Probing of a parametrically pumped magnon gas with a non-resonant packet of traveling spin waves

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The magnon gas created by spatially localized longitudinal parametric pumping in an yttrium-iron-garnet film is probed by a traveling packet of spin waves non-resonant with the pumping field. The analysis of the influence of the magnon gas on the amplitude and phase of the propagating spin waves allows to determine characteristic properties of the parametrically pumped magnon gas. A simple theoretical model is proposed from which the magnon density in the pumping region is calculated.

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Parallel parametric pumping of spin waves is a widely used and established technique to control the magnon density in different areas of the spin-wave spectrum. It is used both in experiments on fundamental properties of magnetic excitations and for the amplification and processing of microwave signals [1]. It has been used to realize spin-wave wavefront reversal [2,3], to amplify spin-wave solitons and bullets [4], to generate Möbius solitons [5] as well as to create Bose-Einstein condensates of magnons at room temperature [6]. The long-time storage and recovery of microwave pulses [7], the microwave spectral analysis [8], and the shaping of microwave pulses [9] has been achieved with this technique.

Parametric pumping amplifies many different spin-wave groups simultaneously. In the process the density of spin waves is increased initially at half the pumping frequency $f_p/2$. These amplified spin waves form an overheated region of the magnon gas which then thermalizes spreading its energy over the whole spin-wave spectrum [10]. For long enough pumping a quasi-stationary magnon gas state obeying a Bose-Einstein distribution with a concentration of magnons near the bottom of the spin-wave spectrum is created.

Due to the high overall density of the magnon gas spatially localized in the pumping area the static magnetization there is decreased and a magnetic inhomogeneity is formed. From this magnon barrier [8] propagating spin waves can scatter similar to the scattering of spin waves on a dc-current induced local magnetic inhomogeneity [11,12]. Also, direct scattering of traveling spin waves on the parametrically excited magnons can occur [13]. As a consequence, the experiments performed so far on the interaction of the traveling spin waves with parametric pumping had to take into account two competing effects: while the pumping field tends to increase the spin-wave amplitude the magnon barrier decreases it via scattering.

In the current paper, we separate these effects by using non-resonant spin-wave pulses with a frequency $f_s \neq f_p/2$. We study the effects of the magnon barrier on the amplitude of a traveling spin-wave independent of any amplification caused by direct interaction with the applied external pumping field.

The magnon barrier also influences the spin-wave phase by introducing an additional phase shift. It is known, that this phase shift is of crucial importance for the amplification by non-adiabatic localized parametric pumping [5,9]. Our measurements have shown that this additionally accumulated phase is more sensitive to the barrier characteristics than the amplitude at intermediate to high pumping powers. Since these regimes are interesting both for practice and fundamental studies (e.g. for the generation of Bose-Einstein condensates), a major part of the current paper is devoted to the investigation of the spin-wave phase.

By measuring the pure scattering of the spin-wave amplitude on the magnon barrier as well as the phase accumulation of the spin wave upon propagating through the pumping region physically relevant characteristic properties of the magnon barrier can be obtained. We illustrate the potential of probing a parametrically generated magnon gas with non-resonant propagating spin-wave packets by estimating the magnon density in the pumping area based on a simple model.
The traveling spin-wave packet is slightly below amplified. Simultaneously, the carrier frequency of makes sure that, first, the pumping threshold is low \[17\]

We note three things: First of all, no signal amplifying powers are shown in the left panel of Fig. 3(a). observation in order to reconstruct its phase \[14\].

The measured pulse shapes for different applied pumping powers are shown in the left panel of Fig. 8(a).

The signal received at the output antenna can interfere with a phase-locked reference signal before detection and observation in order to reconstruct its phase \[14\].

The transmission characteristics presented in Fig. 2(b) show that the frequency of the pumping pulse is above the frequency of ferromagnetic resonance \(f_{\text{FMR}}\) which makes sure that, first, the pumping threshold is low \[17\] and, second, no propagating backward volume spin waves are amplified. Simultaneously, the carrier frequency of the traveling spin-wave packet is slightly below \(f_{\text{FMR}}\), which guarantees its good excitation and detection via the microstrip antennas.

switched on, but takes up to 2 \(\mu s\) to reach a stationary regime.

The observed suppression is understood as the result of scattering of the magnon barrier. With increasing pumping power, the scattering increases together with the magnon barrier. As the magnon barrier is created in the process of the thermalization of magnons excited at half the pumping frequency a relatively slow passage into the stationary regime is expected.

The left panel of Fig. 3(b) shows the measured phase profiles of the output pulse relative to the reference pulse. As for the transmitted intensity, the accumulated phase slowly develops towards a stationary value. This stationary phase depends monotonically on the applied pumping power. However, if we compare the corresponding curves we note that the phase does not seem to saturate even at high powers.

A straightforward model describes the observed phase of the propagating spin-wave in the stationary regime.

In the process of pumping the magnon density in the area around the pumping resonator is increased. This leads to a small reduction \(\delta M\) of the magnetization \(M\) from its initial value \(M_s = 139\) G. This changes the wave vector of the propagating spin wave. The difference between the undisturbed and disturbed wave vector integrated over the distance the spin wave propagates through the pumping region gives the accumulated phase observed in the experiment.

Assume for simplicity that the parametrically generated magnons are homogeneously distributed in a region of length \(l\) around the central pumping resonator. Only in this region the magnetization is reduced and a phase \(\phi\) is accumulated. As a consequence

\[
\phi = \int \left( k(M_s) - k(M) \right) dx = \left( k(M_s) - k(M) \right) \cdot l. \tag{1}
\]
We linearize the dependence of the wave vector on the magnetization of the sample \( k(M) = k(M_0) + c_1 \cdot \delta M \) where the constant \( c_1 = 18.3 \text{ cm}^{-1} \text{G}^{-1} \) can be calculated from the dispersion law and the experimental conditions. Every single parametrically generated magnon decreases the magnetization by one Bohr magneton \( \mu_B \). As a result, if \( N \) denotes the number of magnons created by the pumping source and \( V = l \cdot w \cdot d \) is the volume of the pumping region:

\[
\phi = c_1 \cdot \mu_B \cdot l \cdot \frac{N}{V} = c_1 \cdot \mu_B \cdot \frac{w}{l} \cdot \frac{N}{d}.
\] (2)

The fact, that a stationary amplitude is observed, shows, that the magnon density does not grow infinitely. It is limited by several mechanisms, primarily the phase mechanism [13], which reduces the effective coupling of the pumping field with the parametric magnons.

According to [13], the stationary magnon number for a given wave vector taking into account is given by

\[
N = \frac{1}{S} \sqrt{(h_p V \text{coupl})^2 - \omega_f^2}.
\] (3)

where \( S = (\omega_M/\omega_p)^2 \left( \sqrt{\omega_p^2 + \omega_M^2} - \omega_M \right) / 4, \omega_p = 4\pi f_p, \omega_M = \gamma 4\pi M_s, h_p \) is the pumping magnetic field in the direction of the bias magnetic field, \( V \text{coupl} \) is the coupling coefficient, \( \omega_f \) is the relaxation frequency and \( \gamma \) is the gyromagnetic ratio. Since \( h_p \sim \sqrt{P} \) we get as final result

\[
\phi = \frac{c_1 \cdot \mu_B \cdot l}{V \cdot S} \sqrt{c_2 P - \omega_f^2} \approx \frac{c_1 \cdot \mu_B \cdot l}{V \cdot S} \sqrt{c_2 P}
\] (4)

with \( c_2 \) a constant depending on the geometrical properties of the resonator and the coupling of the spin waves to the external pumping field. The last approximation is justified for pumping powers not too close to the pumping threshold which as it is the case in our experiments.

As Fig. 3(b) shows, the presented model with the single free parameter \( c_2 \) fits the experimental data well.

From the experimentally observed accumulated phase we can calculate

\[
N = 5.5 \cdot 10^{13} \cdot \phi, \quad \frac{N}{V} = 2.3 \cdot 10^{19} \text{ cm}^{-3} \cdot \phi
\]

where we have estimated \( l = 0.2 \text{ mm} \) to obtain the density of parametrically pumped magnons. We note, that the later value agrees well with expected values for the magnon density of \( 10^{18} - 10^{19} \text{ cm}^{-3} \).

In conclusion, we have measured the transmission and phase accumulation of non-resonant spin waves propagating through a parametrically generated magnon barrier. From the accumulated phase the absolute number of magnons constituting the barrier was deduced and the total magnon density was estimated.

Overall, the method of probing the total density of a parametrically controlled magnon gas by the phase of a non-resonant traveling spin wave possesses great potential due to its time-resolution and high sensitivity. It is applicable to thin magnetic materials, e.g. thin magnetic films, where techniques based on other physical effects fail.

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