[1] P. DeGennes, Superconductivity of Metals and Alloys, Benjamin, 1965 (Russian translation, Mir, 1968, p. 197).
[2] B. Rosenblum and M. Cardona, Phys. Lett. 13, 33 (1964).
[3] G. Fisher, Phys. Rev. Lett. 20, 268 (1968).
[4] J. Kirshenbaum and Yi-Han Kao, Phys. Rev. Lett. 22, 1177 (1969).
[5] I.Ya. Krasnopolin and M.S. Khaikin, ZhETF Pis. Red. 12, 76 (1970) [JETP Lett. 12, 54 (1970)].
[6] M.S. Khaikin, V.S. Edel'man, and S.M. Cheremisin, PTE No. 4, 255 (1970).
[7] W.A. Reed, E. Fawcett, P.P.M. Meincke, P.C. Hohenberg, and N.R. Werthamer, Proceedings of Tenth Internations Conference on Low-Temperature Physics, Vol. 11A, p. 368, Moscow, VINITI, 1967; P.C. Hohenberg and N.R. Werthamer, Phys. Rev. 153, 493 (1967).
[8] K. Maki and G. Fisher, Phys. Rev. 184, 472 (1969).
[9] I.O. Kulik, Zh. Eksp. Teor. Fiz. 55, 889 (1968) [Sov. Phys.-JETP 28, 461 (1969)].
[10] G. Fisher and R. Klein, Phys. Rev. 165, 578 (1968).

SPIN-ECHO ENHANCEMENT BY DOUBLE-FREQUENCY PUMPING

V.V. Danilov, V.I. Sugakov, and A.V. Tychinskii
Kiev State University
Submitted 22 March 1972
ZhETF Pis. Red. 15, No. 9, 520 - 522 (5 May 1972)

We propose the following explanation for the experimentally observed enhancement of the echo in ferrites [1]. Owing to the internal nonlinear interactions, the oscillations of the magnetic moment, which are coherent with the first weak pulse (signal), become parametrically amplified by oscillations produced by the second powerful pulse (pump). As a result, when the time interval between the exciting pulses (τ) is increased, the echo signal first increases to a certain value, and then decreases as a result of the relaxation processes.

The propcsed mechanism makes it possible to predict qualitatively a new phenomenon in spin echo, namely, enhancement when pumped at double frequency.

For a quantitative description of the enhanced echo we write down the equations of motion of the oscillation amplitudes of the ν-th mode (a_ν), which interact parametrically with the oscillations produced by the second pulse

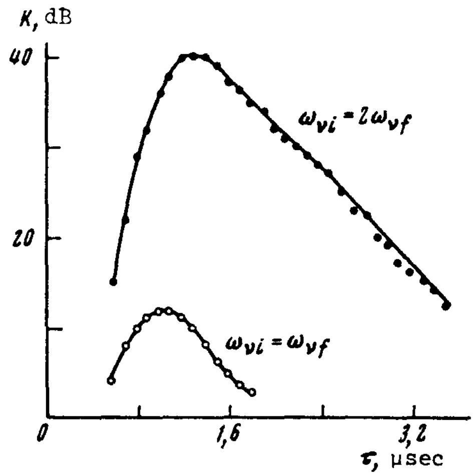
$$\dot{a}_\nu - i\omega_\nu a_\nu + i\alpha_\nu \exp[2i\omega_\nu(t - \tau)]\, a_\nu^* = 0. \quad (1)$$

Here ω_ν is the complex natural frequency of the oscillations of the ν-th mode ($\omega_\nu = \omega_\nu' + i\omega_\nu''$), α_ν is a quantity that depends on the magnetic moment produced by the second pulse and the system parameters.

Solving Eq. (1) with the initial condition $a_\nu = a_\nu^I \exp(i\omega_\nu\tau)$ at $t = \tau$, where a_ν^I is the amplitude of the oscillations produced by the first pulse, we can show that an enhanced echo signal becomes phased-in at $t = 2\tau$. The expression for the gain is

$$K = \frac{1}{4}\left\{\exp\left[\frac{|\alpha|}{2\omega''}(1 - \exp[-2\omega''\tau])\right] - \exp\left[\frac{|\alpha|}{2\omega''}(\exp[-2\omega''\tau] - 1)\right]\right\}\exp(-4\omega''\tau). \quad (2)$$

An equation of motion in the form (1) is obtained under the following conditions: (i) the frequency of the decaying and of the enhanced oscillations are equal ($\omega_{\nu i} = \omega_{\nu f}$); (ii) the frequency of the decaying oscillation is double the frequency of the enhanced one ($\omega_{\nu i}/2 = \omega_{\nu f}$). Relation (2) is valid both when $\omega_{\nu i} = \omega_{\nu f}$ and when $\omega_{\nu i} = 2\omega_{\nu f}$. However, in the second case $|\alpha|$, and consequently also K, is much larger, since it is determined by the lower powers of the expansion of the Landau-Lifshitz equation in powers of m/M_0 [2].



It is therefore advisable to perform the experiment on the enhanced echo at a pump frequency double the signal frequency. Such measurements were performed on a cylindrical single-crystal yttrium-iron-garnet. The power of the 1.3 GHz signal was 10^{-10} W. A pump of 2.6 GHz frequency and 0.5 W power was turned on at a time τ after the application of the signal. The duration of the exciting pulses ranged from 70 to 300 nsec. The enhanced echo pulse was registered at the frequency 1.3 GHz.

The experimental setup made it possible to realize successively both case (i) ($\omega_{\nu i} = \omega_{\nu f}$) and case (ii) ($\omega_{\nu i}/2 = \omega_{\nu f}$). The magnetizing field at which the enhanced echo was observed remained the same on going from the first case to the second. All this has made it possible to compare the efficiency of the echo system under conditions of equal frequencies and for pumping at double the frequency. The results of such a comparison are illustrated in the figure, which shows a plot of the gain $K = P^{echo}/P^{1}$ (P^{echo} and P^{1} are respectively the powers of the echo signal and of the first pulse) on the interval τ between pulses. As seen from the figure, the case (ii) is preferable from the point of view of amplification, as follows indeed from the theoretical analysis. The position of the maximum of the K(τ) curve is determined by the competing processes of amplification and relaxation. Naturally, the larger gain in case (ii) leads to a shift of the maximum towards larger τ.

The system relaxation frequency ω", which was determined from the damping of the K(τ) curve at large τ, retains the same value on going from case (i) to case (ii), since in both situations the same oscillations take part in the formation of the echo and lie near the lower limit of the spin-wave spectrum.

The performed experiments have, first, confirmed the correctness of the given interpretation of the enhanced echo and, second, made it possible to observe a new phemomenon not found in other systems at magnetic resonance, namely echo at different pulse frequencies and, third, made it possible to obtain a much larger gain.

[1] D.E. Kaplan, R.M. Hill, and G.F. Herrmann, Phys. Rev. Lett. 20, 1156 (1968).
[2] H. Suhl, J. Phys. Chem. Sol. 1, 209 (1957).