Giant oscillations in the transmission of quasi-surface spin waves through a thin yttrium-iron garnet (YIG) film

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Predicted giant oscillations of the transmission coefficient of the Daman-Eshbach (DE) wave through a thin epitaxial YIG film [Sov. Phys. Solid State **21**, 556, 1979] are experimentally observed and interpreted for the first time.

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Our study concerns the excitation and propagation of a quasi-surface spin wave (SW) in the structure shown in Fig. 1. The monocrystalline YIG films, deposited on a standard [111] gadolium-gallium garnet substrate were obtained by means of liquid-phase epitaxy[3] from the (Y_2O_3-Fe_2O_3)(PbO-B_2O_3) solution- melt. The film thickness varied from 1.1 μm to 28 μm. The measured linewidth of the FMR was $\lesssim 0.4$ Oe over the entire frequency range used $\nu = 3$–9 GHz. Thin ($\lesssim 0.5\ \mu$m) gold microbands ~ 10-μm in width were photolithographically deposited on the free film surface to serve as the transmitting and receiving antennas. The spacing between microbands $L \approx 4$ mm and their length $\simeq 3$ mm. The structure was placed in a magnetic field H_0 that was parallel to the bands. The output circuit contained a cell capable of fully suppressing the microwave power reflected by the receiver.

The measurement of delay time of a microwave pulse showed that the antennas excite a DE wave, the delay monotonically decreasing with an increase in H_0.[4] Under these conditions and in a continuous operation mode an oscillatory dependence of the received power P_{out} on H_0 and ν was observed for films with thickness $a < 6\ \mu$m. Typical experimental curves (recorded automatically) are shown in Fig. 2. Curve 1 represents the function $f(H_0) = \{10 \log (P_{\text{refl}}/P_0) - 8.5\}$, where P_0 is the power of microwave generator and P_{refl} is the power reflected by the transmitting antenna. Knowing $f(H_0)$, the power withdrawn by the antenna $(P_0 - P_{\text{refl}})$ may be calculated.

When $H_0 \to 0$, the latter is consumed in the conductors and through radiation. Such losses are, clearly, weakly dependent on H_0. In the field range of (623–819) Oe where the DE waves exist, the power withdrawn begins to depend heavily on H_0 and increases. This indicates that a portion of the withdrawn power is now consumed for the excitation of DE waves, and it permits us to evaluate the effectiveness of excitation. According to curve I, SW input power P_{in} is not essentially an oscillatory function of H_0. Curve II represents (in db) the signal at the receiving antenna $K(H_0 = 10 \log(P_{\text{out}}/P_0)$. The observed oscillations in this signal cannot be explained as interference in the output circuit. The interference peaks (between induction and SW, including the SW circulating the film along the substrate boundary) are found from the condition $q_x(H_0)L \sim n\pi$, where $q_x(H_0)$ is the wave number of a DE wave, and

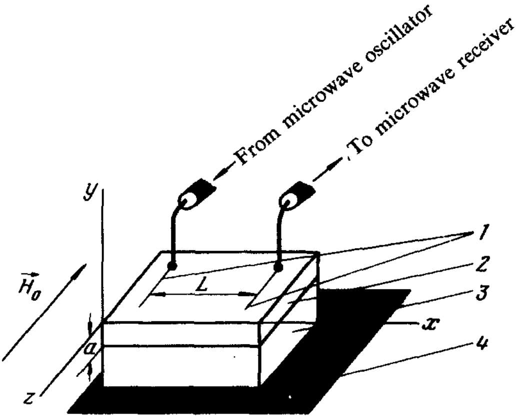

FIG. 1. Layered structure: 1—microbands, 2—YIG film, 3—substrate, 4—metal base.

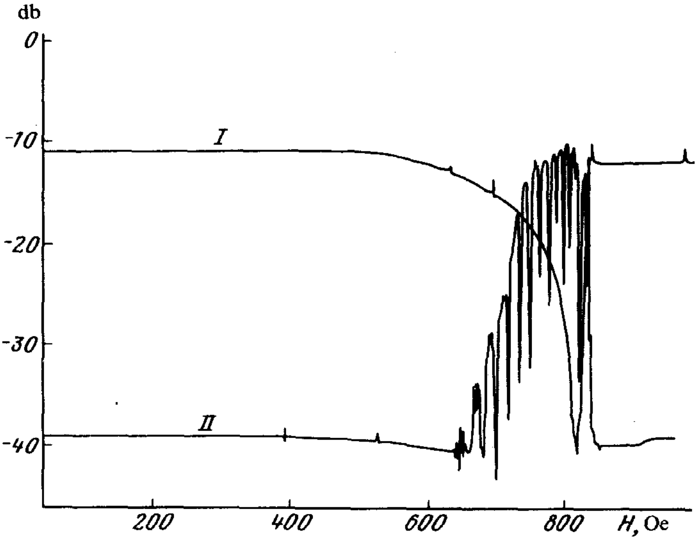

FIG. 2.

n is an integer. Hence, spacing between the peaks along the H_0 axis is obtained for our parameters $\sim 4\times 10^{-2}$ Oe, which is almost one-third of the order of the experimental oscillation period in Fig. 2. Interference is actually observed only at the extreme left portion of the oscillation region, which may be explained by the weakening of the SW amplitude that becomes comparable to the induction amplitude.

On the other side the number and position of dips in Fig. 2. agree accurately with the number and position of transverse spin-wave resonance (SWR) lines[5] that at $n \gg 1$ can be found from the condition $q_x\ (H_0, \nu) = n\pi$, where

$$q_y(H_0, \nu) = \sqrt{\frac{2\pi}{\alpha}}\ \sqrt{\sqrt{1-(\beta/4\pi)+(4\nu^2/\nu_m^2)} - 1 + (\beta/4\pi) - (2\nu_H/\nu_m)}, \tag{1}$$

$\alpha = 3.3\times 10^{-11}$ cm^2 is an inhomogeneous exchange constant for YIG, $\nu_H = \gamma H_0$

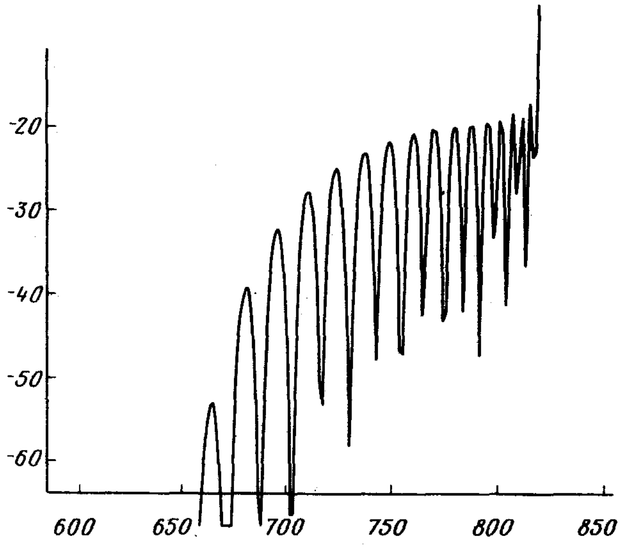

FIG. 3.

($\gamma = 2.8$ GHz/kOe), $\nu_m = 4\pi\gamma M_0 = 1760$ G, the cubic anisotropy is neglected and $\beta M_0 = 130$ Oe is an axial volumetric film anisotropy constant (β was found from the condition of coincidence of the right boundary of the DE spectrum with the resonant field of homogeneous precession). The function q_x (H_0, ν) represents the wave number of spatial SW traveling normally to the film surface. Such waves may be generated by the DE waves in the film,[1] provided there are anisotropy jumps at its surface. When the SWR occurs in the plane-parallel resonator film the highest energy is stored, which derives from the DE wave, which also explains, as we see it, the P_{out} dips in Fig. 2. This explanation agrees with all the experimental data. In particular, as the film thickness "a" increases, oscillations of P_{out} gradually attenuate and at $a > 6$ μm disappear altogether. At sufficiently high values of "a" (see Ref. 1 for a criterion) SW generated at a depth in the film are damped, being unable to reach the opposite edge and reflect. Moreover, attenuation of the DE wave should monotonically depend on H_0[6] and this is observed. We have formulated a theory of DE-wave propagation in a thin film which is generalized[1] for the case of arbitrary values $(2q_x a)$ and allowing for anisotropy. Based on this theory we calculated the function $K(H_0)$ and compared it with the experimental curve II in Fig. 2.

To obtain the best agreement, the parameter for spin attachment at the surface $|d_s|$[5] in 2×10^5 cm^{-1} for the free and 1.4×10^4 cm^{-1} for the film surfaces adjacent to substrate ($d_s < 0$). Such values of d_s lie within a sensible range.[5] The theoretical curve $K(H_0)$ is shown in Fig. 3. As can be seen, it conveys the correct general description of the entire picture of oscillations.

The DE wave spectrum discontinuities observed in Ref. 7 are explained by the excitation of SWR. However, it was a relatively weak effect in Ref. 7. In our case, the question concerns attenuation and not the spectrum. Moreover, giant attenuation oscillations are generated (comparable to attenuation itself). The observed effect is interesting inasmuch as it reveals the neutral structure of a DE wave in the ferrmagnetic films with a narrow FMR line. The existence of the transmission maxima must be considered when undertaking the observation of DE-wave amplification by the electron current in structures with an adjacent semiconductor.

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