Four-magnon decay and the kinetic instability of a magnetostatic traveling wave in yttrium garnet ferrite films

P. E. Zil'berman, S. A. Nikitov, and A. G. Temiryazev
Institute of Radio Engineering and Electronics, Academy of Sciences of the USSR

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The formation of satellite waves has been observed for the first time in yttrium garnet ferrite films which become saturated in a normal magnetic field **H** as a result of propagation of an intense magnetostatic wave. The formation of satellite waves is caused by the four-magnon decay of a magnetostatic wave which becomes a kinetic instability at high supercriticalities.

In this letter we report a study of the propagation of intense, direct, magnetostatic body waves in yttrium garnet ferrite films with (111) and (110) orientations and thicknesses in the range $a = 0.5$–$5\ \mu$m. The magnetostatic waves were excited and received by ~ 6-μm-wide microstrip antennas spatially separated a distance $l = 0.5$–7 mm. A continuous monochromatic microwave signal from an oscillator was received by the input antenna. The signal from the output antenna was sent to the spectrum analyzer. We studied the spectrum as a function of the input power P (the difference between the power received by the input antenna and the power reflected from it).

At relatively small P ($P < 0.5$ mW, for example, for a film with $a = 0.54\ \mu$m) the propagation of magnetostatic waves is linear—the spectrum analyzer detects only the frequency f_s received at the input. Beginning at a certain threshold power $p_{\rm thr}$ ($p_{\rm thr} \sim 0.5$–1 mW at $a \sim 0.5$–$1\ \mu$m and at f_s adequately spaced from the spectral-gap frequencies[1]), in addition to the frequency f_s, the spectrum exhibits discrete frequencies at the output—satellites which are equidistant from f_s (frames 1 and 2 in Fig. 1). A low-frequency satellite generally (but not always—see frame 2 in Fig. 1) has a large amplitude. The amplitude of a high-frequency satellite decreases in many cases to the intrinsic-noise level (frame 3 in Fig. 1). With further increase in P, the number of satellites increases (frames 4 and 5 in Fig. 1) and a broad, noise-like peak forms gradually (frame 6 in Fig. 1). At the center of this peak, the frequency f_n is nearly independent of f_s. Frames 1–3 in Fig. 2 show that if f_s increases and H remains constant, the noise will not move. The amplitude of the peak decreases as $(f_s - f_n)$ is increased. In the films with $a \lesssim 1\ \mu$m, the peak can, however, be observed up to $(f_s - f_n) \sim 300$ MHz. In the films with $a \gtrsim 3\ \mu$m the peak can be observed only if $|f_s - f_n| \lesssim \Delta f_n$, the peak width. Δf_n is in the range 10–20 MHz, depending on the sample. We see from Fig. 3 that as H is reduced (f_s remains constant), the noise peak moves toward lower frequencies. The functional dependence $f_n(H)$ lies on the straight line, whose tangent of the slope angle is equal to the gyromagnetic ratio $(\gamma/2\pi)$. Here f_n is always near the lower boundary of the magnetostatic-wave spectrum, $f_0 (f_0 < f_n)$. A decrease in P (from a high level) leads to the following changes: 1) If $|f_s - f_n| \lesssim \Delta f_n$, a transition will occur to the regime of discrete satellites which has already been described; 2) if $|f_s - f_n| \gg \Delta f_n$, the noise-peak amplitude will either decrease smoothly or the noise will vanish abruptly. In the latter case, the noise reappears abruptly at a P slightly

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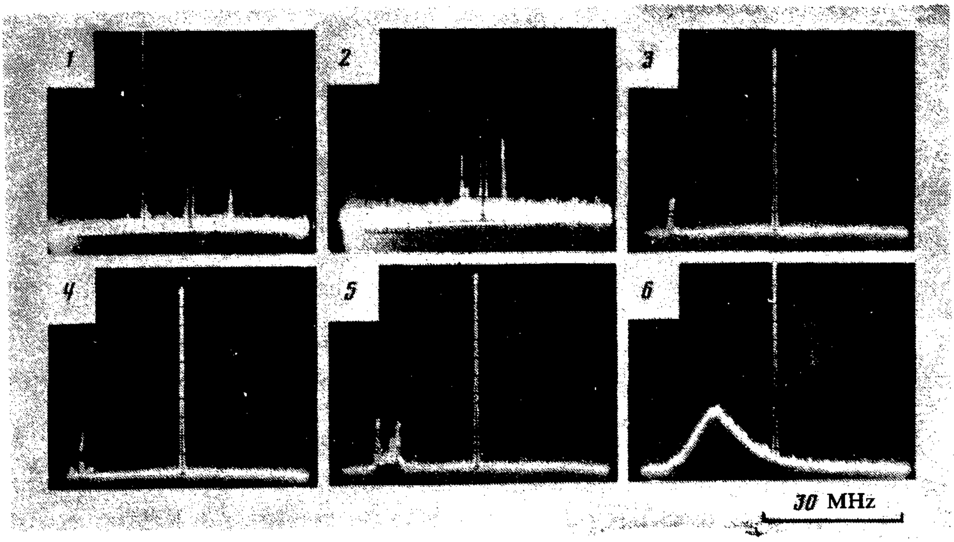

FIG. 1. Output spectra for various P: $a = 0.5\ \mu$m, $f_s = 2400$ MHz; 1—$P = 0.68$ mW, $H = 2471.8$ Oe; 2—$P = 0.51$ mW, $H = 2472.5$ Oe; 3—$P = 1$ mW; 4—$P = 1.2$ mW; 5—$P = 1.5$ mW; 6—$P = 3.1$ mW; 3–6—$H = 2467.2$ Oe.

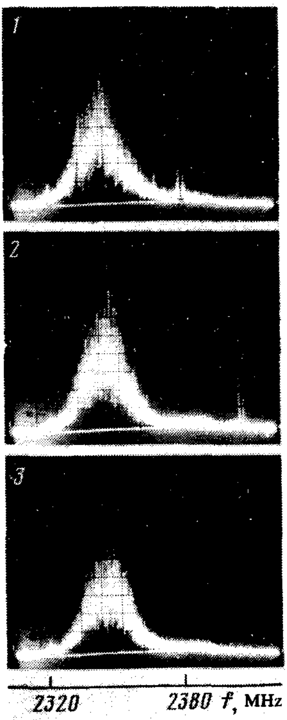

FIG. 2. The spectrum for various f_s: $P = 3$ mW, $H = 2469.7$ Oe, $a = 0.5\ \mu$m; 1—$f_s = 2380$ MHz; 2—$f_s = 2400$ MHz; 3—$f_s = 2415$ MHz.

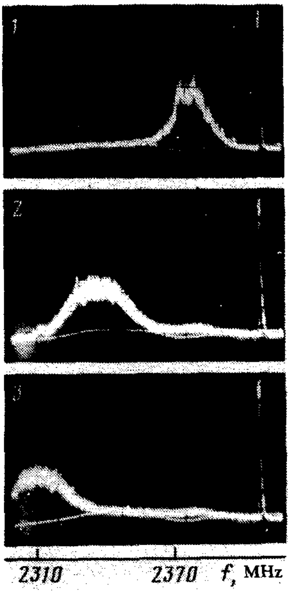

FIG. 3. The spectrum for various H: $P = 43$ mW, $f_s = 2400$ MHz, $a = 0.5$ μm; 1—$H = 2460.3$ Oe; 2—$H = 2442.9$ Oe; 3—$H = 2434.9$ Oe.

higher than that at which it vanishes. This hysteresis and the "hard" excitation evidently stem from the phasing out of some of the relaxation processes at a high noise level.[2]

The creation of satellites and generation of noise cannot be explained, as has been done in Ref. 3, by the three-magnon decay of magnetostatic waves, in which the subthreshold state becomes unstable.[4] In our case, $H > 16\pi M/3$ (M is the saturation magnetization), and the three-magnon decay is forbidden. Our observations of the modulation instability of magnetostatic waves differ from those described in Ref. 5, in which the satellites were observed only near the lower edge of the spectral gap. We have observed them, on the other hand, at arbitrary f_s within the limits of the magnetostatic wave spectrum. Furthermore, at reasonably large P, the satellites did not vanish, as they had in Ref. 5, but instead increased in number and combined into a noise peak. These observations can be explained, in our view, in terms of the four-magnon decay of magnetostatic waves. In such a decay we would have

$$2f(ka) = (k_1 a) + f(k_2 a), \qquad 2\mathbf{k} = \mathbf{k}_1 + \mathbf{k}_2, \tag{1}$$

where $\mathbf{k}$ and $\mathbf{k}_{1,2}$ are the wave vectors of the initial wave and of the satellite waves, $f(ka)$ and $f(k_{1,2}a)$ are the dispersion laws, $k \equiv |\mathbf{k}|$, and $k_{1,2} \equiv |\mathbf{k}_{1,2}|$. The first equation in (1) accounts for the equidistance of the satellite frequencies $f(k_{1,2})$ from $f(ka) \equiv f_s$, in accordance with frames 1 and 2 in Fig. 1. Expanding the first equation in (1) in the first part of the spectrum (ka, $k_{1,2} \ll 1$), we find that the system of equations in (1) has a solution only at

$$\xi \equiv \frac{d^2 f(ka)}{d\,(ka)^2} \Bigg/ \frac{d f(ka)}{d(ka)} < 0. \tag{2}$$

According to the linear theory,[6] condition (2) holds at f_s lower than the frequency of the first gap. At these f_s we have noticed the lowest satellite production threshold in the experiments. We see from our observations that as P is raised, the gaps collapse and (2) becomes applicable in the entire spectrum. At $\xi < 0$, a particular solution of (1) corresponds to each $k_1 (k_1 < k_2)$ in the interval $0 < k_{\min} \lesssim k_1 < k$, where $k_{\min} = (1/2) k^2 |\xi| a$ and $|\xi| \sim 1$; i.e., $k_{\min} \ll k$ (for $ka \ll 1$). Consequently, $\min f(k_1 a) = f(k_{\min} a)$ is near the f_0 boundary of the spectrum, as has indeed been observed. At low supercriticalities, we first observe that frequency $f(k_1 a)$ which corresponds to the lowest threshold (frame 3 in Fig. 1). With increasing supercriticality, all new decay channels (the other permissible k_1) come into play (frames 4 and 5 in Fig. 1). The lines of the single satellites merge to form a broad peak (frame 6 in Fig. 1). The interaction between the satellites causes a randomization of the phase, and the kinetic instability regime sets in.[7] The kinetic instability of the spin waves in bulk samples was discussed in Ref. 8. The kinetic instability of the dipole waves has evidently not been studied previously. We are concerned here with the size effect, since the dipole waves occur in the interval $0 < k \lesssim 1/2a$. Furthermore, in contrast with Ref. 8, the initial magnetostatic wave has a constant **k**. This situation accounts for the fact that that the four-magnon decay with constant phases occurs in the initial stage, and the kinetic instability sets in only when the supercriticality begins to increase because of the engagement of many decay channels. For the same reason, we have not been able to detect an emission at the frequency $2f_n$, which has typically been measured in Ref. 8.

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[1)]At f_s approximately equal to the frequencies at which a weak signal is suppressed ("gaps"),[1] the threshold power $P_{\rm thr}$ turned out to be slightly higher ($P_{\rm thr} \sim 3$ mW for $a \simeq 0.5\ \mu$m). At $P \gtrsim 3$ mW, the gaps could not be detected.

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