surface. Since the lateral dimensions are much larger than the thicknesses, one can solve the one-dimensional heat diffusion equation and find the temperature variation across the YIG/GGG sample. Using the known thermal conductivity and specific heat for YIG/GGG and the surface radiation time estimated from the measurements, we find that the temperature variation across the sample is approximately linear. The temperature on the substrate surface was measured with a thermocouple and fit with a linear plus quadratic dependence on I_1 in the range 0–20 mA. The temperature in the YIG film cannot be measured directly, but it can be inferred from the change in delay time, since the heat reduces the magnetization and shifts down the frequency, increasing the group velocity of the spin-wave packet. Using $\Delta(4\pi M)/\Delta T = -3.6$ G/K for YIG at room temperature [32], we find an approximate relation between the temperature gradient across the YIG/GGG sample with thickness $d = 0.528$ mm with the current: $\nabla T = \delta(I_1 + bI_1^2)$, where $\delta = 1.1$ K/(cm mA) and $b = 0.63$ mA^{-1}. This gives for $I_1 = 20$ mA a temperature gradient of 300 K/cm. From Eq. (3) we obtain an expression for $G(I) = A(I)/A(0)$ and define a critical current I_c given by $\beta\delta(I_c + bI_c^2) = \eta_k$, above which the spin-wave amplitude grows exponentially.

Figure 3(b) shows the data for several frequencies and field values for YIG/Pt and YIG/Mo with the corresponding theoretical fits obtained with Eq. (3). For YIG/Pt with $f = 1.73$ GHz and $H = 188$ Oe, we obtain from the fit $I_c = 15$ mA and $a = 1.5$. Using $L = 5$ mm and $v_g = 1.2 \times 10^7$ cm/s inferred from the measured delay time, we find the relaxation rate $\eta_k = 1.8 \times 10^7$ s^{-1}, which corresponds to a Gilbert damping parameter $\alpha = \eta_k/\omega = 1.6 \times 10^{-3}$ and a linewidth $\Delta H = \eta_k/\gamma = 2.8$ Oe. These values are larger than those for a YIG film because in YIG/Pt there is an additional damping due to spin pumping [33,34]. Using the relation between ∇T and I_1, we find a critical temperature gradient of 272 K/cm.

The fit to the data for YIG/Mo gives $\eta_k = 6 \times 10^6$ s^{-1}, indicating a smaller damping than in YIG/Pt because of the absence of the spin pumping relaxation mechanism. Note in the data for YIG/Pt with $f = 1.19$ GHz in Fig. 3(b) that the gain increases with increasing field because the group velocity decreases so that a increases. The relaxation rates obtained from the fits for the two fields are nearly the same and are smaller than the value for $f = 1.73$ GHz, as expected because it is known that the damping increases with frequency. In sum, the results of the spin-wave model are in very good agreement with the data.

In summary, we have experimentally demonstrated that spin waves propagating in a YIG film can be amplified by the application of a temperature gradient across the film and that the measured amplification gain can be very well explained by a spin-wave model incorporating a spin-transfer torque proportional to the temperature gradient. These results provide additional evidence that a temperature gradient creates a thermal spin-transfer torque that affects the dynamics of the magnetization [26]. We attribute the STT to the spin current created by the temperature gradient through the spin-Seebeck effect. Since in insulators a spin current is carried by magnons [6] which are excitations with spins tilted away from the equilibrium direction, we conjecture that STT is mediated by magnons that diffuse from the hot to the cold surface of the YIG film. We hope that the results of this investigation will stimulate further theoretical work for the full elucidation of the mechanisms behind the spin-Seebeck effect in insulators and also open new possibilities for the use of magnetostatic waves for signal processing in spintronic devices.

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