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The Possibility of Controlling the Dynamics and Structure of a Magnetic Soliton in a Three-Layer Ferromagnetic Structure

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Abstract—Generation and excitation of a magnetic soliton in a three-layer ferromagnet using dc magnetic fields and weak ac fields in the presence of dissipation in the system have been considered. An analysis of the solutions to the equation of motion in an ac field shows the possibility of increasing the magnetic-soliton amplitude with time under certain conditions. The resonance effect is also affected by the geometric parameters of the thin layer: the translational mode of soliton oscillations is excited at a large layer width.

Keywords: three-layer ferromagnet, magnetic soliton, localized magnetic inhomogeneities, self-resonance.

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Lately, there have been many studies devoted to the use of magnetic inhomogeneities (magnetic vortices and skyrmions) in spintronic devices [1, 2]. Soliton-type magnetic inhomogeneities, which have many similar dynamic properties, may serve as an alternative [3]. The development of new experimental techniques that make it possible to analyze the processes of formation and propagation of nanoscale localized magnetization waves and their interaction with domain walls (DWs) [4–6] also stimulated an increase in applied interest in this field [7]. The key problem of designing new devices lies in determining the conditions for generation of stable localized magnetization waves, such as magnetic solitons (MSs) and breathers. It is known that this generation is quite possible in the region of a magnetic "defect," which is a one-, two-, or three-dimensional potential well for a magnetic inhomogeneity (see, e.g., [8–11]). In the one-dimensional case, these magnetic "defects" can be formed by means of multilayer magnetic structures consisting of alternating layers of two materials with different physical properties (e.g., magnetic anisotropy) [12]. The magnetization dynamics can be controlled using an external magnetic field [13] and taking into account damping in the system. The purpose of this Letter was to consider the possibility of controlling the parameters of an MS in a three-layer ferromagnet by dc magnetic fields and weak ac fields using a self-resonance control model in the presence of dissipation in the system.

Let us consider a three-layer ferromagnetic structure consisting of two wide identical layers separated by a thin layer with a changed magnetic anisotropy parameter [14]. The anisotropy parameters are assumed to be functions of coordinate x directed perpendicular to the layer interface. Generally, when solving dynamic problems, it is convenient to move to spherical coordinates θ and φ of magnetization vector $\mathbf{M}$, where $0 \le \theta \le 2\pi$ is the angle in the yz plane between vector $\mathbf{M}$ and the easy magnetization axis (Oz axis) and $-\pi/2 < \varphi < \pi/2$ is the angle describing the emergence of $\mathbf{M}$ from the DW plane. Taking into account the exchange interaction and anisotropy in the energy density of a magnet and assuming that $\varphi \ll 1$, the equation of motion for magnetization can be written as

$$\Delta\theta - \ddot{\theta} - \frac{1}{2} f(\mathbf{r}) \sin 2\theta = h \sin\theta + \alpha\dot{\theta}, \qquad (1)$$

where $f(\mathbf{r}) = K_1(x)/K_1^0$ is the function determining the spatial modulation of the anisotropy constant, K_1^0 is the anisotropy constant in thick layers, $h = (H_Z/4\pi M_S)Q^{-1}$ is the normalized external magnetic field, $\alpha = \alpha_0/\sqrt{Q}$ is the normalized decay constant, $Q = K_1^0/(2\pi M_S^2)$ is the material quality factor, α_0 is the decay constant, time t is normalized to $4\pi M_S \gamma \sqrt{Q}$, and coordinate x is normalized to the width of a static

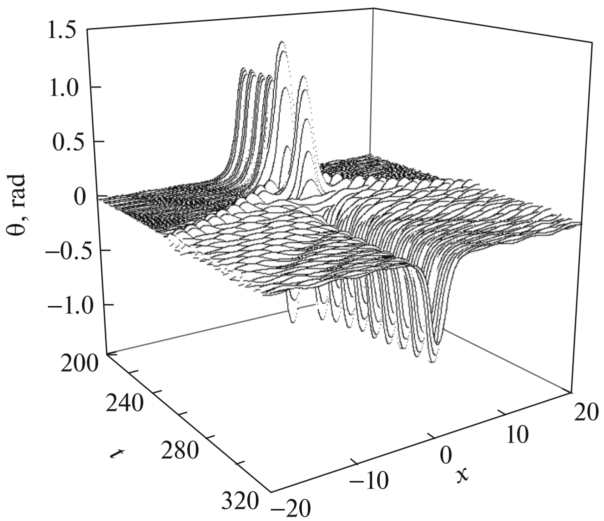

Fig. 1. Magnetization reversal of a soliton-type magnetic inhomogeneity: a resting soliton existed at $h = 0.32$ until instant $t = 220$, and the magnetization reversal occurred after $t = 220$ (a field with $h = 0.6$ is switched on): $W = 2$, $K = -2$, and defect-region center coordinates $x = 0$.

Bloch DW. In the one-dimensional case, function $f(x)$ is simulated for simplicity in the form of a rectangle:

$$f(x) = \begin{cases} 1, & |x| > W_x/2, \\ K, & |x| < W_x/2, \end{cases} \quad (2)$$

where W is the parameter characterizing the thin-layer width and K is the value normalized to the magnetic anisotropy constant in the thin-layer region. It should be noted that other forms of function (2) (e.g., Gaussian) change the set of parameters, which induce the formation of an MS and its eigenfrequency [9].

Equation (1) was solved numerically using the explicit integration scheme [14]. For this purpose, a three-layer scheme of solution with approximation of derivatives using a five-point stencil of cross type was chosen [11]. The scheme of the numerical experiment is as follows. The magnetization distribution at the initial instant was set in the form of Bloch DW $\theta_0(x) = 2\arctan(e^x)$ located far from the thin layer. It is known that, at some values of the thin-layer parameters, a magnetic inhomogeneity in the form of magnetic breather or soliton is formed upon passage of a DW with a constant velocity through this layer. The case of magnetic breather in an external ac magnetic field was considered previously in [14]. Let us now consider soliton-type magnetic inhomogeneities. At a large distance from the thin layer, the Bloch DW velocity and the decay constant are assumed to be, respectively, 0.85 and 0.001 (in dimensionless units). Formation of a soliton-type magnetic inhomogeneity is observed in the thin-layer region beginning with some parameter values ($W = 1.9$ and $K = -1.4$). At $W \geq 2$ and $K < -1.8$, one can observe the formation of a magnetic antisoliton with the opposite (with respect to the soliton) magnetization direction at its center.

Having applied an external dc magnetic field directed opposite to the magnetization at the MS center, one might obviously expect (as for the case of mag-

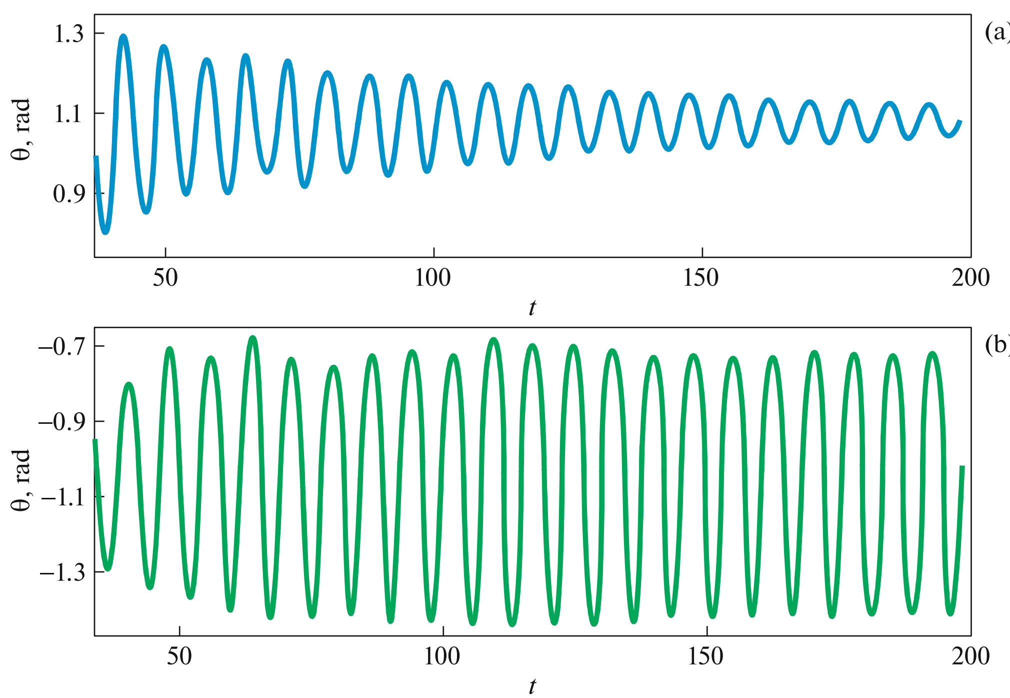

Fig. 2. Time dependences of the soliton amplitude (a) without a field and (b) in an ac field: $h_0 = 0.1$, parameter $\mu = 0.01$, initial field frequency 0.83, and well parameters $W = 2$ and $K = -1.4$.

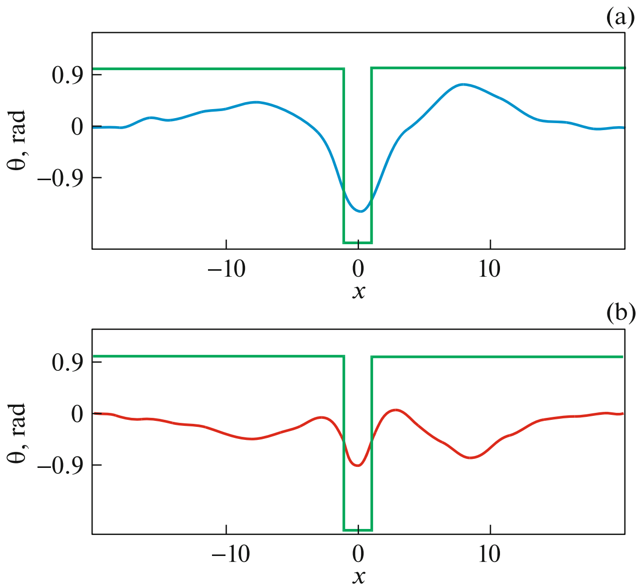

Fig. 3. Oscillations of an antisoliton with emission of spin waves in the absence of damping at different instants: t = (a) 153 and (b) 156 ($W = 2$, $K = –2$, $h_0 = 0.1$, $\mu = 0.01$, and initial field frequency 1.0).

netic vortices in spin-valve structures [11]) magnetization reversal at the MS center at some critical magnetic field strength. Such reversal and MS transformation into an antisoliton were observed at $h = 0.6$, $W = 2$, and $K = –2$ (Fig. 1). Note that, as in the case of magnetic vortices in spin-valve structures [11], a sufficiently strong dc field should be applied.

Let us now consider the case of application of an external ac magnetic field and the use of self-resonance phenomenon for controlling the dynamic characteristics of an MS. It is known that the use of self-resonance control models makes it possible to reduce significantly the magnitude of an external effect on a system [15–17]. The field frequency has the following form: $\omega = \omega_0 + \mu t$, where ω_0 is the soliton eigenfrequency and μ is a small parameter. Let us consider the case of $K = –1.4$ and $W = 2$, where an MS with an oscillating amplitude is generated in the thin layer after passage of a DW through it in the absence of field (Fig. 2a). At $h_0 = 0.1$, $\mu = 0.01$, and $\omega_0 = 0.83$, generation of a magnetic antisoliton is observed after passage of a DW through the thin layer. The soliton amplitude in the absence of magnetic field decreases with time, whereas in an ac field with a certain frequency (related to the MS eigenfrequency), the magnetic antisoliton amplitude increases by a factor of 2 (Fig. 2); however, further increase in the amplitude is limited due to emission of spin waves. A similar situation is observed in an ac magnetic field with an increase in the parameter K: the amplitude of magnetic antisoliton oscillations increases by a factor of 2 (albeit at another, changed frequency, because the antisoliton frequency depends on the thin-layer parameters). This limitation on the increase in the oscillation amplitude is caused by the fact that the antisoliton center does not remain at the thin-layer center and the translational mode of its oscillations along coordinate x is also excited, accompanied by emission of bulk spin waves. These waves are most pronounced in the absence of damping (Fig. 3). A sufficiently small thin-layer width induces disappearance of the translational mode of MS oscillations. In this case, one can achieve a larger increase in the soliton amplitude (by almost an order of magnitude) in an ac magnetic field (in comparison with the case without a field).

It follows from the performed investigation that the self-resonance model of controlling an MS in a three-layer ferromagnet makes it possible to use weak ac fields, which may find application in magnetic memory devices.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. C. Li, S. Wang, N. Xu, X. Yang, B. Liu, B. Yang, and L. Fang, J. Magn. Magn. Mater. **498**, 166155 (2019). https://doi.org/10.1016/j.jmmm.2019.166155
2. L. Shen, J. Xia, G. Zhao, X. Zhang, M. Ezawa, O. A. Tretiakov, X. Liu, and Y. Zhou, Appl. Phys. Lett. **114**, 042402 (2019). https://doi.org/10.1063/1.5080302
3. M. A. Shamsutdinov, I. Yu. Lomakina, V. N. Nazarov, A. T. Kharisov, and D. M. Shamsutdinov, *Ferro- and Antiferromagnetodynamics. Nonlinear Vibrations, Waves and Solitons* (Nauka, Moscow, 2009) [in Russian].
4. R. Kukreja, S. Bonetti, Z. Chen, D. Backes, Y. Acremann, J. A. Katine, A. D. Kent, H. A. Dürr, H. Ohldag, and J. Stöhr, Phys. Rev. Lett. **115**, 096601 (2015). https://doi.org/10.1103/PhysRevLett.115.096601
5. M. V. Gerasimov, M. V. Logunov, A. V. Spirin, Yu. N. Nozdrin, and I. D. Tokman, Phys. Rev. B **94**, 014434 (2016). https://doi.org/10.1103/PhysRevB.94.014434
6. D. Backes, F. Macià, S. Bonetti, R. Kukreja, H. Ohldag, and A. D. Kent, Phys. Rev. Lett. **115**, 127205 (2015). https://doi.org/10.1103/PhysRevLett.115.127205
7. P. J. Metaxas, M. Albert, S. Lequeux, V. Cros, J. Grollier, P. Bortolotti, A. Anane, and H. Fangohr, Phys.

Rev. B **93**, 054414 (2016).
https://doi.org/10.1103/PhysRevB.93.054414

8. E. G. Ekomasov, A. M. Gumerov, R. R. Murtazin, R. V. Kudryavtsev, A. E. Ekomasov, and N. N. Abakumova, Solid State Phenom. 233–234, 51 (2015). doi 10.4028/www.scientific.net/SSP.233-234.51
9. E. G. Ekomasov, R. R. Murtazin, and V. N. Nazarov, J. Magn. Magn. Mater. **385**, 217 (2015). https://doi.org/10.1016/j.jmmm.2015.03.019
10. A. M. Gumerov, E. G. Ekomasov, R. V. Kudryavtsev, and M. I. Fakhretdinov, Pis'ma Mater. **8**, 299 (2018). https://doi.org/10.22226/2410-3535-2018-3-299-304
11. E. G. Ekomasov, R. R. Murtazin, O. B. Bogomazova, and A. M. Gumerov, J. Magn. Magn. Mater. **339**, 133 (2013). https://doi.org/10.1016/j.jmmm.2013.02.042
12. D. D. Tang and Y.-J. Lee, *Magnetic Memory: Fundamentals and Technology* (Cambridge Univ. Press, New York, 2010). https://doi.org/10.1017/CBO9780511676208
13. V. N. Nazarov, L. A. Kalyakin, and M. A. Shamsutdinov, Solid State Phenom. **81**, 168 (2011). doi 10.4028/www.scientific.net/SSP.168-169.81
14. E. G. Ekomasov, V. N. Nazarov, A. M. Gumerov, K. Yu. Samsonov, and R. R. Murtazin, Pis'ma Mater. **10**, 141 (2020). https://doi.org/10.22226/2410-3535-2020-2-141-146
15. L. A. Kalyakin and M. A. Shamsutdinov, Theor. Math. Phys. **160**, 960 (2009). https://doi.org/10.1007/s11232-009-0086-3
16. S. V. Batalov and A. G. Shagalov, Phys. Met. Metallogr. **109**, 1 (2010). https://doi.org/10.1134/S0031918X10010011
17. S. V. Batalov and A. G. Shagalov, Phys. Met. Metallogr. **114**, 103 (2013). https://doi.org/10.1134/S0031918X13020038

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