Photoinduced autowave processes in magnetic materials

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A theoretical model of an active magnetic medium is proposed. Photoinduced autowaves can propagate as a moving periodic domain structure in this medium.

Fedorov *et al.*[1] have discovered an interesting experimental effect: Illuminating iron borate with a nickel impurity ($FeBO_3$:Ni) at a wavelength $\lambda = 0.8$–$1\ \mu$m induces a magnetic structure which is similar to a domain structure and which moves in a steady state. Somewhat analogous effects were observed by Gornakov *et al.*,[2] who observed the motion of a system of Bloch lines induced by an rf electromagnetic field. These moving magnetic structures can apparently be identified as "autowaves" (the term was introduced by R. V. Khokhlov), whose steady-state propagation is maintained by external radiation. Autowaves have been studied experimentally and theoretically in connection with chemical, biological, and semiconducting media.[3] To the best of our knowledge, on the other hand, there has been no previous study of autowave processes in magnetic media. In this letter we propose a theoretical model of an active magnetic medium in which autowaves may exist.

For definiteness, we consider an antiferromagnetic crystal of orthorhombic symmetry, in which the antiferromagnetism vector **l** lies in the xy plane (the easy plane). We specify the orientation of **l** by the angle φ, measured from the x axis. The Lagrangian and a dissipative Rayleigh function of this dynamic problem can be written[4]

$$L = (\chi_\perp / 2\gamma^2)\dot{\varphi}^2 - A(\nabla\varphi)^2 - \Phi(\varphi), \quad R = (\alpha M_0 / 2\gamma)\dot{\varphi}^2, \tag{1}$$

where $\Phi(\varphi) = (1/2) K_1 \cos 2\varphi + (1/8) K_2 \cos 4\varphi$ is the free energy of the homogeneous system, A is the inhomogeneous-exchange constant, $K_{1,2}$ are the anisotropy constants, $\chi_\perp$ is the transverse susceptibility, M_0 is the sublattice magnetization, γ is the gyromagnetic ratio, and α is the damping factor. In the one-dimensional case, the Lagrange-Euler equation of system (1) is

$$\ddot{\varphi} + \alpha\omega_E\dot{\varphi} - c^2\varphi'' = {}^1/_2\, \omega_E\omega_1 \sin 2\varphi + {}^1/_4\, \omega_E\omega_2 \sin 4\varphi, \tag{2}$$

where

$$\omega_E = \gamma M_0 / \chi_\perp, \; c^2 = 2\gamma^2 A/\chi_\perp, \; \omega_{1,2} = 2\gamma K_{1,2} / M_0 .$$

We assume that the light causes a change in the anisotropy constants $K_{1,2} = K_{1,2}(N)$, which is determined by the density (N) of excited ions. This density satisfies

$$\dot{N} = [N_I f(\varphi) - N]/ T, \tag{3}$$

where N_I is proportional to the intensity (I) of the incident radiation ($N_I = \kappa I$), T is the lifetime of the excited states, and the function $f(\varphi)$ characterizes the anisotropy of the excitation rate (i.e., of the rate of the absorption of the radiation) for the various orientations of l. The particular form of the function $f(\varphi)$ is unimportant for our purposes. According to the axial model of the anisotropy in the absorption of light,[5] we can set $f(\varphi) = \cos^2 \varphi$.

Let us assume that the system is near a first-order orientational phase transition, which occurs between the states $\varphi = 0, \pi$ and $\pm \pi/2$ at an excited-ion density $N = N_0$, determined from the conditions $K_1(N_0) = 0$, $K_2(N_0) < 0$. We assume that the lifetime T is long in comparison with the scale times of the magnetic system, $\alpha/|\omega_2|$; i.e., we assume that we have a small parameter $\epsilon = \alpha/|\omega_2|T \ll 1$. In this case the motion of the system described by Eqs. (2) and (3) can be broken up into regions of fast and slow motions.[6] Slow motions are characterized by a change in the density N described by Eq. (3) with $\varphi = \text{const}$, while fast motions are characterized by a change in the angle φ, determined from (2) with $N = \text{const}$.

The overall picture of the steady-state motion of the system is conveniently described by trajectories in an N, φ, φ' phase space (Fig. 1). In the case of a homogeneous system, there may be a self-oscillatory motion, which corresponds to trajectory *KLPQ*. We are interested in the steady-state motion of the inhomogeneous system $[N = N(x - vt), \varphi = \varphi(x - vt)]$, consisting of a periodic domain structure of alternating phases $\varphi = 0, \pi/2$. It corresponds to a trajectory of the type *DRABSC* in Fig. 1. The regions of fast motion, *DRA* and *CSB*, correspond to moving 90° domain walls between the $\varphi = 0$ and $\pi/2$ phases. The distribution of the angle φ in them is determined by Eq. (2) with $N = \text{const}$ and is given by

$$\tan\varphi = \exp\left[\pm(x - vt)/\Delta(v)\right], \quad \Delta(v) = \Delta_0 (1 - v^2/c^2)^{1/2}, \tag{4a}$$

$$v = \mp \mu H_A(N)\left[1 + \mu^2 H_A^2(N)/c^2\right]^{-1/2} \equiv \mp u(N), \tag{4b}$$

where $\Delta_0 = [A/|K_2(N)|]^{1/2}$, $H_A(N) = 2K_1(N)/m_s$, $\mu = \gamma\Delta_0 m_s/\alpha M_0$ is the mobility of a domain wall, and m_s is the spontaneous weak-ferromagnetic moment. Expression (4b) links the velocity (v) of a domain wall to the deviation of the system from the point of the phase equilibrium, N_0, characterized by the anisotropy field $H_A(N)$.

We now consider slow motions corresponding to regions *AB* and *DC* in Fig. 1, in which there is a change in N with $\varphi' = 0$ and $\varphi = 0, \pi/2$. We denote the period of the domain structure by $x_0 = x_1 + x_2$, where $x_{1,2}$ are the dimensions of the domains of the $\varphi = 0$ and $\varphi = \pi/2$ phases. Assuming $N(0) = N(x_0) = N_2$ and $N(x_1) = N_1$ at $t = 0$, we find from (3)

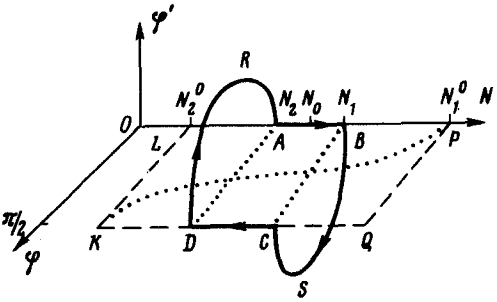

FIG. 1. Phase diagram of system (2), (3) for self-oscillatory processes (dashed lines) and autowave processes (solid lines).

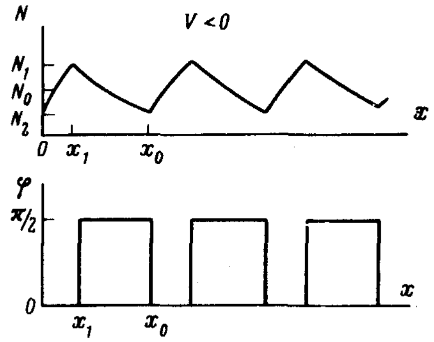

FIG. 2. Distribution of the density N and of the angle φ in a moving periodic domain structure.

$$N(\tilde{x}) = \begin{cases} N_I - (N_I - N_2)\exp(\tilde{x}/vT), & mx_0 < \tilde{x} < mx_0 + x_1, \quad \varphi = 0, \\ N_1 \exp[(\tilde{x} - x_1)/vT], & mx_0 + x_1 < \tilde{x} < (m+1)x_0, \quad \varphi = \pi/2, \end{cases} \tag{5}$$

where $\tilde{x} = x - vt$, $m = 0, \pm 1, \pm 2, \ldots$. From the condition that all the domain walls in the structure move at the same velocity v, we find from (4b) a relationship among v, N_1, and N_2: $v = -u(N_1) = u(N_2)$. If the deviation (ΔN) from N_0 is small, we find

$$N_{1,2} = N_0 \pm \Delta N, \qquad v = -\mu(dH_A/dN)_0 \Delta N. \tag{6}$$

For definiteness, we assume $(dH_A/dN)_0 > 0$; at $N_1 > N_2$ the velocity of the domain wall is then negative, while at $N_2 > N_1$ it is positive. Figure 2 shows N and φ as functions of x for $N_1 > N_2$. The physical mechanism for the motion of the domain structure as a whole is that the inhomogeneous distribution of the density (N) of excited ions within a single $\varphi = 0$ or $\pi/2$ domain causes a pressure force in the same direction to act on the corresponding domain walls, since the density N at one end is higher than N_0, while that at the other is lower than N_0. Under the self-consistency conditions (6), these forces are identical. From (5) and (6) we easily find the relationship between the velocity (v) of the autowave and its period x_0. For $\Delta N \ll N_0$ we have

$$v^2 = \mu\left(\frac{dH_A}{dN}\right)_0 N_0 \left(1 - \frac{N_0}{N_I}\right)\frac{x_0}{2T}. \tag{7}$$

To find the maximum autowave velocity $(N_I \gg N_0)$ for a given x_0, we adopt $\mu = 10^3$ cm/(s·Oe), $(dH_A/dH)_0 N_0 \sim 10^{-2}$–1 Oe, and, in accordance with Ref. 1, $x_0 \sim 10$ μm and $T \sim 10^2$ s. We find $v = 10$–100 μm/s.

This model can be generalized quite easily to any magnetic material which has a first-order orientational phase transition at which there is a photoinduced change in the anisotropy energy. This model can also be generalized to systems (e.g., ferroelectrics) with a first-order phase transition at which there is a photoinduced change in the parameters of the Landau thermodynamic potential.

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