Observation of coupled photon-phonon oscillations with parametric excitation of magnetoelastic waves in an antiferromagnet

A. V. Andrienko and V. L. Safonov

Institute of Molecular Physics, Russian Scientific Center "Kurchatov Institute," 123182 Moscow, Russia

(Submitted 20 April, 1995; accepted for publication 21 June 1995)
Pis'ma Zh. Éksp. Teor. Fiz. **62**, No. 2, 147–151 (25 July 1995)

The spectrum of coupled oscillations of electromagnetic and magnetoelastic waves in the nonlinear system of the antiferromagnetic $FeBO_3$ antiferromagnet, excited by a microwave field in a cavity, was investigated. © *1995 American Institute of Physics.*

Formulation of the problem

Information about the nonlinear wave system of magnetic materials is obtained mainly from studies of the paramagnetic resonance of spin and magnetoelastic waves (magnons and phonons) in a microwave magnetic field. All measurements are usually performed using a microwave cavity into which the experimental sample is inserted (see, for example, Refs. 1–4). In an analysis of the results, however, the dynamics of the forced electromagnetic oscillations of the cavity was ignored: In the established theory[5,6] a sample in a classical external microwave magnetic field is studied.

In a recent study[3] of the electromagnetic radiation from an excited phonon system we determined that the dynamics of the characteristic cavity oscillations plays an exceedingly important role in the formation of the nonequilibrium state of the experimental system. This observation is highly nontrivial, since it is ordinarily assumed that the cavity does not influence the state of the experimental system but only increases the amplitude of the microwave magnetic field and makes the experimental object more sensitive to the absorption of microwave power. The necessity for taking into account the dynamics of the characteristic cavity oscillations was pointed out in Ref. 7 . The calculation performed in Ref. 8 showed that the nonlinear coupling of parametrically excited waves with the cavity photons leads to a positive nonlinear damping. The effect of the cavity Q on transthreshold state of magnons in the ferrite YIG was observed experimentally in Ref. 9 according to the change in the threshold for self-excited oscillations.

Analysis of the theoretical model which we proposed in Ref. 3 shows that the cavity–sample system must be treated as a system of two coupled oscillators. The first oscillator is the cavity with the characteristic frequency ω_R and is linearly excited by the external "force" $F\exp(-i\omega_p t)$, where ω_p is the frequency of the pump field. The second oscillator is the forced resonance oscillation of the nonlinear medium, which is excited from the first oscillator and is described by a pair of waves whose frequencies are $\omega_p/2$ and whose wave vectors are equal in magnitude but oppositely directed. Below the threshold of paramagnetic resonance, the coupling with the second oscillator is zero, and in the transthreshold region the coupling between the oscillators depends on the amplitude of the parametrically excited waves. It is obvious that such a system is naturally described in terms of normal modes in which the components of the initial uncoupled oscillations are present. In the present case this is an electromagnetic wave in the cavity and a pair of magnetoelastic waves in the sample. The present work is devoted to the experimental study of the spectra of the coupled photon-phonon oscillations that arise.

Experimental procedure

The experimental antiferromagnetic $FeBO_3$ was placed in a 0.5-cm-diameter spiral cavity with a characteristic frequency $\omega_R \simeq 2\pi \cdot 800$ MHz. The cavity was made from a segment of a copper wire. Using a $\simeq 0.02\text{-cm}^3$ single crystal, we obtained a large filling factor for the sample in the cavity ($\simeq 5\%$); this increased the efficiency of the photon-phonon coupling.

Signals from microwave oscillators were fed into the cavity by two antennas and were received by a third antenna. The coupling with all external microwave circuits was weak so as to decrease their effect on the cavity. The signal from a powerful microwave oscillator for parametric excitation of phonons in the sample was fed through the first antenna. The signal from the probe microwave oscillator, which did not excite paramagnetic resonance (the response to this signal was always linear), was fed from the second antenna; this signal was used to investigate the spectrum of the coupled photon-phonon oscillations in the cavity–sample system. The signal from the receiving antenna was fed into a spectrum analyzer and the receiver.

The measurements were performed at temperatures $T = 77$ K and 293 K in external magnetic fields $H =$ 30–500 Oe. The static and microwave magnetic fields were parallel to one another and they lay in the easy-magnetization plane of the crystal. To avoid overheating the sample, the microwave pumping was performed in the pulsed mode. The pulse length was 300–1500 μs and the repetition frequency was 50 Hz. The threshold of paramagnetic resonance of magnetoelastic waves was recorded according to the characteristic drop that appears in the microwave pulse transmitted through the cavity.

Results and discussion

Figure 1a shows the line shape of a cavity with the sample in the case where the input microwave pump power is zero ($P = 0$). As the pump oscillator power increases to the threshold value P_c, this spectrum of the response of the system to the action of a microwave probe signal remains constant. Above the threshold power ($P > P_c$), the resonance peak, as expected, splits, exhibiting repulsion of the spectra of the normal modes in the system of coupled oscillators. The typical shape of the spectrum of coupled photon-phonon oscillations is shown in Fig. 1, b and c, for the case in which the pump frequency ω_p is equal to the characteristic frequency ω_R of the cavity. Measurements of the response of the system in the frequency range $|\omega - \omega_R| \leqslant 2\pi \cdot 0.2$ MHz are difficult to perform because of the presence of the powerful microwave pump signal.

We see from Fig. 1, b and c, that the frequency of one mode of coupled photon-phonon oscillations is lower, and that of the other mode is higher than the pump frequency. As a result, the external microwave pump is not in resonance with the new

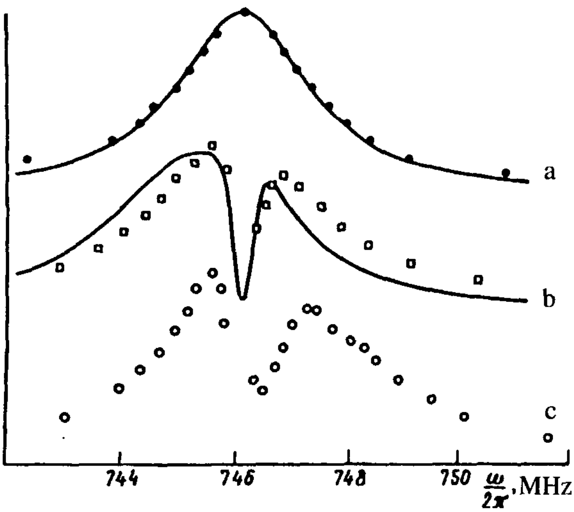

FIG. 1. Spectrum of the signal transmitted through the cavity. a — Below the threshold for parametric excitation of phonons (the solid line is a Lorentzian with $\omega_R = 2\pi \cdot 746.1$ MHz and $Q = 270$); b, c — beyond the threshold of parametric excitation of phonons ($\omega_P = \omega_R$). b: $P/P_c = 5.1$ (the solid line corresponds to the theory — see text); c: $P/P_c = 29.7$, $H = 144$ Oe, and $T = 77$ K.

normal modes; this limits the amplitude of the microwave field in the cavity. As the pump power increases further, the splitting between the peaks increases (see Fig. 2). This is naturally explained by an increase in the coupling constant between the photon and phonon subsystems with increasing P/P_c. Since the shift of the cavity frequency leads to a change in the input coupling constant, the indicated values of P/P_c characterize the microwave pump power at the cavity entrance.

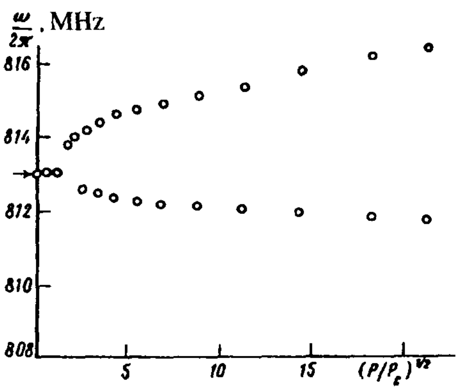

FIG. 2. Frequency of normal oscillations in the photon-phonon system as a function of the amplitude of the microwave pump; $\omega_P = \omega_R$ (marked by the arrow), $T = 77$ K, $H = 143$ Oe.

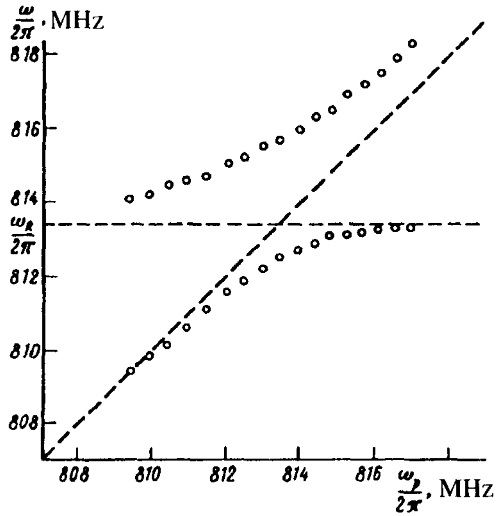

FIG. 3. Frequency of normal photon-phonon oscillations versus the microwave pump freqeucny with constant pump power; $\omega_R = 2\pi \cdot 813.4$ MHz, $T = 77$ K, $H = 144$ Oe, $P/P_c = 125$.

Figure 3 shows the repulsion of the frequencies of the normal oscillations with a fixed pump amplitude as a function of the pump frequency. We note that in the entire frequency range presented, the pump power is always higher than the threshold power. It is obvious from Fig. 3 that if the frequency of the exciting microwave field is far from the characteristic frequency of the cavity, then the deviations of the frequencies of the normal oscillations of the system from the frequencies of the "pure" modes are small: In practice, the frequency of one mode is equal to the pump frequency and the frequency of the other mode is equal to the cavity frequency. As the frequencies ω_p and ω_R converge, however, increasingly stronger repulsion of the branches of the mixed photon-phonon oscillations is observed, i.e. the typical picture of the spectra of coupled oscillations near the crossing point of their frequencies is observed.

Let us consider the experimental results from the standpoint of the theoretical model which was proposed in Ref. 3 and which extends the S-theory of Ref. 5 to the case of the excitation of waves in the sample in the cavity. The equations of motion of the coupled cavity–sample system have the form

$$i\left(\frac{d}{dt}+\Gamma\right)\tilde{R} = -(\omega_p - \tilde{\omega}_R)\tilde{R} - \frac{1}{2}GN_k \exp(i\theta_k) + F + F_1 \exp[i(\omega_p - \omega)t],$$

$$\frac{d}{dt}\theta_k - G[\tilde{R}\exp(-i\theta_k) + \text{c.c.}] = \omega_p - 2\tilde{\omega}_k - 2SN_k, \qquad (1)$$

$$\frac{d}{dt}N_k + 2\gamma_k N_k = iN_k G[\tilde{R}\exp(-i\theta_k) - \text{c.c.}].$$

Here $\tilde{\omega}_R \equiv \omega_R + T^{(R)} N_k + \Phi_R |\tilde{R}|^2$ and $\tilde{\omega}_k \equiv \omega_k + 2TN_k + T^{(R)} |\tilde{R}|^2$ are the renormalized frequencies of the photons in the cavity and the parametrically excited phonons and Γ and γ_k are their relaxation rates, respectively; N_k is the number of excited phonons; and θ_k is the phase between the forced magnetoelastic oscillations and the pump field. In addition, G is the amplitude of the decay of a photon into a pair of phonons (and emission of a photon by a pair of phonons); the coefficients S and T are responsible for the nonlinear phonon-phonon interactions and $T^{(R)}$ and Φ_R are responsible for the effective photon-phonon and photon-photon interactions. These parameters are calculated from the Hamiltonian of the system in order of magnitude, for example, $G \sim i(2\pi\hbar\omega_p/v_R)^{1/2} \partial\omega_k/\partial H$ and $T^{(R)} \sim G^2/\Gamma$; v_R is the volume of the cavity.

The response of the excited system (1) to the probe microwave field $F_1 \exp(-i\omega t)$ is determined by linearizing the equations with respect to the complex amplitudes $\tilde{R}$, $\tilde{R}^*$ of the electromagnetic field in the cavity and the parameters N_k and θ_k of the excited magnetoelastic waves near the stationary state. The solid line in Fig. 1b represents the theoretical curve, calculated using the experimental value $\gamma_k = 2\pi \cdot 0.2$ MHz and the following parameter values: $G^2/2\Gamma|T| = 6$, $h/h_c \equiv GF/\Gamma\gamma_k = 1.6$, $S = T < 0$, $T^{(R)}/T = 50$, and $\Phi_R \simeq 0$. Qualitative agreement between theory and experiment remains even with higher microwave pump power, but the approximation used ceases to be valid as the energy flux through the excited system increases.

A method similar to the one employed in our experiment was used in Ref. 4 , where the "weak-signal absorption spectrum" similar to that shown in Fig. 1b was observed, to study the parametric resonance of spin waves in the ferromagnetic YIG. The interpretation presented in Ref. 4 failed to take into account the possibility for the existence of coupled oscillations and reduced to the following assertion: "... immediately beyond the threshold, a relatively narrow absorption peak appears on the crest of the resonance curve, increases with increasing pump power, and shifts toward higher frequencies." This decrease of the transmitted signal was attributed to the degradation of the cavity Q as a result of the absorption of the microwave field by magnons and was used to calculate the nonlinear magnetic susceptibility of the sample. This interpretation is based on the assumption of weak coupling in the cavity–sample system, when the standard procedure for determining the electromagnetic fields in a cavity with a small sample is applicable (see, for example, Ref. 10). We assume that taking into account the coupled photon-magnon oscillations in the cavity–sample system will make it possible to refine the interpretation of the experimental results of Ref. 4 . However, an additional investigation toward this end is required.

In summary, our results show that in analyzing the experiments on the parametric excitation of phonons, it is necessary to take into account the possibility for the appearance of coupled oscillations in the cavity–sample system. Since the specific nature of the phonons in this case does not play a fundamental role, this result can also be extended to other investigations of the resonance properties of materials.

We thank A. S. Borovik-Romanov, L. A. Prozorov, and A. I. Smirnov for helpful discussions of the results. This work was supported by the Russian Fund for Fundamental Research (project 95-02-03960) and the International Science Foundation (grant N94000).

[1] A. V. Andrienko and L. V. Podd'yakov, Zh. Éksp. Teor. Fiz. **95**, 2117 (1989) [Sov. Phys. JETP **68**, 1224 (1989)].
[2] A. V. Andrienko and L. V. Podd'yakov, Zh. Éksp. Teor. Fiz. **99**, 313 (1991) [Sov. Phys. JETP **72**, 176 (1991)].
[3] A. V. Andrienko and V. L. Safonov, JETP Lett. **60**, 800 (1994).
[4] V. V. Zautkin, V. S. L'vov, and S. S. Starobinets, Zh. Éksp. Teor. Fiz. **63**, 182 (1972) [Sov. Phys. JETP **36**, 96 (1973)].
[5] V. E. Zakharov, V. S. L'vov, and S. S. Starobinets, Usp. Fiz. Nauk **114**, 609 (1974) [Sov. Phys. Usp. **17**, 896 (1975)].
[6] V. S. L'vov, *Nonlinear Spin Waves* [in Russian], Nauka, Moscow, 1987.
[7] P. H. Bryant, C. D. Jeffries, and K. Nakamura, Phys. Rev. A **38**, 4223 (1988).
[8] V. L. Safonov, J. Magn. Magn. Mater. **97**, L1 (1991).
[9] H. Yamazaki, Y. Yunoki, M. Mino *et al.*, J. Magn. Magn. Mater. **104–107**, 1059 (1992).
[10] A. G. Gurevich and G. A. Melkov, *Magnetic Oscillations and Waves* [in Russian], Nauka, Moscow, 1994.

Translated by M. E. Alferieff