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CONDENSED MATTER

Inverse "Foldover" Resonance in an Yttrium Iron Garnet Film

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Nonlinear magnetic resonance is studied in an in-plane magnetized yttrium iron garnet (YIG) film. For YIG films magnetized perpendicular to the plane, the effect referred to as the foldover resonance is well known. It arises because the precession frequency increases with the deviation of the magnetization. When the field is reduced, the frequency of the precession remains resonant because the demagnetizing field decreases with the deviation of the magnetization. The signal disappears when the radio frequency pump power is insufficient to maintain a nonequilibrium state of the system. In the in-plane magnetized yttrium iron garnet film, the precession frequency decreases with an increase in the pump amplitude. Accordingly, the foldover effect arises under an increase in the field. The fundamental difference is that the precession in the latter case should be unstable with respect to the decay into spin wave modes. The deviation angles of magnetization of about 10° are reached, and the rate of decay of the uniform precession into spin waves, which depends on the deviation angle of the magnetization, is measured. This study opens up another way of achieving the magnon density corresponding to the formation of its Bose–Einstein condensate.

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Here, we report the results of experiments in an in-plane magnetized yttrium iron garnet (YIG) film, where the inverse "foldover" magnetic resonance was observed. The frequency of magnetic resonance in this case is well known and can be written as

$$\omega = \gamma\sqrt{H(H + 4\pi M_S \cos\beta)}, \tag{1}$$

where H is the applied magnetic field, $4\pi M_S$ is the demagnetizing field, γ is the gyromagnetic ratio, and β is the deviation angle of the precessing magnetization. With an increase in the angle β, the precession frequency decreases. In terms of quasiparticles, this means that the frequency decreases with an increase in the magnon density because of the attractive interaction between magnons. The properties of nonlinear magnetic resonance in YIG films with perpendicular magnetization were previously studied. Under such conditions, the magnetic resonance frequency is

$$\omega = \gamma(H - 4\pi M_S \cos\beta). \tag{2}$$

Accordingly, the precession frequency increases with the angle β, and magnons are characterized by a repulsive potential. This dynamic state of magnetization is stable and does not decay into spin waves [1].

Under these conditions, the precession frequency of the magnetization with decreasing magnetic field can remain equal to the pump frequency. In this case, the reduction of the applied magnetic field is compensated by a decrease in the demagnetizing field caused by the deviation of the precessing magnetization. This nonequilibrium state is accompanied by the relaxation of magnons to phonons, which is quadratic in the angle of deviation β. As soon as the radio frequency (RF) pump power becomes insufficient to maintain the nonequilibrium state, the resonance signal disappears. This effect was called the foldover magnetic resonance and was qualitatively explained in [2]. The theory developed in [2] describes well the results of experiments with microscopic samples [3], which can be considered as individual single oscillators. This effect was also studied in detail for YIG films with perpendicular magnetization. The experimental results agree well with the theory at relatively small angles β [4]. However, a more careful analysis of these results indicates that they are inconsistent with the theoretical description at large deviation angles of the magnetization.

The studies of magnetization precession in the limit of large deviations, i.e., at high magnon densities, are of particular interest. These studies were performed to analyze the formation of a magnon Bose–Einstein condensate. Since magnons are bosonic quasiparticles, they must form the magnon Bose–Einstein condensate at a given temperature and a sufficient density. The critical density of magnons needed to form the magnon Bose–Einstein condensate in a YIG film with the perpendicular magnetization at room temperature was estimated in [5] and corresponds to the deviation angle of the precessing magnetization of about 3°. In other directions of the magnetic field, the critical angle for the formation of the magnon Bose–Einstein condensate is in the range from 2° to 4°.

The results of experimental studies of the magnetic resonance in the YIG film with perpendicular magnetization at high pump amplitudes were reported in [6]. They demonstrate that the theory developed in [2], in which the resonance state is determined by the RF pump amplitude, is applicable at relatively small deviation angles of the magnetization. On the contrary, the state of the magnon system at the deviation angles of the magnetization exceeding 3° is determined by the pump frequency, provided that the pump power is sufficient to maintain an excited state. This property is inherent in magnon Bose–Einstein condensation, as previously shown in experiments with antiferromagnetic superfluid ^{3}He [7–9]. This result is explained by the formation of the magnon Bose–Einstein condensate at fairly large angles of deviation, the state of which is determined by the chemical potential of the bound magnon–photon system, i.e., by the pump frequency rather than by the pump power.

The analogy between magnon Bose–Einstein condensation in antiferromagnetic ^{3}He and in YIG films was theoretically demonstrated in [10], where an in-plane magnetized quasi-two-dimensional thin film was considered. For a thick film (thicker than 1 μm) with perpendicular magnetization, the analogy becomes clearer, since the interaction between magnons in this case is repulsive, as in ^{3}He-B. Therefore, it is not surprising that magnons at a high density have properties similar to those of antiferromagnetic ^{3}He.

However, the problem of Bose–Einstein condensation in systems with the attraction between quasiparticles is of great interest. In this case, the frequency of magnetic resonance decreases with an increase in the magnon density, and the coherent state becomes unstable. Earlier, the magnon systems with attraction in antiferromagnetic ^{3}He-A were studied in [11, 12], where it was demonstrated that the uniform precession was unstable after the RF pump was switched off. However, it should be taken into account that the coherence of the precession under resonant excitation is supported by the RF pump. We compared the absorbed energy in the same film in the cases of in-plane and out-of-plane magnetizations at high resonant pump amplitudes.

These studies were performed with an X-range Varian E-12 EPR spectrometer. The usage of the EPR spectrometer has certain advantages over the strip-line technique employed in [4]. First, the excitation of resonance is spatially uniform over the sample. Second, studies are performed at a fixed frequency, which eliminates the effects of the matching of the RF line. The experiments were performed using a 6-μm-thick disk YIG film 0.3 mm in diameter at a frequency of 9.26 GHz and room temperature.

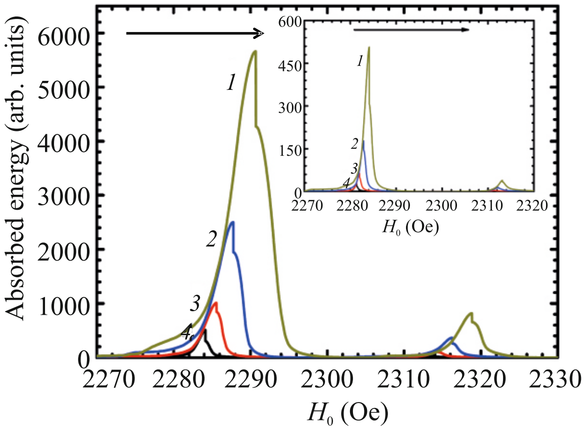

Fig. 1. (Color online) Absorbed energy at the in-plane magnetization of the film at RF pump powers of (*1*) 100.0, (*2*) 30.0, (*3*) 10.0, and (*4*) 3.0 mW and in the inset at RF pump powers of (*1*) 3.0, (*2*) 1.0, (*3*) 0.3, and (*4*) 0.1 mW. Signals corresponding to the second ferromagnetic resonance mode in a higher field are clearly seen.

As in [6], we characterize the signal just by the absorbed energy, which is the absorption signal intensity multiplied by the root of the pump power. In Fig. 1, we plot this parameter as a function of the applied magnetic field directed along the film at different RF pump powers.

It is clearly seen that the absorbed energy is determined by the deviation of the field from its resonance value and is independent of the pump power. Thus, we have the same situation as in the formation of the magnon Bose–Einstein condensate in the case of perpendicular magnetization. For comparison, in Fig. 2, we show the experimental results obtained using the same sample and with the same pump powers, but with the magnetization perpendicular to the sample.

The absorbed energy signal in the case of the perpendicular magnetization vanishes completely when the maximum field deviation is achieved, whereas rearrangement to some new mode occurs in the case of the in-plane magnetization. In the current optical measurements, we find out that this mode corresponds to a spatially inhomogeneous state, the details of which will be reported later. However, the collapse of a homogeneous state is clearly seen. In Fig. 3, we show the field deviations at which the pump energy is insufficient to maintain the magnon Bose–Einstein condensate and, correspondingly, the homogeneous state decays at both in-plane and out-of-plane magnetizations of the film. The results are shown for two samples of the same diameter.

The field naturally deviates in different directions for the in-plane and out-of-plane magnetizations. However, let us express these shifts in terms of the

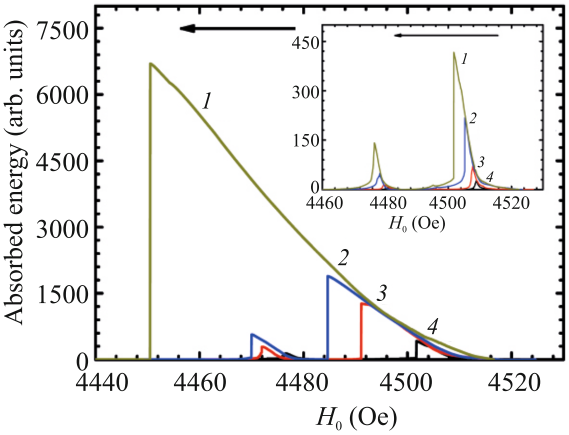

Fig. 2. (Color online) Absorbed energy at the out-of-plane magnetization of the film at pump powers of (*1*) 100.0, (*2*) 30.0, (*3*) 10.0, and (*4*) 3.0 mW and in the inset at pump powers of (*1*) 3.0, (*2*) 1.0, (*3*) 0.3, and (*4*) 0.1 mW. Signals corresponding to the second FMR mode are clearly seen at lower field values.

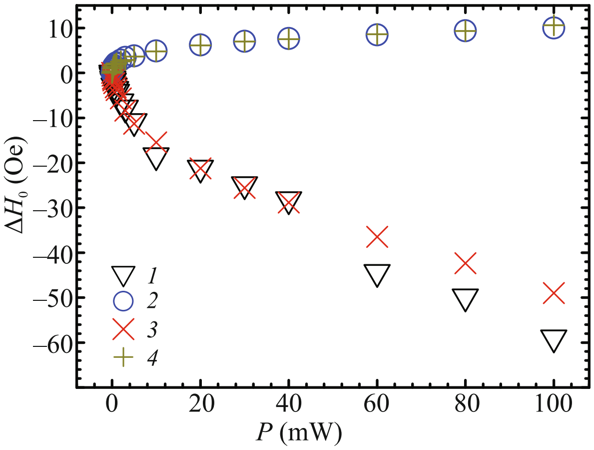

Fig. 3. (Color online) Magnetic field shift at the decay of the uniform precession at different RF pump powers for the (*1*, *3*) out-of-plane and (*2*, *4*) in-plane magnetizations in the (*1*, *2*) first and (*3*, *4*) second sample of the same size versus the RF pump power.

deviation of the magnetization according to Eqs. (1) and (2). The critical angles of the decay of the uniform precession at various pump powers are shown in Fig. 4.

According to Fig. 4, the critical angles of the decay of the uniform precession at different directions of the magnetization are quite close at relatively small angles of deviation. The difference occurs at angles exceeding 7°. To maintain the uniform precession in the out-of-plane magnetized film, an increase in the RF pump power corresponding to the quadratic dependence of the relaxation of magnons on the angle of deviation is necessary. This dependence corresponds to the relaxation of magnons into phonons. In the case of the in-plane magnetization, the necessary pump power increases sharply. So, at $\beta = 11°$, an additional pump power of 50 mW is required to compensate the additional relaxation of magnons with $k = 0$. Thus, an additional rapidly growing relaxation channel arises stepwise at an angle of deviation exceeding 7°.

The state with $k = 0$ in the case of the out-of-plane magnetization corresponds to the energy minimum, whereas in the case of the in-plane magnetization, the frequency increases for magnons with $\mathbf{k}$ directed across the magnetic field and decreases for magnons with $\mathbf{k}$ directed along the field [1]. There is a saddle point in energy; i.e., magnons have anisotropic mass. The mass is positive and negative for magnons moving across and along the magnetic field, respectively. Therefore, a channel for the decay of magnons into spin waves with $\mathbf{k}$ directed along the field, which have a lower energy, arises for the in-plane magnetization. According to our experimental results, this process has a threshold at an angle of deviation of 7°. A similar process of thermalization of magnons to a state with the minimum energy is also observed in the case of longitudinal parametric excitation of magnons [13].

Thus, we have experimentally obtained the coherent state of magnons in an in-plane magnetized YIG film under conditions of magnon attraction. This state is stable under the permanent excitation of magnons by the RF field. In this case, the existence of a global energy minimum for magnons with nonzero k leads to an additional relaxation process. Further study of this state by optical methods using the setup described in [14] is of great interest, in particular, because YIG films along with superfluid ^{3}He [15] have properties characteristic of topological matter. This

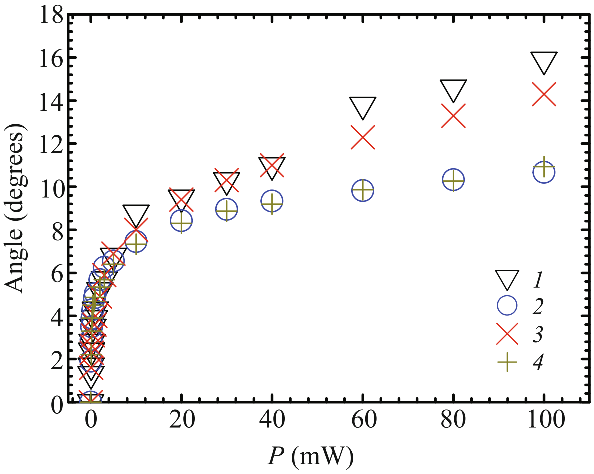

Fig. 4. (Color online) Deflection angle of the precessing magnetization at the decay of the uniform precession for the (*1*, *3*) out-of-plane and (*2*, *4*) in-plane magnetizations in the (*1*, *2*) first and (*3*, *4*) second sample of the same size versus the RF pump power.

suggests the formation of a magnon Berry phase [16, 17]. Possibly, the observation of a long-lived induction signal in a YIG film [18] is just due to the formation of such a magnon gas phase at the sample boundary. Another important line of further research is the study of the formation of a coherent magnon–phonon state, which was mentioned in [19]. The studies of magnon Bose–Einstein condensation in YIG films are also very interesting [20]. In this case, different types of Bose–Einstein condensation of magnons should be taken into account [21]. In conclusion, using the magnon Bose–Einstein condensate, it is possible to construct a quantum qubit operating at room temperatures, as proposed in [22]. Possible practical implementations of such a qubit were considered in [23].

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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