Susceptibility of the ferrite spin system above the parametric excitation threshold

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(Submitted August 8, 1972)

Zh. Eksp. Teor. Fiz. 65, 1905–1910 (November 1973)

The imaginary (χ'') and real (χ') parts of the nonlinear magnetic susceptibility of ferrite single crystals are measured as functions of the pumping power P. It is shown that the $\chi'(P)$ curve practically coincides with the abscissal axis in the initial range of power extending to 1.5–2 dB above the Suhl threshold. The behavior of $\chi'(P)$ is observed to differ considerably in longitudinally and transversely polarized pump fields.

It has been predicted in theoretical studies of nonlinear ferromagnetic resonance (NFMR)[1,2] that certain properties of the strongly excited spin system of a ferromagnet will exhibit interesting peculiarities. This pertains to the behavior of the real (χ') and imaginary (χ'') parts of the nonlinear magnetic susceptibility, mainly in the initial range of pumping power P, up to a small excess (1.5–2 db) above the NFMR threshold. For this range the respective conclusions of[1,2] differ very decidedly. Thus it would follow from[1] that $\chi'(P)$ differs from zero only outside of the given range. In other words, the threshold that characterizes $\chi'(P)$ would be separated by a considerable gap from the threshold of NFMR excitation. The behavior of $\chi'(P)$ outside this gap is determined only qualitatively. In[2], however, it is predicted that $\chi'(P)$ is approximately linear in the very same region (inside the gap).

The published experimental data on χ' and χ'' [2] are, in our opinion, insufficiently complete to permit a quantitative test of the theory. The principal shortcoming of these investigations is the relatively low precision of the measurements. For example, according to the data in[2] the absolute error of the χ' measurements was $\pm 5 \times 10^{-3}$, so that the spread of the values was more than 100% in the entire initial region.

In the experimental results presented here the absolute error of χ' within the initial segment was reduced by about an order of magnitude due to the following steps that were taken: (1) A frequency-modulated klystron was used as the pumping source, (2) the Q of the (cavity) resonator loaded by the ferrite sample was increased, and, most importantly, a high-precision frequency meter (an echo chamber) was employed.

The experiments were performed using a reflection scheme at a pump frequency of 9450 MHz. The pump signal was detected after being reflected from the ferrite-loaded resonator; the envelope was received by an oscilloscope. When the frequency meter was inserted into the circuit the oscilloscope screen displayed the resonance curve of the loaded resonator along with a wavemeter marker. The frequency shift of the loaded resonator was measured by moving the wavemeter marker into position at the center of the resonance curve.

Using the described procedure, the first of the aforementioned steps enabled us to completely eliminate any error due to frequency instability of the pumping source. The second step led to enhanced precision in positioning the wavemeter marker at the center of the resonance curve of the loaded resonator. It was found expedient to limit the maximum Q of the resonator to the value at which the width of the resonator curve (at the half-power level) was about one order greater than the smallest experimentally resolvable width of the marker. In our case the limit of minimum resonator-curve width was ~200 kHz; in the employed resonator the width was ~2000 kHz. The echo chamber permitted high precision in measuring the "zero" frequency of the loaded resonator (precision in locating the center of the loaded-resonator curve).

When measuring the entire initial segment of the χ' curve the spread of the frequency meter readings did not exceed ±10 kHz. We considered this interval as the maximum error incurred in measuring the frequency shift of the ferrite-loaded resonator. Accordingly the maximum absolute error of the χ' measurements did not exceed $\pm 0.4 \times 10^{-3}$ until the pumping power exceeded the threshold P_{thr} by about 8 dB. Above this higher level the curve of the loaded resonator exhibited distortions (asymmetry, a double hump, etc.), which were especially strong when the sample was magnetized in the [001] direction. The distortions of the curve augmented the measurement errors severalfold. We did not evaluate the errors exactly in the $P/P_{thr} \gtrsim 8$ dB region, where even comparatively rough measurements of the frequency shift of the ferrite-loaded resonator did not substantially affect the final results.

We determined values of χ'' from those of the reflection coefficient, which was measured by compensation of attenuation with the aid of a measuring attenuator. The absolute errors of χ'' measurements were at most $\pm 10^{-3}$.

Figures 1–5 show the experimental results for a spherical yttrium iron garnet sample of 2-mm diameter that exhibited an absorption linewidth $2\Delta H = 0.2$ Oe for both longitudinal and transverse pumping. The study of these results led to the following conclusions.

1. The χ'' and χ' curves behave substantially differently in the initial range of P values. We believe that one can speak of two thresholds, the first at the break[1)] of the $\chi''(P)$ curve (the Suhl threshold, P_{thr}), and the second at the break of the $\chi'(P)$ curve. Between the two breaks (i.e., in the gap) the difference in pumping power applied to the sample was 1.5–2 dB. This effect is observed over the entire region where nonlinear susceptibility exists with respect to the magnetizing field. In order to test for the presence of a break in the $\chi'(P)$ curve, we performed additional calculations with the aim of finding a simple function that could be used to approximate the experimental curve within the experimental error limits. The calculations shows that functions of the type $\chi' = A(P/P_{thr})^n$ or

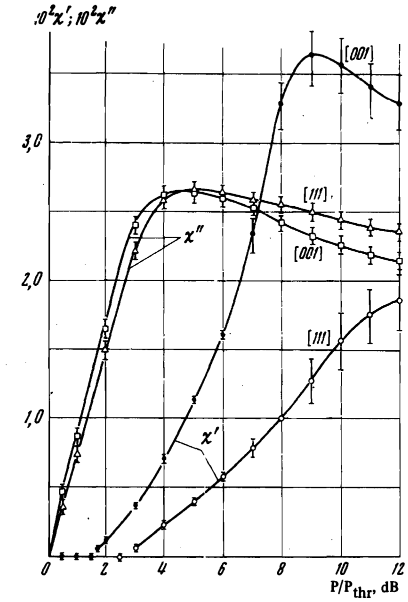

FIG. 1. Imaginary (χ'') and real (χ') parts of the nonlinear susceptibility vs longitudinal pumping power.

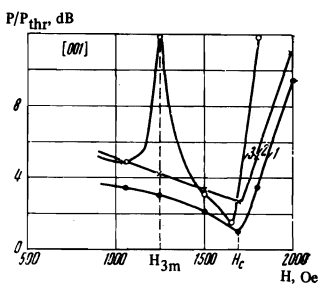

FIG. 2. Thresholds of nonlinear ferromagnetic resonance (1), real part of the nonlinear susceptibility (2), and self-pulse modulation (3) vs magnetizing field with longitudinal pumping.

A exp(P/P$_{thr}$) (where A is an experimentally determined coefficient and n is any positive number) are unsuitable for such an approximation. Different approximations are evidently needed along the different segments of the piecewise-broken curve of $\chi'(P)$.

2. The χ' curve is strongly anisotropic. In the case of longitudinal pumping with magnetization in the [001] direction the magnitude of χ' is a few times greater than with magnetization in the [111] direction. The sign of χ' for longitudinal pumping does not depend on the strength of the magnetizing field.

3. For transverse pumping the sign of χ' depends on the strength of the magnetizing field, but coincides with the sign for longitudinal pumping when $H \geq 2000$ Oe. Here the appreciable anisotropy of χ' is greater with magnetization in the [111] direction than in the [001] direction.

In our experiments we also observed sudden absorption of power at the threshold level (P$_{thr}$) when the frequency was about 500 kHz higher than the resonant frequency of the loaded resonator. This abosrption appeared as a small spike ~500 kHz wide[2)] on the resonance curve. With increasing pumping power the spike was shifted toward lower frequencies and disappeared from the field of view at P/P$_{thr}$ ~ 1.5–2 dB, while the frequency of the loaded resonator remained unshifted within experimental error limits. The spike reappeared at P/P$_{thr}$ ~ 8–9 dB, and its behavior was the same as that already described. The nature of the spike was not determined.

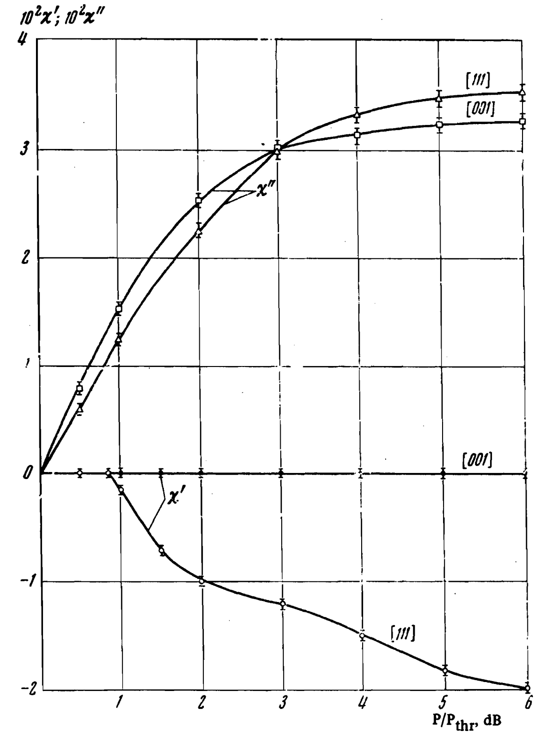

FIG. 3. Imaginary (χ'') and real (χ') parts of the nonlinear susceptibility vs transverse pumping power. The magnetizing field was H = 1600 Oe.

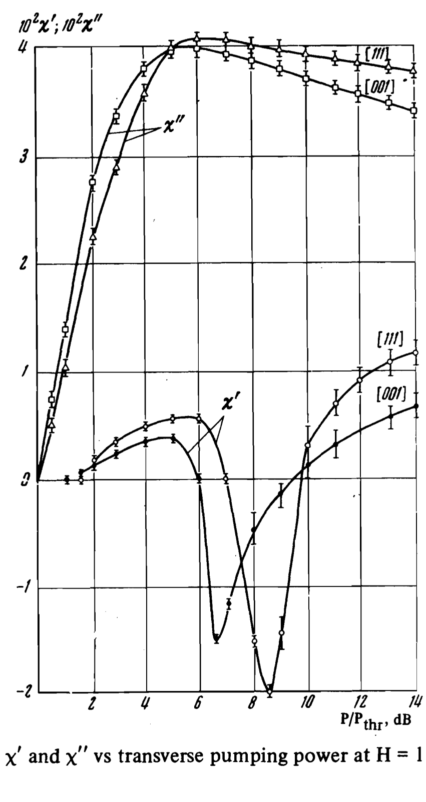

FIG. 4. χ' and χ'' vs transverse pumping power at H = 1800 Oe.

It is interesting to compare our experimental results with the theoretical conclusions in[1,2]. The following experimental results support the theoretical conclusions of[1].

1) The existence of a gap between the χ'' and χ' curves. This gap is about 1–1.2 dB greater than the gap between the respective thresholds of self-pulse modulation (of high-frequency oscillations) and non-

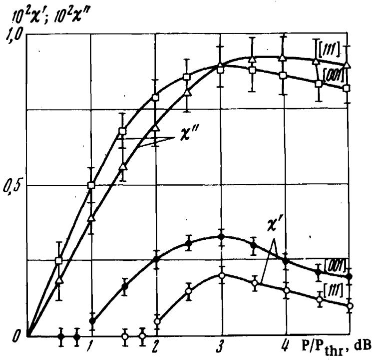

FIG. 5. χ' and χ'' vs transverse pumping power at H = 2100 Oe.

linear ferromagnetic resonance in almost the entire region where nonlinear magnetic susceptibility exists.

2) For transverse pumping, experiment and theory agree regarding the order of magnitude of the magnetizing field at which the sign of χ' is reversed. The theoretical field difference $H - H_c$ is 120 Oe; the experimental result was $(H - H_c) \sim 100$ Oe.

Other theoretical conclusions of[1] disagrees with experiment as follows. 1) For longitudinal pumping with magnetization in the [111] direction the gap between the χ' and χ curves close to the magnetizing field strength $H \approx H_{3m}$ (H_{3m} is the field corresponding to the upper boundary of the region of three-magnon merger) and for $H > H_c$ is considerably smaller than the gap between the respective thresholds of self-pulse modulation and NFMR (see Fig. 2). 2) The anisotropy of χ' does not duplicate the anisotropy of the intensity of self-pulse modulation. For example, in the case of longitudinal pumping the self-pulse modulation intensity is minimal in the [001] direction, while χ', on the other hand, is maximal in this direction. This noncorrespondence also exists for transverse pumping.

The theoretical conclusions of[2] can be compared with experiment only for longitudinal pumping. Experiment confirms (as noted by the authors of[2]) the following theoretical conclusions given in[2]. 1) In the [001] direction there is agreement for the ratio χ'_{max}/χ''_{max}, which equals ~ 1.4 in the theoretical calculation and ~ 1.5 experimentally. 2) χ' and χ'' have the same (positive) sign in the entire region of nonlinear susceptibility. 3) The maximum value of χ' appear at $P/P_{thr} \sim 9$ dB.

The disagreement between the experimental results and the theory in[2] consists in the very existence of a gap between the χ' and χ'' curves. We consider this to be of fundamental significance.

We note that the experimental magnitude of χ' is relatively small, especially with magnetization in the [111] direction. This result also disagrees with the conclusions in[2] and with calculations in[1].

The data presented here may possibly indicate that the present theories are neglecting an equilibrium mechanism which is operative above the excitation threshold of the ferrite spin system.

1)The segment to the left of the point $P = P_{thr}$ coincides with the horizontal axis to the degree of accuracy shown in Figs. 1 and 3–5, and is not shown here.

2)Yu. R. Shil'nikov was the first to report the observation of such a spike.

1Ya. A. Monosov, Nelineĭnyĭ ferromagntnyĭ rezonans (Nonlinear Ferromagnetic Resonance), Nauka, 1971.
2V. V. Zautkin, V. E. Zakharov, V. S. L'vov, S. L. Musher, and S. S. Starobinets, Zh. Eksp. Teor. Fiz. 62, 1782 (1972) [Sov. Phys.-JETP 35, 926 (1972)].

Translated by I. Emin
194