Parametric spin-wave excitation in amorphous ferromagnetic wires

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A parametric excitation of spin waves has been observed during transverse pumping in amorphous thin ferromagnetic wires. This excitation is made possible by an induction "intensification" of the magnetic field through the placement of the sample at an antinode of the electric field of a microwave resonator.

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The parametric excitation of spin waves during both transverse[1] and longitudinal[2] pumping has been studied in detail experimentally in nonmetallic ferrimagnets and antiferrimagnets. Parametric spin-wave excitation in metals[3–5] has attacted much less attention. In recent years, metallic glasses have attracted much interest.[6] A study of parametric spin-wave excitation in glassy materials may yield important information about these materials, but we know of no studies of parametric spin-wave excitation in magnetically ordered glassy materials. Our purpose in the present study was to observe parametric spin-wave excitation in metallic glass wires—the same ones which were used in Ref. 6.

It is difficult to observe the parametric excitation of spin waves in thin metal wires placed at an antinode of the magnetic field of a resonator (as in experiments with nonmetallic samples) because of the comparatively large width of the resonance curve, the small wire diameter d, and (if the skin thickness satisfies $\delta < d$) the small value of δ. These difficulties can be overcome by using an induction effect: the excitation of a strong magnetic field at the surface of a metal wire at an antinode of the electric field of the resonator.[7] This effect has been used previously[6] to study a ferromagnetic resonance in glassy wires.

It would hardly be possible to observe parametric spin-wave excitation by means of this induction effect in the case of longitudinal pumping in a wire. We have observed first-order parametric spin-wave excitation with transverse pumping.[1]

The samples are glassy wires with the composition $(Fe_{1-x}M_x)_{80}P_{10}B_{10}$, where M = Ni, Co, Cr, with diameters 2–10 μm in a thin (~1-μm) glass jacket, fabricated by the Taylor method.[8] Pieces of wire ~1 mm long are placed at an antinode of the electric field of a rectangular TE_{103} reflection resonator. The electric field and the static magnetic field $\mathbf{H}_0$ are parallel to the wire axis. A magnetron generator operating in the 8-mm range produces pulses with a reciprocal duty factor ~1000 and a length of ~10 μs. The intrinsic quality factor of the resonator with the sample, Q_0 is ~1000. This quality factor is monitored during the measurements, and the changes are taken into account in the determination of the threshold field. In the measurements, the quality factor of the coupling is established slightly lower than Q_0, and the threshold for the parametric excitation is identified from the slowing of the growth in the height of the reflected pulses upon a smooth increase in the incident power arranged with a precision attenuator.

The pulsed input power did not exceed ~30 W. Breakdown occurred at higher power levels, causing the wires to overheat and switch irreversibly to a polycrystalline state, for which the threshold for parametric spin-wave excitation could not be reached because of the increased width of the resonance curve.

Figure 1 shows the experimental threshold values of the microwave magnetic field h_c (in arbitrary units) versus the static magnetic field H_0 for one of the samples, along with some calculated results. In the calculations we ignored the anisotropy, and we adopted the Kittel[10] model of a thin film (with the thickness of the skin layer), which is customarily used in studies of ferromagnetic resonance in metals. For the wire which we used, the skin thickness was comparable to the diameter (a calculation

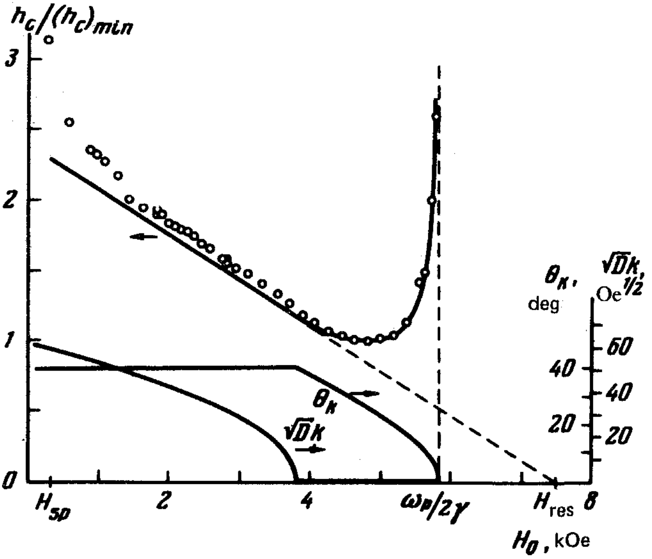

FIG. 1. The threshold field and the parameters of the spin waves excited for a first-order parametric spin-wave excitation with transverse pumping in a $Fe_{56}Ni_{24}P_{10}B_{10}$ glassy wire versus the static external magnetic field. Solid curves—Calculated; points—experimental. $4\pi M_0 = 11750$ G; pump frequency of 36.24 GHz; room temperature; the sample is 1.32 mm long; the wire is ~3 μm in diameter.

of δ with $\mu = 1$ yielded ~ 1.5 μm), and it was by no means obvious at the outset that this model was applicable. In our case we have the following expression, according to Ref. 9, for the model which we are adopting:

$$h_c = \frac{\omega_p}{\omega_M} \frac{|\omega_p^2 - \gamma H_0(\gamma H_0 + \omega_M)|}{F(\omega_p, \omega_M, H_0, \theta_k)} 2\Delta H_k, \tag{1}$$

where ω_p is the pump frequency, γ is the magnetomechanical ratio, $\omega_M = \gamma 4\pi M_0$, M_0 is the constant magnetization, $2\Delta H_k$ is the relaxation parameter of the excited spin waves, with wave vector **k**, θ_k is the angle between k and M_0, and the expression for the function F follows from Eq. (35) in Ref. 9. The theoretical curve $[h_c/(h_c)_{\min}](H_0)$, shown in Fig. 1 was obtained by minimizing expression (1) with respect to θ_k under the assumption $\Delta H_k = \text{const}$. The values found for θ_k in this manner are shown along with $\sqrt{D}\,k$, is the same figure (D is the inhomogeneous exchange constant, whose value is not known for this particular material).

The calculated values of h_c in the region $\theta_k \cong \text{const}$ (Fig. 1) approach a straight line which intersects the abscissa at the point corresponding to the field of a homogeneous ferromagnetic resonance. If the anisotropy is ignored, this field can be written

$$H_{\text{res}} = \sqrt{(\omega_p/\gamma)^2 + (2\pi M_0)^2} - 2\pi M_0 . \tag{2}$$

As the field $H_0 = \omega_p/2\gamma$, corresponding go the lower boundary of the spin-wave spectrum, is approached, h_c increases rapidly.

The experimental value of the resonant field turned out to be 35 Oe lower than the calculated value. This difference lies within the effective field of the magnetoelastic anisotropy of such wires (in glass jackets).[6] We are thus justified in shifting the calculated curve along the H_0 axis to bring the calculated and experimental values of H_{res} into coincidence.

It can be seen from Fig. 1 that after this shift the experimental data agree with the calculations in the vicinity of the large change in θ_k and $k \cong 0$. This agreement is apparently evidence that ΔH_k is independent of θ_k in this case. There is some discrepancy between the experimental and calculated values, which increases with increasing k, in a region with $\theta_k \cong \text{const}$. This discrepancy can be attributed to the part of ΔH_k caused by the intrinsic relaxation of the spin waves, which increases with increasing k. The sharp increase in h_c occurs at a field H_0 near the calculated field H_{sp} at which three-magnon splitting comes into play. This field can be found from energy conservation.[11]

For other samples, of other compositions, including samples with $M = \text{Co}$, Cr, and samples with different dimensions, we found corresponding results. In agreement with Ref. 7, the threshold power level was found to fall off with decreasing wire diameter and with increasing wire lengths.

We were not able to determine the absolute values of h_c or thus $2\Delta H_k$, in the absence of accurate calculations of the magnetic field at the surface of a wire in the electric field of a resonator, i.e., in the absence of calculations of the field "intensification" achieved by the Rodbell induction method. If we assume that $2\Delta H_k$ is not onlyindependent of k and θ_k but also equal to the width of the homogeneous resonance line, $2\Delta H_0$, we can use (1) to calculate h_c and estimate the field "intensification." Adopting $2\Delta H_0 = 85$ Oe, found through an interpolation of the data of Ref. 6 to the frequency of the spin waves that were excited (this frequency was half the pump frequency), we find that the (power) amplification exceeds 10^3 (it is 32 dB if the fields are compared at a fixed resonator quality factor, or it is 30 dB if we take into account the increase in Q_0 as the sample is moved from an antinode of the electric field to an antinode of the magnetic field of the resonator).

In summary, this has been the first observation (to the best of our knowledge) of the parametric excitation of spin waves (specifically, the first-order process with transverse pumping) in ferromagnetic metallic glasses. It has been found that the experimental dependence of the threshold field on the static external magnetic field agrees well with results calculated from the thin-film model.

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