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Spin pumping by parametrically excited short-wavelength spin waves

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We use both parallel and perpendicular parametric pumping techniques to excite short-wavelength spin waves in an yttrium iron garnet film and study the spin current generation from spin waves excited by these pumping methods with the help of the inverse spin-Hall effect in the adjacent Pt layer. We observed clear spin current generations for these pumping techniques and find that the efficiency is nearly independent of the magnitude and the direction of the wave vectors of excited spin waves. These experimental results are important for future spintronic devices operated by short-wavelength spin waves. © *2011 American Institute of Physics*. [doi:10.1063/1.3652911]

In the last decade, great progress has been achieved in the field of spintronics, where the spin of electron facilitates data acquisition and processing in solid-state devices based on spin transport effects, such as giant/tunnel magnetoresistance and spin transfer torque.[1,2] Recent investigations in the field have shown that the high-frequency magnetic dynamics is of special importance for further development of ultra-fast spintronic devices. In particular, mutual conversion of (spin) angular momentum of electrons and spin waves has been demonstrated,[3] which sheds light on the important role of spin waves for spintronic applications. It was shown that magnetization precession in an insulating ferromagnetic layer transfers a part of its angular momentum into an adjacent non-magnetic metal layer in the form of a spin current,[4–6] which then induces a voltage by the inverse spin Hall effect (ISHE).[7–9]

Most of the works on the spin pumping by precessing magnetization were concentrated on using the uniform ferromagnetic resonance (FMR) mode[7–9] or spin-wave resonances[10,11] as a source of spin current. Very recently, the possibility of spin pumping by parametrically excited large-wave-vector spin waves has been also demonstrated.[12] However, the excitation geometry used in Ref. 12 implies coexistence of both parallel and perpendicular parametric excitation mechanisms and does not allow one to separate contributions from different groups of spin waves excited by different types of pumping.

Here, we report a study of the spin pumping by large-wave-vector (i.e., short-wavelength) spin waves excited by different parametric excitation mechanisms. Controlling the spin-wave spectrum by the static magnetic field and using separately perpendicular and parallel parametric pumping configurations, we were able to excite spin waves with different, well defined magnitudes and directions of the wave vector. Our results show that the efficiency of the spin-current injection by different spin waves is nearly independent of their wave vectors.

As well known, to excite the FMR linearly, one needs to apply a microwave magnetic field $\mathbf{h}$ perpendicular to the static field $\mathbf{H}_0$ at the FMR frequency f_0.[13] However, due to the nonlinearity of magnetic system, parametric excitation of dynamic magnetization is also possible without fulfilment of the FMR condition, provided that the amplitude of the microwave magnetic field is large enough to overcome the spin-wave relaxation.[14] There are two different mechanisms of the parametric excitation: parallel and perpendicular pumping. In the first case where $\mathbf{h}||\mathbf{H}_0$, the microwave magnetic field with the frequency f_p directly couples to the parallel component of magnetization, resulting in the excitation of spin waves at the frequency $f_p/2$. In the second case with $\mathbf{h} \perp \mathbf{H}_0$, the field first non-resonantly excites magnetization precession at f_p, which then serves as a pumping for spin waves at $f_p/2$. In the both cases, two spin waves with equal and opposite wave vectors $\pm\mathbf{k}$ are excited, but the magnitudes of the wave vectors and their directions are essentially different for the two mechanisms.[14,15]

The wave vector selection rules for perpendicular and parallel pumping are illustrated in Figs. 1(a) and 1(b), respectively. These figures show parts of the spin-wave dispersion spectrum relevant for the two pumping geometries. The spectrum of spin waves in magnetic films is anisotropic and depends on the angle θ between $\mathbf{k}$ and the film plane and on the angle φ between $\mathbf{k}$ and $\mathbf{H}_0$. In the case of perpendicular pumping[15,16] [Fig. 1(a)], spin waves with the wave vector in the plane of the film ($\theta = 0$) are excited independently of the pumping frequency f_p, whereas the angle φ varies with f_p. At large pumping frequencies, the excited spin waves have the property of $\varphi \approx 45°$. With the decrease of f_p the magnitude of $\mathbf{k}$ decreases, whereas φ stays unchanged, as shown in Fig. 1(a) by the solid curve. As $f_p/2$ decreases below the FMR frequency f_0, φ increases stepwise and then continuously decreases to zero, while the magnitude of $\mathbf{k}$ decreases from about 3×10^5 to $5 \times 10^4\,\mathrm{cm}^{-1}$. In the case of parallel pumping[17] [Fig. 1(b)], spin waves with the wave vectors perpendicular to the plane of the film ($\theta = 90°$) are excited at large f_p. With the decrease in f_p, the magnitude of $\mathbf{k}$ decreases and vanishes at $f_p/2 = f_0$, as shown by the green curve in Fig. 1(b). Further decrease in f_p results in the excitation of spin waves with $\mathbf{k}$ parallel to the plane of the film ($\theta = 0$) and $\varphi = 0$. Their wave vector increases with decreasing f_p.

The above discussion shows that by varying f_p at constant H_0, one can controllably excite spin waves with

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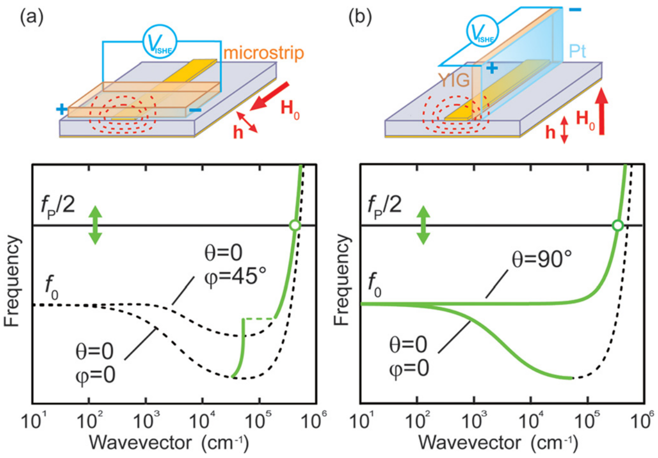

FIG. 1. (Color online) The schematics of experimental geometries and wave-vector selection rules for (a) perpendicular and (b) parallel parametric excitations. Arrows in the schematics indicate directions of the static and dynamic magnetic fields for each of geometries. As the spin current created by the spin pumping flows in to the Pt layer, spin Hall voltage V_{ISHE} is generated in its plane and measured in the experiment. Dashed lines in graphs show spin-wave dispersion characteristics for different angles θ and φ defined by the orientation of the wave vector with respect to the film plane and the static magnetic field, respectively. Solid curves show the states available for the parametrically excited spin waves as a function of the pumping frequency f_p. f_0 is the FMR frequency.

different directions and magnitudes of the wave vector. In the experiment, however, the magnetic field H_0 was changed at constant f_p. In this case, the whole spin-wave spectrum moves in the frequency space with respect to $f_p/2$, which, in analogy with the above picture, enables controllable excitation of different spin waves.

The sample used in the experiments is a layered system consisting of 5.1 μm-thick monocrystalline yttrium iron garnet (YIG) film epitaxially grown on a gallium gadolinium garnet substrate and a 15-nm thick Pt film deposited on top of YIG by magnetron sputtering. The lateral dimensions of the sample are 1.5×3.5 mm. Excitation of spin waves is realized using 0.5 mm wide standard 50 Ω microstrip transmission line or a half-wave resonator made of such line. To realize different types of the parametric excitation, the following two experimental geometries were used. (1) The YIG-film was attached to the strip, while $\mathbf{H}_0$ was applied parallel to the microstrip axis (Fig. 1(a)). (2) The YIG-film was mounted close to the edge of the microstrip perpendicularly to the holder surface (Fig. 1(b)); the latter being also oriented perpendicular to $\mathbf{H}_0$. In this way, geometries with perpendicular or parallel orientation of the microwave magnetic field **h** with respect to $\mathbf{H}_0$ were realized, as indicated in Fig. 1.

Excitation of spin waves is equivalent to an injection of the angular momentum causing a reduction of the component of magnetization M_z parallel to the static magnetic field. This reduction is proportional to the number of excited spin-wave quanta (magnons). Due to the exchange interaction between YIG and Pt at the YIG/Pt interface, part of the angular momentum is transferred to electrons in Pt layer, which can be regarded as a spin current $\boldsymbol{j_s}$ flowing across the YIG/Pt interface: $j_s \sim \delta M_z$.[3] Due to the ISHE, the spin current induces an electric field along the direction perpendicular to $\mathbf{H}_0$.[6] The corresponding voltage V_{ISHE} was measured using two electrodes attached to the Pt layer, as shown in Fig. 1. In addition, the microwave power absorbed by the sample and proportional to the number of excited magnons was measured by a calibrated network analyzer.

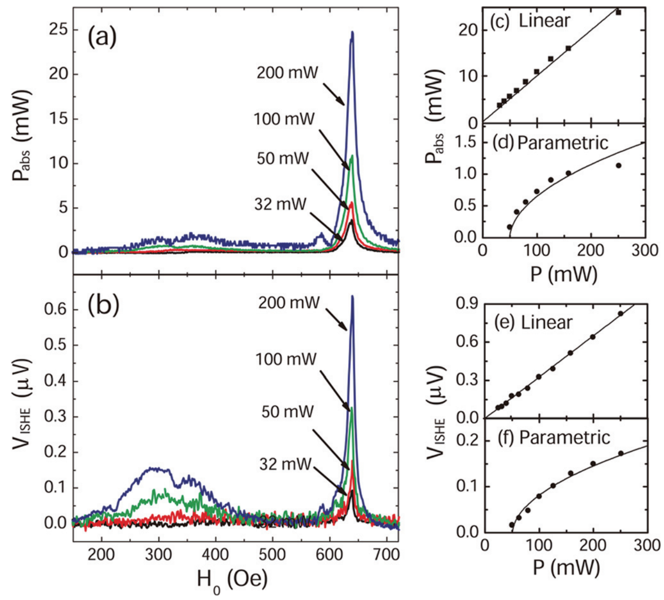

FIG. 2. (Color online) Field dependences of (a) the absorbed microwave power P_{abs} and (b) the inverse spin-Hall voltage V_{ISHE} obtained at different powers P applied to the microstrip. The data were recorded in the perpendicular pumping geometry for $f_p = 3.5$ GHz. (c)–(f) show the excitation power dependences of P_{abs} and V_{ISHE} for linear and parametric excitation as labeled. For the linear case, we plot the measured P_{abs} and V_{ISHE} at $H_0 = 640$ Oe and both plots are fitted by linear functions. For the parametric case, we plot the measured P_{abs} and V_{ISHE} at $H_0 = 300$ Oe and both plots are fitted by a function of $a\sqrt{P - P_{thr}}$, where a is a fitting parameter and $P_{thr} = 50$ mW is used.

First, we compared the spin-pumping efficiency for the cases of linear and parametric excitation using the perpendicular pumping geometry. For this, a relatively small pumping frequency $f_p = 3.5$ GHz was chosen to enable observation of both linear and parametric excitation within the interval $H_0 = 100$–800 Oe. Figures 2(a) and 2(b) show the field dependences of the absorbed microwave power P_{abs} and the inverse spin-Hall voltage V_{ISHE}, respectively, obtained at different powers P applied to the microstrip. Sharp narrow peaks seen in both figures at $H_0 \approx 640$ Oe correspond to the linear excitation of FMR. As expected for the linear excitation, the dependence of P_{abs} on P is linear [Fig. 2(c)]. A similar linear dependence [Fig. 2(e)] was also obtained for V_{ISHE}, which confirms that V_{ISHE} is proportional to the number of excited magnons.

In addition to the FMR peak, a wide peak corresponding to the parametric excitation of spin waves is seen in Figs. 2(a) and 2(b) at $H_0 = 200$–400 Oe. In contrast to the linear excitation, both P_{abs} and V_{ISHE} are proportional to $\sqrt{P - P_{thr}}$, where P_{thr} is the threshold power of the parametric process [see Figs. 2(d) and 2(f)]. This is in agreement with the theory of the parametric excitation[15] and the conclusion that V_{ISHE} is proportional to the number of excited magnons.

Comparing the data for the two different excitation mechanisms, we found that the efficiency of spin-current generation κ given by the ratio V_{ISHE}/P_{abs} is essentially higher for the parametric excitation ($\kappa \approx 0.09$ mV/W) than for the linear excitation ($\kappa \approx 0.03$ mV/W). This can be

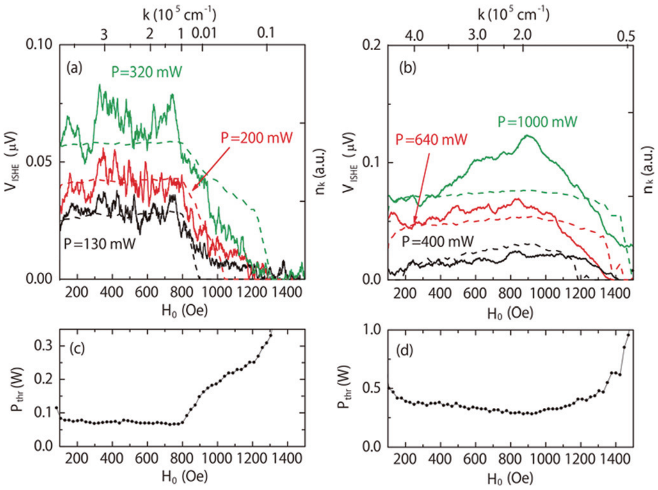

FIG. 3. (Color online) (a) and (b) show the field dependences of measured inverse spin-Hall voltage V_{ISHE} (solid curves) and of the calculated number of excited magnons n_k (dashed curves) for different pumping powers P, as labelled, for parallel and perpendicular pumping, respectively. (c) and (d) measured the field dependences of the threshold power P_{thr} for parallel and perpendicular pumping, respectively. The pumping frequency is 8.2 GHz.

associated with the enhancement of the spin current by the process of the splitting of one magnon at f_p into two magnons at $f_p/2$ requiring additional flow of the angular momentum from the lattice.[18]

Second, we used parametric pumping in the two different configurations to excite short-wavelength spin waves and to study the efficiency of the spin-current generation by spin waves with different wave vectors. In order to provide large amplitudes of the pumping field, enough to overcome the threshold of parametric pumping in wide range of $\mathbf{H}_0$, a half-wave microstrip resonator with the length of 6.3 mm was used. The corresponding resonant frequency was $f_p = 8.2$ GHz. Figures 3(a) and 3(b) show the field dependences of V_{ISHE} for different pumping powers P in the cases of parallel and perpendicular pumping. The magnitude of the wave vector k obtained from the theoretical analysis for different H_0 (see discussion of Fig. 1) is shown in the upper horizontal axes. Measured V_{ISHE} is determined by the number of the excited magnons n_k with a given k and the efficiency of spin-current generation by these magnons. The number of magnons, in turn, is determined by the ratio between the pumping power P and the threshold power P_{thr}. We measured the field dependences of P_{thr} [Figs. 3(c) and 3(d)] and calculated $n_k(H_0)$ using the theory of Ref. 15. The results are presented in Figs. 3(a) and 3(b) by dashed curves.

The analysis of the results is straightforward in the case of the parallel pumping [Figs. 3(a) and 3(c)], since P_{thr} stays constant in the wide range $H_0 = 150$–800 Oe, corresponding to k varying from 0 to $4.5 \times 10^5\ \mathrm{cm}^{-1}$. The data of Fig. 3(a) show that V_{ISHE} also stays nearly constant within this interval, although some slight variations of the voltage above the noise level are observed.[19–21] These almost constant P_{thr} and V_{ISHE} for $H_0 < 800$ Oe lead to a conclusion that the efficiency of the spin-current generation does not depend on k of the excited spin waves. Moreover, the measured $V_{ISHE}(H_0)$ follows the calculated $n_k(H_0)$ reasonably well, which allows one to extend the above conclusion to higher H_0 where P_{thr} is not constant.

In the case of perpendicular pumping [Figs. 3(b) and 3(d)], the analysis is not as simple as for the parallel geometry, since P_{thr} depends on H_0. Nevertheless, comparing the calculated dependences $n_k(H_0)$ with experimental dependences $V_{ISHE}(H_0)$, one can see rather good agreement, which shows that the previous conclusion is also valid for spin waves with $\mathbf{k}$ oriented at 45° with respect to $\mathbf{H}_0$. We note that the deviation $P = 1000$ mW is probably because the used parametric excitation theory is only valid for the small P/P_{thr} condition.

In conclusion, we have experimentally shown that short-wavelength spin waves excited using two different parametric excitations mechanisms generate spin currents in YIG/Pt structures. The generation efficiency is nearly independent on the magnitude and the direction of their wave vectors. Our findings contribute to understanding of the spin-pumping phenomena and suggest the large potential of spin pumping using short-wavelength spin waves for technical applications in spintronic devices.

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