Magnons Parametric Pumping in Bulk Acoustic Waves Resonator

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We report on the experimental observation of excitation and detection of parametric spin waves and spin currents in the bulk acoustic wave resonator. The hybrid resonator consists of ZnO piezoelectric film, yttrium iron garnet (YIG) films on gallium gadolinium garnet substrate, and a heavy metal Pt layer. Shear bulk acoustic waves are electrically excited in the ZnO layer due to piezoeffect at the resonant frequencies of the resonator. The magnetoelastic interaction in the YIG film emerges magnons (spin waves) excitation by acoustic waves either on resonator’s eigenfrequencies or the half-value frequencies at supercritical power. We investigate acoustic pumping of magnons at the half-value frequencies and acoustic spin pumping from parametric magnons, using the inverse spin Hall effect in the Pt layer. The constant electric voltage in the Pt layer, depending on the frequency, the magnetic field, and the pump power, was systematically studied. We explain the low threshold obtained (∼0.4 mW) by the high efficiency of electric power transmission into the acoustic wave in the resonator.

The studies in the field of magnons or magnon spintronics direct to employ microwave spin waves (SW) as main carriers of information data transmission and processing. Therefore, the problem of interaction between SW (or their quanta – magnons) and other condensed matter excitations (phonons, electrons, etc.) is of great importance. The numerous manifestations of SW - acoustic wave (AW) interaction in micro- and nanoscale structures, especially the conversion of magnetic energy into elastic and vice versa, are of interest both for practical applications and fundamental physics.

The elastic excitation of SW can be carried out without the alternating magnetic fields, which substantially reduce ohmic losses in comparison with the inductive current-driven excitation. So the magnon-phonon interaction is very promising for the development of low energy SW logic circuits and memory elements.

Linear excitation of acoustically driven spin waves (ADSW) was demonstrated in various hybrid magnon-phonon structures containing piezoelectric (PE) and ferromagnetic layers. To excite ADSW, the close contact between the layers is unnecessary, and a high-Q acoustic medium can separate the layers with neither PE nor ferromagnetic properties. Strain-induced magnon effects, such as SW generation, propagation, and amplification in magnetoelectric structures with close contacts of PE and thin ferromagnetic films also gained a lot of attention recently.

Ferromagnetic (at microwave frequencies) yttrium iron garnet (Y3Fe5O12 - YIG) grown onto gadolinium gallium garnet (GGG) substrate has extremely low losses of spin waves and acoustic waves, and their high conversion efficiency. It makes YIG-GGG the perfect candidate for magnon spintronics devices. Thus, investigations of acoustically driven spin waves (ADSW) in heterostructures with YIG-GGG are now quite a hot topic in scientific research.

A widely used spin pumping method is now implemented to study SW dynamics in micro- or nanoheterostructures. Spin pumping (SP) is a transform of the spin angular momentum of magnons into a spin current at the ferromagnetic-nonmagnetic metal interface. The electrical detection of SW results from the spin to charge current conversion in heavy metal like Pt due to the inverse spin Hall effect (ISHE). We will refer to this method as SP/ISHE further.

Spin pumping from linearly excited ADSWs with a surface AW was experimentally exhibited. In Refs. we demonstrated the piezoelectric ADSWs excitation and their SP/ISHE detection in the spintronic hypersonic High overtone Bulk Acoustic wave Resonator (HBAR) with ZnO/YIG/GGG/YIG/Pt structure. In a similar HBAR structure, the influence of the parametric acoustic pumping on the propagation of SW excited via traditional microstrip antennas was studied.

The excitation of short wavelength parametric magnons is currently studied in connection with the tendency to reduce the size of magnonic structures. Therefore, the source of low energy parametric magnons is highly relevant. Apparently, purely acoustic parametric excitation of SW in HBAR has not been reported previously. The SP/ISHE method for detecting parametric ADSWs up to the present day was considered only theoretically.

In this work, we report the observation of the parametric ADSW excitation in a spintronic HBAR with YIG/Pt structure used previously in Ref. for the linear ADSW excitation. We studied the frequency and magnetic field dependences of the ISHE constant voltage signal under the resonator’s excitation in the GHz frequency range. The signal from the parametric ADSW was observed when: i) the pump frequency coincided with one of the HBAR resonant frequencies, ii) half of the pump frequency coincided with one of the SW frequencies.
for a given magnetic field, iii) the pump power exceeded a threshold, depending on the field.

which magnetized the YIG films to saturation $4\pi M_s = 845 \text{ G}$ if $H > H_s \sim 10 - 20 \text{ Oe}$, where $H_s$ is the saturation field.

In YIG films, ADSWs are excited due to the interaction between the magnetic and elastic subsystems. For their detection by the SP/ISHE method, a 12 nm thin Pt layer was deposited on the bottom YIG film’s surface underneath the PE transducer aperture. Spin pumping from ADSW results in the time-averaged spin current $j \propto n(M \times \partial M/\partial t)_z = j_z n$ polarized along $z$ and flowing from YIG into Pt parallel to the normal $n(x)$. The ISHE in Pt leads to an electrostatic field $E_{ISHE} \propto -j_z \times z$ in the $y$-direction, and the dc voltage $U_{ISHE} = -\partial E_{ISHE} / \partial y$ between Pt stripe’s ends. Frequency dependencies of $U_{ISHE}(f)$ and $|S_{11}(f)|$ were simultaneously measured at a fixed magnetic field, varied in the range $H_s \leq |H| \leq 1 \text{ kOe}$.

Figure 1(d) displays the resonance frequencies’ rearrangement due to linear ADSW excitation under magnetoelastic resonance (MER) at the field $H_{MER} \approx 520 - 525 \text{ Oe}$. Similar to our previous works (see Refs. 27–30), a voltage $U_{ISHE}(f, H)$ from the excitation of linear ADSW was also observed in the vicinity of $H_{MER}$ that will be discussed later.

FIG. 2. 3D dependence of $U_{ISHE}(f, H)$ at the applied power $P = 9 \text{ mW}$.

While the magnetic field increases above the range shown in Fig. 1(d), the frequency spectrum does not experience a noticeable effect, and there is no dc voltage signal. When the field decreases below the range, the spectrum also remains almost unchanged, but the voltage signal $U_{ISHE}(f, H)$ is clearly detected, as shown in Fig. 2. The maxima of $U_{ISHE}(f, H)$ correlate with the positions of the HBAR resonance frequencies $f_n$ and $f_{n-1}$, indicated by arrows. Note, when the field direction is reversed, the voltage changes the sign, which is typical for the ISHE symmetry. Narrow region of magnetic fields $|H| \sim 2-3 \text{ Oe} < H_s$, where the voltage changes the sign during magnetization reversal, is of undoubted interest, but outside of the scope of this research and will be discussed in the further work.

Let us consider in details the magnetic field dependence of the voltage at a fixed frequency in an infinite medium $f_0 = f_n$ in comparison with the dependencies of the characteristic SW frequencies $f_{SW}(q, H) = \gamma / (H_{eff}(q)(H_{eff}(q) + 4\pi M_s \sin^2 \theta)) =
\[ \sqrt{f_H(q)} \times (f_H(q) + f_M \sin^2 \theta). \]

Here, \( \gamma = 2.8 \) MHz/Oe, \( H_{\text{eff}}(q, H) = H + 4\pi M_s(\lambda q)^2, \lambda \sim 10^{-6} \) cm is the exchange length, and \( \theta \) is the angle between the wave vector \( q \) and \( H \).

In the field region \( H < H_c \), the spectrum of parametric SW is a set of the backward volume SW, propagating in-plane at angles \( 90^\circ > \theta > 0 \).

The results are fitted by the expression for the critical energy \( f = f_H(0) + f_M/2 \) for dipole (non-exchange) surface SW in the plate.

The solid arrow marks the critical field \( H_c \) for the parametric instability. According to the previous consideration (Fig. 3(b)), the parametric process is possible with the creation of SW at a frequency \( f_H/2 \) and with \( q = k = 0 \) as it can be seen, the local minima of the threshold power \( P_{\text{th}}(H) \) is also located in this region.

The data are fitted by the expression for the critical energy \( f = f_H(0) + f_M/2 \) for dipole (non-exchange) surface SW in the plate.

The experiments described above were conducted at a fixed power level of 9 mW. Next, we study the voltage dependence \( U_{\text{ISHE}}(P) \) at lower power levels up to 3 mW. Figure 4(a) shows the \( U_{\text{ISHE}}(P) \) for three values of the magnetic field \( H > H_c \).

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U and ISHE in Pt. The dependence of the voltage on the AD SW were detected using the spin pumping from YIG to waves – AD SW – was observed in the resonator of bulk preceding, we conclude that the voltage observed results in the consistent with the experiment (see Fig. 4). Thus, based on the ∆ we found ∆ behavior is precisely at H.

Here C = 0.5πα2C0V0(MαΔHq/B2)2 ≈ 20...160 μW. Here C0 = 7.64 × 1011 dyne/cm2 and V0 = 3.85 × 105 cm/s are the elastic modulus and velocity for shear AD SW, respectively; B2 = (5...7) × 106 erg/cm3 is the magnetoelastic constant, ΔHq = 0.25...0.5 Oe. The relationship of this power with the power applied to the electrodes can be found from P5 = PthΔS11[2], where ΔS11[2] is the value of the dip |S11(Δ)|2 in the vicinity of the resonant frequency fn[41]. From Fig. 1(c), we found ΔS11[2] ≈ 0.2; hence Pth = 0.1...0.8 mW, which is consistent with the experiment (see Fig. 1). Thus, based on the preceding, we conclude that the voltage observed results in the detection of parametric AD SW with the SP/ISHE method.

In summary, the acoustic generation of parametric spin waves – AD SW – was observed in the resonator of bulk AW containing YIG/GGG/YIG/Pt structure. Parametric AD SW were detected using the spin pumping from YIG to Pt and ISHE in Pt. The dependence of the voltage on the pump power shows that the minimum thresholds are quite small, which is due to the excitation efficiency of the high-Q hybrid HBAR by the PE transducer strictly at the resonant frequencies. It should be noted the Q-factor of our resonator at 2.4 GHz was Q ≈ 4 × 104, that is far from the possible values (Q > 105) which can be obtained in HBAR at this frequency. Thus increasing Q-factor and excitation frequency as well as decreasing the ferromagnetic film thickness makes it possible to excite magnons with wavenumbers exceeding q ≈ 105 cm⁻¹ reported in this work.

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The authors declare no conflicts of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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FIG. 4. (a) The dependences U ISHE (P) at different magnetic fields. The symbols – experiment results, the lines – the fitting with the relation U ISHE ∝ (P − Pth(H))²/3. (b) Color-density plot represents U ISHE (H, P) measured at f0 = fn = 2.412 GHz. White circles show Pth (H).

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