Unique features of the parametric excitation of nuclear magnons in antiferromagnetic materials in the presence of magnetic field modulation

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Regularly spaced peaks have been found in the dependence of the threshold of parallel UHF pumping of nuclear magnons in $MnCO_3$ and $CsMnF_3$ on the magnetic field modulation frequency. A model of general character is proposed that explains these features qualitatively, is based on taking account of the large changes in the phase of parametric magnons under modulation conditions.

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The influence of the modulation of the constant magnetic field on the threshold of parallel UHF pumping of electron magnons in ferrites and antiferromagnetic materials was investigated in Refs. 1–4. We have conducted a similar study for nuclear magnons[5] in the easy-plane antiferromagnetics $MnCO_3$ (a Dzyaloshinskii field $H_D = 4.4$ kOe) and $CsMnF_3$ ($H_D = 0$). The experiment was conducted for $h^{\text{UHF}} \| \mathbf{H}_m \| \mathbf{H}_0 \perp C_3$ in the temperature interval $T = 1.7–4.2$ K at a UHF pumping frequency $\omega_p/2\pi = 1$ GHz, the modulation frequency of the field was $F = \Omega/2\pi \leqslant 220$ kHz, and the modulation amplitude was $H_m \leqslant 3$ Oe.

Figure 1 shows the relative increase h_c/h_{c0} of the threshold (h_{c0} is the threshold

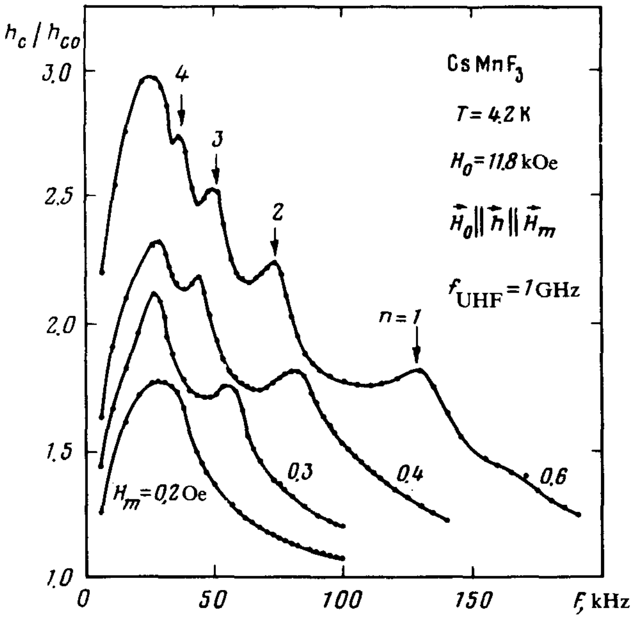

FIG. 1. Relative increase of threshold as a function of modulation frequency and amplitude for $CsMnF_3$ at $T = 4.2$ K, $H_0 = 1.18$ kOe.

without modulation) in a $CsMnF_3$ sample as a function of the modulation frequency and amplitude. Unlike the similar curves for electron magnons, measured on the same antiferromagnetics[4] and yttrium iron garnet,[3] peculiarities are observed here in the form of peaks, which are displaced toward higher frequencies with an increase in H_m. At large H_m we were able to resolve up to $n = 10$ peaks.

We performed detailed measurements of the dependence of the locations F_n of these peaks on the experimental parameters H_0, H_m, T, H_D and the number n of the peak. It was found that within the above-stated variation ranges of the parameters the locations of the peaks were described quite well (with an accuracy of $\sim 10\%$) by the following relationship

$$F_n = c\,\frac{(2H_0 + H_D)\,H_m T}{n}, \tag{1}$$

where c is a coefficient depending only on ω_p whose values are identical for $MnCO_3$ and $CsMnF_3$ within the same accuracy limit.

The following qualitative explanation can be suggested for the observed peculiarities and the functional relationships (1) associated with them. The threshold of parametric excitation is the amplitude of the UHF pumping at which the power $\overline{P}_+$, absorbed by a pair of magnons ω_k and ω_{-k} from pumping, averaged over a period $2\pi/\omega_p$, is equal to the power P_-, transferred by this pair to the heat reservoir in the relaxation process. It is easy to show that $\overline{P}_+ \sim \sin\Psi_k$ for an isolated pair of magnons, where Ψ_k is the "time phase of the pair", see Ref. 6, which is the phase shift of the oscillations of the longitudinal magnetization of the sample relative to the pumping.

An estimate, similar to that given in Ref. 3 Eq. (14), shows that in the region of modulation frequencies where the peculiarities are observed, we can ignore changes of the wave vector $\mathbf{k}_p$ of the excited magnons. Field modulation leads only to a modulation of the natural frequency of the magnon:

$$\omega_{n\mathbf{k}} = \frac{\omega_p}{2} + \frac{\partial \omega_{n\mathbf{k}}}{\partial H} H_m \cos \Omega t = \dot{\phi}_{\mathbf{k}},$$

where $\phi_{\mathbf{k}}$ is the phase of the magnon. Then for $\Psi_{\mathbf{k}}$ we have:

$$\Psi_{\mathbf{k}} \equiv \phi_{\mathbf{k}} + \phi_{-\mathbf{k}} - \omega_p t = \Psi_{\mathbf{k}}^{(0)} + Z \sin \Omega t,$$

where $Z \equiv 2 \dfrac{\partial \omega_{n\mathbf{k}}}{\partial H} \dfrac{H_m}{\Omega}$, and $\Psi_{\mathbf{k}}^{(0)}$ is the integration constant, which we assume is equal to $\pi/2$ since it is precisely at this value that maximum absorption of the pumping power by the pair occurs in the absence of field modulation.

For a very small excess beyond threshold the exponential increase in the amplitude of the magnons occurs very slowly; therefore it is valid to average the power P_+ not only over a pumping period but also over the modulation period T_m: $\overline{P}_+ \sim \overline{\sin \Psi_{\mathbf{k}}}$, where

$$\overline{\sin \Psi_{\mathbf{k}}} = 1/T_m \int_0^{T_m} \cos (Z \sin \Omega t)\, dt \approx J_0(Z),$$

and $J_0(Z)$ is the zero-order Bessel function. Equating $\overline{P}_+ = P_-$, we obtain

$$h_c = h_{c0} / J_0(Z), \tag{2}$$

where h_{c0} is the threshold in the absence of modulation, determined from the relation $(\overline{P}_+)_{max} = P_-$. The roots of the Bessel function $Z_n \approx \pi(n - 1/4)$ determine the frequencies at which anomalies must be expected on the curve of $h_c(F)$:

$$F_n = \tilde{c} \frac{(2H_0 + H_D) H_m T}{n - 1/4}. \tag{3}$$

This expression is obtained after specification of the form of Z with the known spectrum of magnons $\omega_{n\mathbf{k}} = \omega_n (1 - \omega_E \omega_N / \omega_{e\mathbf{k}}^2)^{1/2}$ taken into account.[5] The functional relationships following from (3) agree remarkably with those found empirically (1), considering the qualitative character of the proposed explanation. The relationship $\tilde{c}(\omega_p) = \text{const}\,\omega_p^{-1} \left(1 - \dfrac{\omega_p^2}{4\omega_n^2}\right)^2$ obtained for $\tilde{c}$ stimulated us to investigate the relationship $F_n(\omega_p)$ for fixed H_0, T, H_m. It was found that in the frequency range $\omega_p/2\pi = 1.0$–1.2 GHz $c(\omega_p) = \kappa \tilde{c}(\omega_p)$, where $\kappa = 1.7$ for $MnCO_3$ and $\kappa = 1.9$ for $CsMnF_3$. The difference between κ and unity may be due to the crudity of the model. A more serious defect is the fact that an infinite increase in the threshold at the frequencies F_n follows from Eq. (2), which makes no physical sense, accompanied, moreover, by a change in its sign (denoting a flow of power from the pair to the pumping). It can be assumed that all these discrepancies are removable if simultaneously with the rigorous solving of the equation of motion for $\Psi_{\mathbf{k}}$ consideration is given to the fact that the search for the minimum threshold of the parametric instability for the large modulation of the magnon phase, with which we are dealing, must be made in the $(\Psi_{\mathbf{k}}^{(0)},\Delta_{\mathbf{k}})$ plane, where $\Psi_{\mathbf{k}}^{(0)}$ is the set of initial phases of the pair, and $\Delta_{\mathbf{k}}$ is the possible constant frequency detuning of the magnon with respect to the nominal value $\omega_p/2$.

It is obvious that the proposed model nowhere utilizes the specific aspects of nuclear magnons and is completely general in nature. An estimate shows that for the excitation of electron magnons in these same antiferromagnetic materials these peculiarities should be observed for $H_m > 1.5$ Oe. We have performed a corresponding experiment at a pump frequency of 36 GHz and found the peculiarities we were looking for; their location agrees quite well with calculation.

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