Dynamics of photoinduced self-propagating spin waves in magnetic materials

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A theory of light-induced formation of self-propagating macroscopic spin waves in a weak ferromagnet with a photoinduced magnetic anisotropy is derived.

Fedorov *et al.*[1] detected in a weak ferromagnet—iron borate with a nickel impurity ($FeBO_3$:Ni)—the formation and light-induced motion of periodic planar macroscopic magnetization inhomogeneities, which may be classified as self-propagating spin waves with a low frequency ω, $\omega \sim 10$ Hz. It was also shown in Refs. 1 and 2 that a prolonged exposure of $FeBO_3$:Ni to light leads to the appearance of a photoinduced uniaxial magnetic anisotropy (PUMA) of the type

$$W = \frac{1}{2} fM_0^2 \cos [2(\varphi - \varphi')], f > 0, \qquad (1)$$

where M_0 is the sublattice magnetization, φ specifies the instantaneous direction of the weak ferromagnet, the moment **m** in the basal plane, and φ' is the direction of **m** during the exposure to light. The given sign of the PUMA constant, $f > 0$, corresponds to the electric displacement of the easy axis for **m**, which is perpendicular to **m** during the exposure to light, a possible cause, as was noted in Ref. 1, of the instability of **m** and the appearance of self-propagating waves.

In this letter we give a systematic description of the photoinduced nonlinear self-propagating waves, taking into account the photoinduced uniaxial magnetic anisotropy such as that in (1) in a dynamic regime. We will work from the effective equation for **m** (see Ref. 3) in an easy-plane weak ferromagnet, which is written in terms of the angle φ with allowance for the lag due to the continuous "adjustment" of the easy axis in the basal plane to match the direction of **m**:

$$\frac{\alpha}{c^2}\frac{\partial^2\varphi}{\partial t^2} - \alpha\,\Delta\varphi + \frac{\lambda}{gM_0}\left(\frac{\partial\varphi}{\partial t}\right) + \beta\sin 6\varphi + \frac{2(\mathbf{H}+\mathbf{H}_m)}{M_0}\frac{\partial\mathbf{m}}{\partial\varphi}$$

$$= f\hat{L}\{\varphi\} = f\int_{-\infty}^{t}\sin(2[\varphi(t)-\varphi(t')])\exp[(t'-t)/\tau]\,dt'/\tau\,. \qquad (2)$$

Here c is the velocity of the spin waves; α is the inhomogeneous-exchange constant; **H** is the external field; $\mathbf{H}_m$ is the demagnetizing field of the free ferromagnet; $\mathbf{m} = m_\perp^0(\mathbf{e}_x\cos\varphi + \mathbf{e}_y\sin\varphi) + \mathbf{e}_z m_z^0\sin 3\varphi$, $m_z^0 \ll m_\perp^0$; and λ is the damping constant. In writing the anisotropy (the component $\beta\sin 6\varphi$) and $\mathbf{m}(\varphi)$ we work from the rhombohedral symmetry of the weak ferromagnet with the basal plane in the xy plane. The right side (the integrated term) in (2), which defines the PUMA in the dynamic regime, allows us to describe the dynamics of **m** for arbitrary relationship between the characteristic variation time of **m**; $t_{\text{char}} \sim 1/\omega$, and the time τ it takes the PUMA to form (according to a quasistatic experiment,[2] $\tau \sim 10^3$ s). We will show that this term changes the dynamics of **m** significantly. If φ changes slowly ($\omega\tau \ll 1$), we have $f\hat{L}\{\varphi\} = 2f\tau(\partial\varphi/\partial t) + \ldots f(\omega\tau)^2$, and PUMA renormalizes the damping: $\lambda \to \lambda_{\text{eff}} = \lambda - 2f\tau g M_0$. If the value $(\omega\tau)$ is fairly large, the anisotropy constant β is also renormalized (see the discussion below).

For the case $f > 0$, which is realized in $FeBO_3$:Ni, allowance for PUMA reduces the effective relaxation.[1)] If f is large enough, $2f\tau g M_0 > \lambda$ (for $FeBO_3$:Ni this condition is satisfied with a wide margin even when $\lambda \sim 1$), the sign of the effective damping will change, which may destabilize the low-frequency magnetization perturbations and lead to the appearance of self-propagating waves.

To describe the self-propagating waves, we seek a periodic steady-state solution of Eq. (2) against the background of the ground state ($\varphi = \varphi_0 = 0$). A slightly nonlinear self-propagating wave in a weak ferromagnet in the form of a parallel-face plate of thickness l, cut out parallel to the basal plane, is described by

$$\varphi = a(z)\sin(k_x x + k_y y - \omega t) + a_3(z)\sin[3(k_x x + k_y y - \omega t)] + \ldots, \qquad (3)$$

where $a \ll 1$, $a_3 \sim a^3$; the functional dependence $a(z)$ is determined by the nonlocal magnetic-dipole interaction (the field H_{mz}).

If $l \gg l_0 \cong (\alpha/\pi)^{1/2}(M_0/6m_z^0)$, $a(z) = a\cos(\pi z/l)$; z is reckoned from the middle of the plate. The relationship between the parameters of the self-propagating wave, ω and $\mathbf{k}$, and the amplitude a in a field $\mathbf{H}$ oriented in the basal plane along the easy axis x is given by (if $\omega\tau > 1$)

$$\omega^2 = \omega_c^2\,(1 - 3a^2/4), \quad Aa^2 + Ba^4 = H_c(\mathbf{k}) - H, \tag{4}$$

where

$$\omega_c = (2fgM_0/\lambda\tau)^{1/2}, \quad A = (M_0/4m_\perp^0)\,(11f - 105\beta), \quad B > 0, \tag{5}$$

$$H_c(\mathbf{k}) = (M_0/m_\perp^0)\{\,2f - 6\beta - \alpha k^2 - (4\pi/k^2)\,[(m_\perp^0 k_y)^2 + (m_z^0\pi/l)^2\,]\,\}. \tag{6}$$

Let us analyze on the basis of Eqs. (4)–(6) the generation of a self-propagating wave in the case of a decreasing external field H. We consider the case $A > 0$, which corresponds to a large enough value of f ($f \gtrsim 9.5\beta$). There is no self-propagating wave solution (3) in the case of high fields H. Such a solution first appears when H is equal to the maximum value of the function $H_c(\mathbf{k})$. Equation (6) implies that this equality is achieved if the wave vector $\mathbf{k}$, which is parallel to the x axis, is nonzero, in complete agreement with the experiments of Refs. 1 and 5. According to these experiments, a self-propagating wave with a wave vector $\mathbf{k}$ parallel to the field is formed in an external field $\mathbf{H}$ parallel to the easy magnetization axis, while three systems of self-propagating waves with various $\mathbf{k}$, but in each domain of $\mathbf{k}$ having parallel magnetization, are generated in the demagnetized state ($H = 0$).[1] The value $k \cong k_0$, $k_0 = 2[9\pi^3(m_z^0)^2/\alpha l^2]^{1/4} \sim (ll_0)^{-1/2}$ corresponds to the time at which a self-propagating wave is generated. The nonlocal magnetic-dipole interaction jointly with PUMA thus determines the direction of propagation of a self-propagating wave and forms its spatial period.

Upon further decrease of H, the amplitude of the self-propagating wave increases in accordance with (see Fig. 1).

$$a = [\,(H_c\,(k_0) - H)\,/\,A\,]^{1/2}. \tag{7}$$

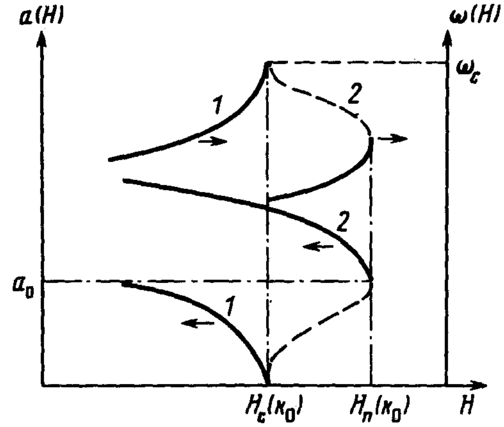

FIG. 1. The amplitude a and the frequency ω of a self-propagating wave versus the external field H. Curves 1—$A > 0$; curves 2—$A < 0$. Dashed curve—regions corresponding to an unstable self-propagating wave.

In the case of smaller values of f ($f < 9.5\beta$, $A < 0$), there is a propagating-wave solution at $H = H_p(k_0)$, $H_p(k_0) > H_c(k_0)$ with a finite amplitude a_0, $a_0 \cong [-A/B]^{1/2}$ when $|A| < B$. If $f > 3\beta$, the homogeneous ground state will be unstable with respect to the periodic perturbations with $k \cong k_0$ if $H_c(k) > 0$ (see Fig. 1). If, on the other hand, $(\lambda / 2gM_0\tau) < f < 3\beta$, then at $H > 0$ the ground state will be stable with respect to the periodic perturbations, but there will be a kind of instability of spatially inhomogeneous perturbations with imaginary k, of the form[6] $\varphi \propto \exp(\pm |k| x)$. Such perturbations occur near static domain-wall magnetization inhomogeneities, near macroscopic defects, etc. If the value of f is small, the amplitude of the self-propagating wave will be fairly large ($a \sim 30°$) and its shape will be nonsinusoidal.[6]

The appearance of a self-propagating wave can thus be treated as a bifurcation (a phase transition in a nonequilibrium system) in a magnetic field. This is a first-order phase transition if f is small and a second-order transition if $f > 9.5\beta$. The latter case is apparently realized in the experiment. For typical values of the constants $2fM_0 \cong 0.1$ Oe, $\tau \sim 10^3$ s, $\lambda \sim 0.1$, and $\omega_c \sim 10$–100 Hz. An estimate of l_0 shows that it is on the order of the thickness of the plate used in the experiment, and the period of the self-propagating wave, $\Lambda \cong (ll_0)^{1/2} \sim l_0$, is found to be $\Lambda \sim 100$ μm. These estimates, the structure of self-propagating wave (3), and the dependence $\omega_c^2 - \omega^2 \propto a^2$ [see Eq. (4)] are in good agreement with the experimental data of Refs. 1, 5, and 7.

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[1)] At $f > 0$ such a behavior stems from the fact that PUMA in this case destabilizes the instantaneous position of **m**, while at $f < 0$ it stabilizes the instantaneous position of **m**. Without consideration of the microscopic nature of PUMA, we note that in a system close to thermodynamic equilibrium the instantaneous position of **m** can only be stabilized (magnetic viscosity is an example). Since an optically pumped magnetic material is a system in a strongly nonequilibrium state, f can have any sign. Experiment shows that $f > 0$ in nickel- and chromium-doped iron borate and $f < 0$ in manganese- and copper-doped iron borate.[2,4]

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