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OBSERVATION OF NONLINEAR FMR IN AMORPHOUS MICROWIRES USING STANDARD X-BAND SPECTROMETER

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Experimental technique for investigation of nonlinear ferromagnetic resonance in thin metallic wires is described. It uses a simple home-made X-band FMR spectrometer with static magnetic field and microwave electric field parallel to the wire. Electric polarization of the wire induces microwave current and large circumferential AC magnetic field on the wire surface. This reduces the critical power for the onset of nonlinear effects. Moreover, in Fe-rich amorphous metals the condition of coincidence of the main and the subsidiary resonances is satisfied at X-band frequencies which further reduces the critical field for the onset of instability. Then the microwave power of few mW is sufficient for observation of nonlinear FMR. The nonlinear resonance curves of very thin wires show well distinguished fine structure with the period inversely proportional to the wire diameter. The observed phenomenon is explained by the parametric excitation of dipole-exchange resonance modes of a long circular cylinder.

Keywords: ferromagnetic resonance, amorphous microwires, nonlinear phenomena, spin waves

1 INTRODUCTION

Applications of magnetic microwires and nanowires in spintronic and microwave devices may involve large RF currents flowing through the wires. It can result in large amplitude of magnetization precession and consequently to frequency multiplication, additional power losses, soliton wave propagation, and other nonlinear effects. The nonlinear effects, therefore, play important role in practical applications and should be thoroughly understood. The nonlinear ferromagnetic resonance (FMR) is a common experimental technique for investigation of nonlinear effects in spin dynamics. Until recently, most experimental work on nonlinear FMR has involved only yttrium iron garnet (YIG), microwave ferrites, and similar materials (for a review of early works see *eg* [1]). Because the damping of spin precession in such materials is small the threshold fields for onset of instability are relatively low. In ferromagnetic metals, where the resonance linewidth is of the order of 100 Oe, large microwave powers (up to few kW) were required to observe the nonlinear effects in Permalloy thin films [2]. Therefore only few high power FMR investigations of Permalloy thin films have been published until recently [3]. There has been a resurgence of interest in nonlinear effects in ferromagnetic metals because of increasing applications of such materials in magnetic recording. New experimental techniques have been developed which allow to investigate the nonlinear phenomena in metallic thin films using moderate and low power microwave generators [4,5].

The large aspect ratio and electric conductivity of metallic wires make them particularly suitable for investigation of nonlinear effects. It has been shown by Rodbel [6] that electric polarization of the wire by the microwave electric field leads to high curl magnetic field at the wire surface which allows obtaining locally intense microwave magnetic field with relatively modest power levels. This technique has been used for investigation of nonlinear phenomena in glass-covered amorphous microwires [7-10].

In this paper we describe a simple FMR spectrometer which can be used for nonlinear FMR experiments at X-band frequency.

2 EXPERIMENTAL METHOD

The effect of electric polarization is schematically shown in Fig.1. When a conducting body is placed in external electric field the electric charges on its surface rearrange so that the electric field in the interior vanishes. This leads to electric polarization of the body and appearance of electric dipole moment. In RF electric field the alternating electric charges on the surface produce electric current along the wire and strong circumferential magnetic field h_ϕ in the wire. For a large aspect ratio the electric charges at the ends can be approximated by point charges $\pm q \propto e_z L^2$, where L is the sample length and e_z the component of electric field $\boldsymbol{e}$ parallel to the axis. Then the circumferential RF magnetic field h_ϕ is proportional to L^2 and the absorbed power to L^5, as was experimentally verified [6]. The circumferential field can be several orders of magnitude higher than the microwave magnetic field in an empty waveguide or microwave cavity.

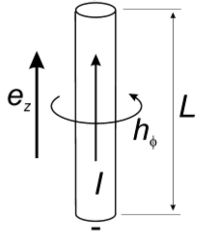

Fig. 1. Electric polarization of wire

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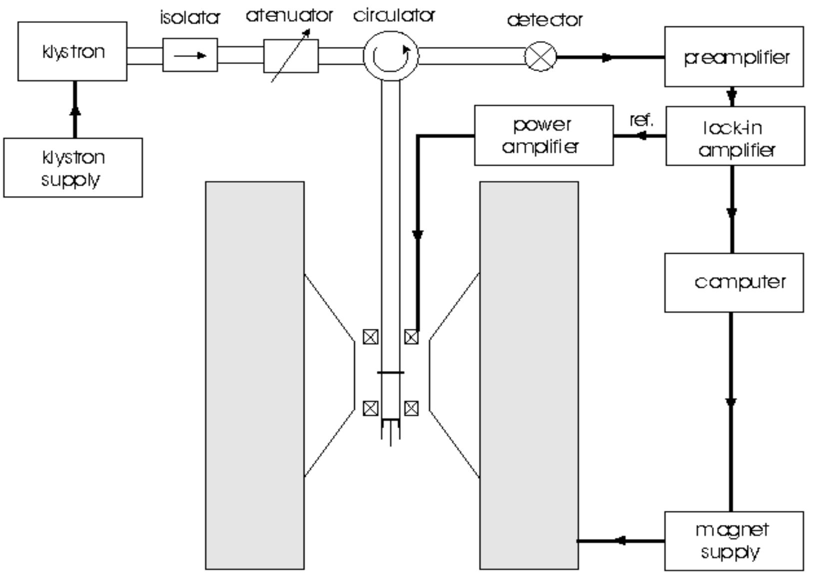

Fig. 2. Schematic block diagram of FMR spectrometer

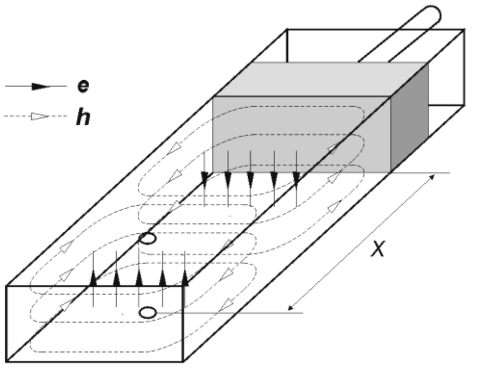

Fig. 3. Short-ended rectangular TE_{10} waveguide: ***e*** and ***h*** - the lines of force of microwave electric and magnetic fields, *x* – the distance of sample from the tuning plunger

The block diagram of FMR spectrometer is shown in Fig.2. The sample, inserted in a thin quartz capillary, is placed in the middle of rectangular TE_{10} waveguide through small holes drilled in the wider waveguide walls (see Fig.3). The static magnetic field and the microwave electric field are parallel

to the wire. The waveguide is short-ended by a tuning plunger, by the position, *x*, of which the intensity of electric field at the sample can be controlled. The maximum electric field, and consequently the intensity of FMR signal, are obtained when *x* is equal to an odd multiple of $\lambda_g/4$, where λ_g is the wavelength in the waveguide. For the generation of microwaves the klystron with the maximum output power about 25 mW at 9.53 GHz is used. The incident power is controlled by the microwave attenuator. The resonance curves (the field derivative of reflected power, dP/dH) are measured using the field modulation and lock-in amplification technique.

3 BRIEF INTRODUCTION TO NONLINEAR FMR

At low microwave powers the response of magnetization to the exiting microwave magnetic field, *h*, is linear. It means that the amplitude of the spin precession is proportional to *h*. If the microwave power is increased above some threshold value the nonlinear response appears. The nonlinear FMR is characterized by two separate phenomena called the resonance saturation and the subsidiary absorption. The resonance saturation means a decrease of loss at resonance and broadening of resonance line. The subsidiary absorption manifests itself as an increase of absorption over a broad range of magnetic fields below the FMR field.

The theory of nonlinear FMR in bulk ferromagnetic insulators was developed by Suhl [11]. According to the theory the uniform precession mode excited by microwave field becomes unstable when *h* exceeds the threshold field h_c and starts to decay into spatially non-uniform spin waves. Two different mechanisms are responsible for the subsidiary absorption and the saturation of resonance. The first-order spin-wave instability with

$$h_c^{(1)} = \min\left(\frac{\omega}{\gamma M_s} \frac{\Delta H_k}{W_k^{(1)}} \right) \tag{1}$$

is responsible for the subsidiary absorption and the second-order instability with

$$h_c^{(2)} = \min\left(2\sqrt{\frac{\omega}{\gamma} \frac{\Delta H_k}{W_k^{(2)}}} \right) \tag{2}$$

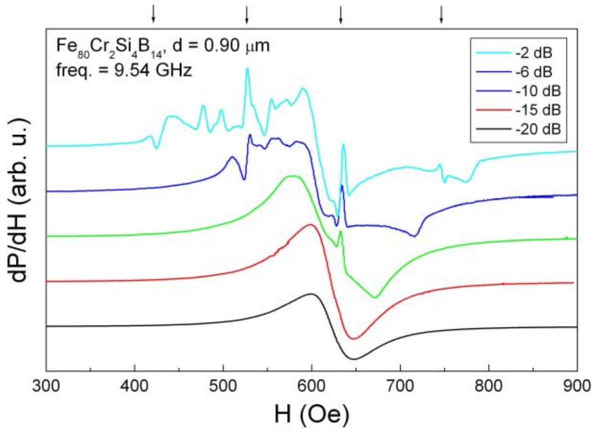

Fig. 4. Nonlinear FMR curves for different microwave power levels - the numbers in the legend indicate the attenuation of incident power

for the saturation of resonance. Here ω is the circular frequency, γ spectroscopic splitting factor, M_s saturation magnetization, ΔH_k spin-wave linewidth, and $W_k^{(n)}$ dimensionless coupling coefficient for *n*th-order instability. The coupling coefficients depend on the frequency, sample shape, wave vector $\boldsymbol{k}$, static magnetic field $\boldsymbol{H}$ and also on the polarization of microwave magnetic field $\boldsymbol{h}$ [12]. The minimization in (1) is done over all spin waves with frequency $\omega_k = \omega/2$ and for $\omega_k = \omega$ in (2). The first-order instability threshold is usually lower than the second-order one. Far from resonance the coupling coefficient $W_k^{(1)}$ is of order of unity and the threshold field $h_c^{(1)}$ is comparable to ΔH_k. But for the frequency ω approaching the resonance frequency ω_{res} the coupling coefficient $W_k^{(1)}$ sharply increases. and $h_c^{(1)}$ decreases. If the condition for coincidence of subsidiary and main resonance, $\omega = 2\omega_k \cong \omega_{res}$ is fulfilled an exceptionally small threshold field of the order $\Delta H_{res}\Delta H_k/M_s$ is obtained (ΔH_{res} is the resonance linewidth).

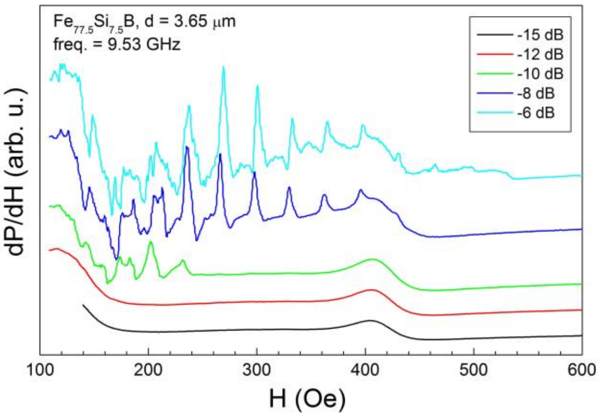

Fig. 5. FMR resonance curves of amorphous $Fe_{77.5}Si_{7.5}B_{15}$ wire with diameter of 3.65 μm

For metallic wires the Suhl theory has to be modified. First, the resonance mode is not the uniform precession but the circumferential resonance mode due to electric polarization of the wire [13]. Then for the resonance frequency in the coincidence condition the Kittel resonance condition

$$\omega_{res} = \gamma\sqrt{H(H + 4\pi M_s)} \tag{3}$$

for a tangentially magnetized thin film should be used. Then the coincidence condition can be fulfilled only for microwave frequency $\omega < 8\pi\gamma M_s/3$. Second, in tiny wires the continuous spin-wave manifold, assumed by Suhl, should be replaced by a discrete spectrum of the dipole-exchange modes of a long cylinder.

4 EXAMPLES OF MEASUREMENTS

Nonlinear FMR spectra were measured on glass-covered amorphous wires prepared by the Taylor-Ulitoskii method. The lowest threshold field is obtained for the coincidence condition, which is better fulfilled for materials with higher saturation magnetization and lower microwave frequencies. For example, for $4\pi M_s = 10^4$ Gauss it is fulfilled for frequencies less than 20 GHz. Therefore Fe-rich amorphous alloys are more suitable for observation of nonlinear FMR.

Fig.4 shows the nonlinear FMR curves for a glass-covered amorphous microwire $Fe_{80}Cr_2Si_4B_{14}$ with the metallic core diameter of 0.9 μm. For the low incident power (-20 dB) the usual linear resonance is observed. With increasing microwave power the amplitude of the resonance curve increases. At a certain critical value (-15 dB) a small distortion on the central part of the curve appears. Then distortion extends in both directions and a very sharp dip develops inside the distorted part. With further increase of power more complicated structure of the resonance curve comes out. Among the several peaks a series of well distinguished nearly equidistant peaks can be found (see the arrows in Fig.4). The period of this fine structure depends on the wire diameter. In Fig.5 the FMR curves of a $Fe_{77.5}Si_{7.5}B_{15}$ wire with diameter 3.65 μm are shown. In this case the linear resonance shows a long tail on the low field side of resonance curve and the “low-field absorption” below 150 Oe, which indicate incomplete saturation of the wire at low magnetic fields. In this case the nonlinear distortion starts below the main resonance and extends upwards.

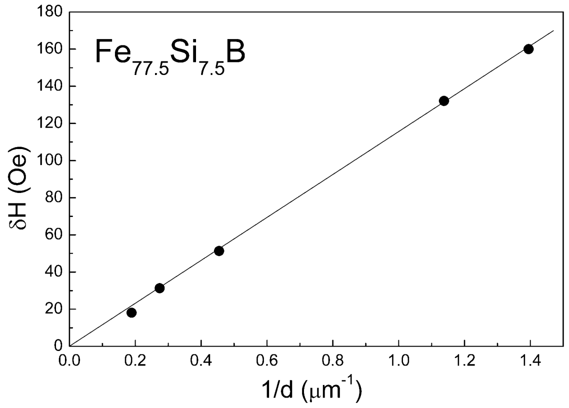

Fig. 6. Period δH of fine structure in amorphous $Fe_{77.5}Si_{7.5}B_{15}$ wires with different diameters

The fine structure of the resonance curves is well pronounced. The distance δH between the subsequent peaks for amorphous wires $Fe_{77.5}Si_{7.5}B_{15}$ with different diameters is shown in Fig.6. As can be seen, δH is inversely proportional to wire diameter.

The theoretical explanation of the observed phenomenon is based on the modified Shul's theory [14]. It is assumed that the fine structure of the nonlinear FMR is caused by parametric excitation of dipole-exchange modes via the first order instability process. The sharp minimum in absorbed power appears when the circumferential resonance mode with the frequency ω splits into a pair of dipole-exchange modes with the frequencies $\omega_{m,n,\beta} = \omega_{m,-n,\beta} = \omega/2$, where m and n are the radial and azimuthal mode numbers and β the propagation constant along the cylinder axis. The eigenfrequencies $\omega_{m,n,\beta}$ depend on mode numbers, material parameters, magnetic field H and exchange boundary conditions. They have been theoretically calculated by Lai Wu-Yan *et al.* [15]. Unfortunately, no analytic solution for the dispersion relation has been found so the calculations have been done numerically. By a rough estimate of the dispersion relation we came to the conclusion that the period of fine structure should be proportional to $1/d$, as was found experimentally. For the details see ref. [14].

5 CONCLUSION

We have shown that polarization of a wire by the electric microwave field can substantially increase the microwave magnetic field on wire surface. This effect, if combined with the coincidence of the main and subsidiary resonance, allows to investigate the nonlinear phenomena with a standard FMR spectrometer. In very thin amorphous microwires a fine structure of nonlinear FMR was observed. This phenomenon has been explained by the parametric excitation of dipole-exchange modes.

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