Observation of spin-wave solitons in ferromagnetic films

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The phenomenon of self-induced transparency of spin systems is observed for the first time in pulse propagation of ultrahigh-frequency (uhf) spin waves in ferromagnetic films (FF). The experimentally recorded facts and the theoretical models reveal a soliton nature of the observed phenomenon.

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The investigations were conducted at room temperature using thin single-crystalline iron-yttrium garnet (IYG) films magnetized perpendicularly to saturation with low magnetic losses (dissipation parameter $\Delta H_k = 0.2$–0.3 Oe), grown on gadolinium-gallium garnet substrates with [111] orientation. The excitation and reception of spin waves (SW) were implemented with the help of the usual arrangement,[1] including short-circuited exciting and receiving microstrip antennas 30 μm wide and 4 mm long, formed photolithographically on a ceramic substrate. The distance between the antennas was 4 mm.

To perform the experiments, we chose specimens which were observed experimentally to be FF with fixed surface spins. Fixing of the surface spins leads to dipole-dipole "repulsion" of the dispersion branches, corresponding to waves with the same type of symmetry.[2] The dipole "repulsion," together with the exhange splitting (for thin FF, make the SW spectrum essentially a discrete spectrum[1)] (see Fig. 1a). The dispersion of the group velocity of SW is strong at frequencies near the dipole "gaps." Figure 1a shows the spectrum of symmetric type SW calculated for an IYG film with a thickness of $L = 5.8$ μm (with $\alpha = 3.1\times 10^{-12}$ cm^{-2}, $\omega_M = 4.9$ GHz, $\omega_H = 4.312$ GHz) according to the dispersion equation[2]:

$$(\omega^2 - \omega_n^2)(\omega^2 - \omega_\beta^2) = (\omega_H + \omega_M \alpha k_n^2)(\omega_H + \omega_M \alpha k_\beta^2) P_{n\beta}^2 \ . \qquad (1)$$

All of the notation is explained in Ref. 2. In the long-wavelength $kL < 1$ approximation, the matrix element is $P_{n\beta} = 2kL(2 - kL)/\pi^2 n^2 \beta^2$. Figure 1b shows the frequency dependences of the group velocities $V_g = \partial\omega/\partial k$, calculated using (1) for the fastest spin waves in the given frequency intervals. Curves of $\omega(k)$ and $V_g(\omega)$ in the vicinity of the "gap" $\beta = 1$, $n = 17$ are shown in the insert in Fig. 1c in a magnified scale.

The experiments on the pulsed linear propagation of SW were performed as follows. Pulses with duration $\tau = 100$ ns were introduced into the input antenna with repetition frequency 10^4 Hz with a power guaranteeing linear propagation of SW. The carrier frequency was chosen in one of the intervals between "gaps" (for example, equal to ω_1 in Fig. 1c), i.e., in the region of comparatively weak dispersion. A delayed pulse was then recorded by the output antenna (Fig. 2a) (the first pulse in the oscillo-

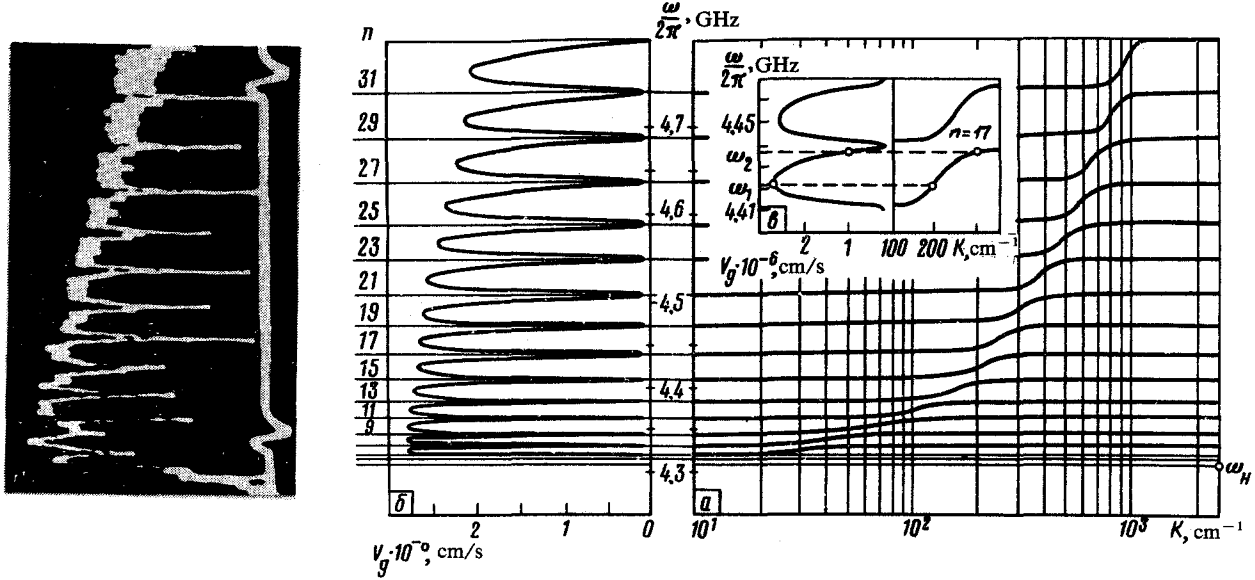

FIG. 1. Spectrum (a,c) of SW, group velocity of SW (b,c), and amplitude-frequency characteristic (d) of the FF obtained in the linear regime.

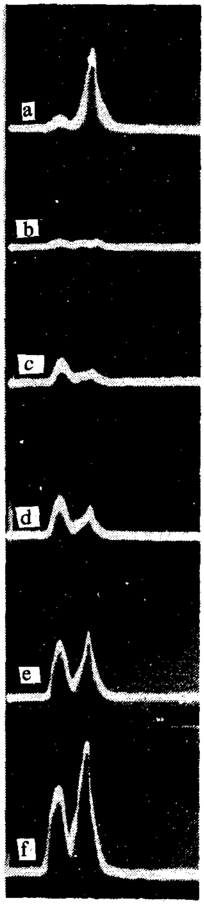

FIG. 2. Oscillograms of the envelope of the signal pulse, passing through the FF for different values of the carrier frequency (a,b) and output power (c,d,e,f). (The oscillograms were obtained at frequencies situated near "gaps" $\beta = 1$, $n = 17$.)

grams in Fig. 2 correspond to the input signal). The carrier frequency was then gradually increased while holding the power level of the input pulse $P_{\rm in}$ constant. This led to dispersion spreading of the delayed pulse and to a change in its shape so that at the frequency ω_2 near the "gap" (Fig. 1c) this pulse acquired a double-hump with two peaks, corresponding to the longer and shorter delay times, while its amplitude decreased (Fig. 2b). Further increase in $P_{\rm in}$ while keeping the carrier frequency ω_2 constant led to the formation of a soliton from the second peak of the delayed pulse (corresponding to the longer delay time). Figures 2c–2f illustrate the change in shape of the soliton with increasing input power. Figure 3 shows the dependence of the delay of the pulsed UHF signal passing through the FF on its power. It is evident that a soliton forms at some value of $P_{\rm in}$ (see Fig. 2c), i.e., self-induced transparency of the spin system arises; in addition, at $P_{\rm in} = P_1$ we have a maximum "bleaching" (Fig. 3) and a maximum amplitude of the soliton (Fig. 2f). With a further increase in $P_{\rm in}$, the soliton fragments and its amplitude decreases.

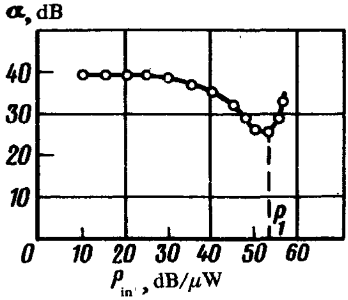

FIG. 3. Dependence of damping of the signal pulse propagating in FF on the input power.

Soliton formation was recorded on FF with a thickness from 4 to 7 μm and, in addition, it always occurred at frequencies lying in direct proximity to, but 1–3 MHz lower than, one of the dipole "gaps," where V_g decreases with increasing frequency. In the frequency intervals between "gaps," soliton formation was not observed up to an input power of 1 W.

The observed effect can be explained qualitatively within the framework of the theory of nonlinear waves.[3]

For dipole-exchange SW, described by the dispersion equation (1), using a well-known method,[3] we obtain a nonlinear parabolic equation describing the evolution of the envelope of the complex amplitude of the variable magnetization $\varphi(x, t)$ SW:

$$\mathrm{i}\left(\frac{\partial\varphi}{\partial t} + V_g\frac{\partial\varphi}{\partial x}\right) + \frac{1}{2}\frac{\partial^2\omega}{\partial k^2}\frac{\partial^2\varphi}{\partial x^2} - \frac{\partial\omega}{\partial|\varphi|^2}|\varphi|^2\varphi = 0\,. \tag{2}$$

Equation (2) has soliton solutions if $(\partial\omega/\partial|\varphi|^2\,\partial^2\omega/\partial k^2) < 0$. Introducing into the dispersion law (1) the dependence on $|\varphi|^2$, analogously to Refs. 4 and 5, and calculating the derivatives, it is not difficult to verify that the inequality presented above is satisfied in the frequency ranges below the "gaps," where $\dfrac{\partial^2\omega}{\partial k^2} = V_g\dfrac{\partial V_g}{\partial\omega} < 0$. Thus the predictions of the theory coincide with experiment in regions of strong dispersion of SW below the dipole "gaps" in the spectrum.

The theory[5] constructed in the no-exchange approximation predicts the formation of solitons of weakly dispersive SW. In the experiments described, such solitons could have been observed between the "gaps," where the dispersion of SW is comparatively weak. However, we were unable to record solitions in these sections of the spectrum. This can presumably be attributed to the consiserable difference in the real dipole-exchange and no-exchange dispersion laws, which occurs at frequencies lying not only near the "gaps" but between them as well, if the "gaps" are situated sufficiently close to each other.

The described behavior of solitons is very similar to the behavior of magnetoacoustic solitons in $KMnF_3$,[6] which were also observed in the region of strong dispersion, where $\partial V_g/\partial\omega < 0$.

We also observed the formation of solitons in tangentially magnetized IYG films with excitation of the quasisurface SW. It also occurred in frequency ranges near, but above the dipole "gaps" in the spectrum, while the soliton, in contrast to the case of perpendicular magnetization of FF, formed out of the first maximum of the pulse corresponding to the shorter delay time, rather than from the second maximum of the delayed pulse (see Figs. 2b and 2c).

[1)]In the case of free surface spins, the dipole "gaps" in the spectrum are so small that they "are smeared" by relaxation processes.

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