Electromagnetic emission by a system of nonequilibrium quasiphones in an antiferromagnet

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Electromagnetic emission has been observed from a system of excited quasiphonons in $FeBO_3$ after a monochromatic microwave pump pulse has ended. The frequency of the emission differs from that of the exciting field. The intensity of the emission has a nonmonotonic time evolution. A theoretical model which explains the experimental data is constructed. © *1994 American Institute of Physics.*

Studies[1,2] of the parametric resonance of magnetoelastic waves (and of their quanta: quasiphonons) in $FeBO_3$ in a microwave magnetic field $h\cos\omega_p t$ have yielded a great deal of information on this convenient nonlinear wave system. According to data on the nonlinear magnetic susceptibility, the primary mechanism limiting the absorption is a nonlinear decay of the excited waves. In this letter we show that phase correlations in pairs of excited quasiphonons with a frequency $\omega_k + \omega_{-k} = \omega_p$ also play an important role in shaping the nonequilibrium state. We establish this fact from features of the emission of electromagnetic waves by quasiphonons excited in a sample by a parallel-pumping method. This emission is observed after the end of the microwave pump pulse, so the evolution of this nonequilibrium system in the absence of the external driving force can be studied.

EXPERIMENTAL PROCEDURE AND RESULTS

Magnetoelastic waves were excited in an $FeBO_3$ single crystal by a method of parallel microwave pumping[1] at a frequency $\omega_p/2\pi \simeq 1.2$ GHz at temperatures of 77 and 293 K in magnetic fields $H = 0$–500 Oe. The threshold for the parametric excitation was determined from the sharp feature which characteristically arises on the microwave pulse transmitted through the resonator. The microwave signal was detected by a D603 crystal detector and displayed on an oscilloscope. We studied the signal which arose after the end of the microwave pulse.

When the amplitude of the pump field is below the threshold, the signal from the detector on the trailing edge of the microwave pulse transmitted through the resonator decreases by a factor of about 6 over 0.1 μs (Fig. 1). The reason is that the signal which is detected is proportional to the number of photons in the resonator, and the photon decay time is determined by the quality factor of the resonator, $Q \simeq 300$. When the microwave signal is detected directly from the RG4-04 source, the signal from the detector falls off by a factor of 30 over the same time after the end of the pulse. Accordingly, we can ignore this small tail, which results from the finite speed of the source and

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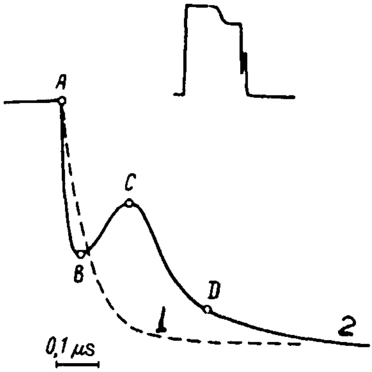

FIG. 1. Oscilloscope traces of the trailing edge of the microwave pulse transmitted through the resonator. 1—For the case $h \simeq 0.9h_c$; 2—$h \simeq 2h_c$ (the ends of the two pulses have been superimposed). Pulse 2 is shows in its entirety at the top. $H=37$ Oe, $T=293$ K. The frequency shift of the emission with respect to the pump frequency, $\omega_p/2\pi=1217.4$ MHz has the following values at the points marked: A) 0; B) 5 MHz; C) 2 MHz; D) 0.5 MHz.

the detector, in analyzing the evolution of the microwave signal from the detector at times $\tau \gtrsim 0.1$ μs after the pump is turned off.

When the pump field exceeds the threshold h_c, we observe emission from the sample after the trailing edge of the pulse (Fig. 1). First, there is a sharp decrease in the microwave power transmitted through the resonator (the trailing edge of the pulse is steeper than below the threshold for excitation of the parametric resonance of quasiphonons). The signal then begins to rise. Its amplitude reaches a maximum at a time $\tau_1=0.1-0.5$ μs after the end of the pulse. Then there is an exponential decay of the emission intensity with a time scale $\tau_2 \simeq 2\tau_1$. Neither the time τ_1 nor other characteristics of the emission depend on the length or repetition frequency of the microwave pulses. The only important point is that the pump pulse be long enough for a parametric instability to occur in the sample and for a steady-state absorption level to be reached.

Zhitnyuk and Melkov[3] have mentioned a similar nonmonotonic behavior of the electromagnetic emission from a system of parametrically excited spin waves in the ferrite yttrium iron garnet, but no detailed information about the effect is available.

We also measured the characteristic emission frequency (see points A, B, C, and D in Fig. 1). We found that it is lower than the frequency of the pump field. The difference increases with increasing value of h/h_c (the extent to which the pump exceeds the threshold) and falls off rapidly with increasing strength of the static magnetic field H.

Interestingly, the nonmonotonic nature of the emission is also seen if a short microwave pulse is applied to the sample after the pump field has been turned off (Fig. 2). This effect, however, is not analogous to the echo effect studied by Govorkov and Tulin[4] in a system of parametrically excited nuclear spin waves in the antiferromagnet $MnCO_3$.

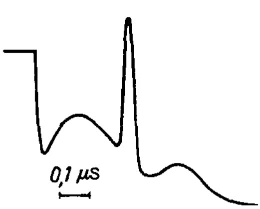

FIG. 2. Oscilloscope traces of the trailing edge of the microwave pulse transmitted through the resonator in the case in which yet another (short) microwave pulse (the narrow peak) is applied to the sample. $h \simeq 2h_c$, $T=77$ K, $\omega_p/2\pi=1210$ MHz.

THEORETICAL MODEL AND DISCUSSION

The nonmonotonic behavior of the emission signal which has been observed here can be explained on the basis of an interference of photons in the resonator after the microwave pump has ended with photons emitted from the excited sample. To describe the effect we use the classical Hamiltonian formalism. We generalize the basic model of the theory of the parametric resonance of spin waves (the so-called S theory[5,6]). It has been suggested previously that the role of the resonator reduces to simply one of increasing the amplitude of the microwave field at the test sample, so the pump field has previously been treated as a classical field. Here, in contrast, we take account of the dynamics of the resonator modes. That this factor must be taken into account was first pointed out by Bryant *et al.*[7] Safonov[8] later showed that a nonlinear coupling of photons with excited quasiparticles can be the cause of a positive nonlinear decay of the latter.

We write the Hamiltonian of the system in the form

$$\mathcal{H}=\omega_R R^*R+\sum_k \omega_k b_k^* b_k+\tfrac{1}{2}\sum_k (G_k R b_k^* b_{-k}^*+\text{c.c.})$$
$$+[FR^*\exp(-i\omega_p t)+\text{c.c.}]+\mathcal{H}_{\text{int}}. \tag{1}$$

Here ω_R, R^*, R and ω_k, b_k^*, b_k are the frequencies and complex amplitudes of the resonator modes and the magnetoelastic waves, respectively; $G_k=i|G_k|$ is a parameter of the nonlinear coupling between photons and quasiphonons; $F=F^*$ is a parameter of the pump field; and

$$\mathcal{H}_{\text{int}}=\sum_{k,q}(T_{kq}b_k^*b_kb_q^*b_q+\tfrac{1}{2}S_{kq}b_kb_{-k}b_q^*b_{-q}^*)+\sum_k T_k^{(R)}R^*Rb_k^*b_k \tag{2}$$

is the interaction Hamiltonian, in which T_{kq}, S_{kq}, and $T_k^{(R)}$ are corresponding matrix elements. This is the first time the last term in (2) has been considered. This term is responsible for a nonlinear shift of the frequencies of the resonator and the magnetoelastic waves. A nonlinearity of this type is unavoidable in this system, according to an analysis. It is not possible to describe the evolution of the emission frequency without considering this nonlinear term.

We write the equations of motion with phenomenological relaxation parameters,

$$i\left(\frac{d}{dt}+\Gamma\right)R=\delta\mathcal{H}/\delta R^*, \quad i\left(\frac{d}{dt}+\gamma_k\right)b_k=\delta\mathcal{H}/\delta b_k^*,$$

and we transform to the slow variables

$$R=\tilde{R}\exp(-i\omega_p t), \quad b_k=c_k\exp(-i\omega_p t/2).$$

We are interested in normal and anomalous correlation functions:

$$N_k=N_{-k}\equiv\langle|c_k|^2\rangle, \quad \sigma_k\equiv\langle c_kc_{-k}\rangle=N_k\exp[i(\theta_k-\pi/2)],$$

where $\langle...\rangle$ means an average over the individual phases of the waves, and the collective variable θ_k describes the dephasing of the excited oscillations of the medium and the pump field.

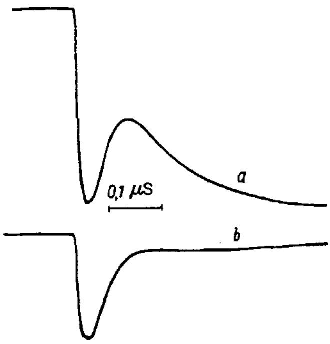

FIG. 3. a—Theoretical oscilloscope trace of the trailing edge of the microwave pulse transmitted through the resonator; b—frequency shift of the emission with respect to the pump frequency (the maximum deviation is −0.15 MHz). $h=2.2h_c$, $T=S<0$, $T^{(R)}/|T|=57$, $\eta_{rd}/|T|=8$, $\gamma_k=2\pi\times0.3$ MHz.

We restrict the discussion to the simplest case, i.e., the single-mode approximation for the magnetoelastic waves which are excited. The equations of motion of the system can then be written

$$\begin{aligned} i\left(\frac{d}{dt}+\Gamma\right)\tilde{R} &= -(\omega_p-\tilde{\omega}_R)\tilde{R}-\tfrac{1}{2}GN_k\exp(i\theta)+F,\\ \frac{d}{dt}\theta_k-G[\tilde{R}\exp(-i\theta_k)+\text{c.c.}] &= \omega_p-2\tilde{\omega}_k-2SN_k,\\ \frac{d}{dt}N_k+2\gamma_kN_k &= iN_kG[\tilde{R}\exp(-i\theta)-\text{c.c.}], \end{aligned} \tag{3}$$

where $\tilde{\omega}_R\equiv\omega_R+T^{(R)}N_k$ and $\tilde{\omega}_k\equiv\omega_k+2TN_k+T^{(R)}|R|^2$ are renormalized frequencies of the resonator and the quasiphonons, respectively. It follows from Eqs. (3) that the microwave power absorption is limited not only the phase mechanism (which plays the leading role in the S theory) but also by a nonlinear decay of quasiphonons which arises as the latter interact with the resonator and by the nonlinear frequency shift of the resonator. Our estimates indicate that the two latter mechanisms are governing. Interestingly, the nonlinear frequency shift of the resonator can be represented as an effective phase detuning of the stimulated oscillations of the medium from the pump field. The coefficient of the nonlinear (radiative[9]) decay can be written

$$\eta_{\text{rd}}=G^2/2\Gamma\simeq2\pi\hbar QV_k^2/v_R, \tag{4}$$

where V_k is a coefficient of the coupling of a pair of quasiphonons with the pump field h ($hV_k\equiv FG/\Gamma$, $h_cV_k=\gamma_k$) in the resonator, and v_R is the volume of the resonator. An estimate of η_{rd} agrees in order of magnitude with the experimental data of Ref. 2 on the parametric excitation of quasiphonons.

We have carried out a numerical simulation of the behavior of system (3) in the pump field and after the pump field has ended. It was found that the nature of the decay of the number of photons ($|R|^2$) in the resonator and the evolution of the frequency of the electromagnetic emission from the resonator agree qualitatively with experimental data for the trailing edge of the microwave pulse (Fig. 3). The fact that the maximum calculated shift of the frequency of the electromagnetic emission is about an order of magnitude smaller than the observed value indicates that there are changes in the parameters γ_k, η_{rd}, and S above the threshold for the excitation of magnetoelastic waves.

In summary, we have observed an emission of electromagnetic waves by a system of excited magnetoelastic waves. The nonmonotonic nature of the emission can be explained by a model which incorporates the nonlinear coupling of nonequilibrium quasiphonons with photons in the resonator and also a phase correlation of pairs of quasiphonons. The interaction of a photon with a pair of quasiphonons contributes substantially to the nonlinear decay of the magnetoelastic waves. The scattering of photons by quasiphonons results in a nonlinear frequency shift of the branch of magnetoelastic waves and of the resonator.

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