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Interaction of Lamb Waves with Domain Walls in an Iron Borate Plate

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This work presents the calculation results of the Lamb wave spectra in a plate of iron borate. Experimental data on how flexural vibrations in a borate plate influence its domain structure are provided.

Keywords: Weak ferromagnets; Iron Borate, Domain walls, Helmholtz coils, Dispersive dependencies

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1. INTRODUCTION

At present, a nonlinear character of domain walls (DWs) in weak ferromagnets – orthoferrites and iron borate [1] are the generally recognized facts. To describe the DW retardation mechanism, a number of different proposals have been advanced that are related to the generation of various wave types including Lamb waves [2, 3] and plate's vibrations. Now, the interest in the Lamb waves is dictated by the perfection of experimental methods due to the expansion of frequency range up to terahertz frequencies [4]. However, there is no yet consistent explanation of the features for the dependence of the DW velocity υ as a function of the driving magnetic field H in these ferromagnets.

In its turn, in the field of a sound wave, the formation of a domain structure [5] and DW drift [6] may occur.

The present work presents the calculation results of the Lamb wave spectra in a plate of iron borate. The velocities and frequencies at which the energy transfer of DW into acoustic subsystem can occur are predicted. Experimental data on how flexural vibrations in a borate plate influence its domain structure are provided.

2. THEORY. SPECTRA OF LAMB WAVES IN $FEBO_3$

Consider weak easy-plane antiferromagnet $FeBO_3$ bounded by planes $z = h/2$ and $z = -h/2$, where h – plate thickness. Axis z coincides with the principal crystal axis, plate xy – basal plane. We will consider plane monochromatic waves polarized along x and z travelling along axis x.

Dispersion equations were derived according to [7] with consideration for a rhombohedral symmetry of the crystal. For antisymmetric (A) and symmetric (S) Lamb waves these can be given as:

$$2\left(C_{33}-C_{13}\right)k^2\kappa_l\kappa_t sh\left(\frac{\kappa_{t,l}h}{2}\right)ch\left(\frac{\kappa_{t,l}h}{2}\right)- \\ -\left(\kappa_t^2+k^2\right)\left(C_{33}\kappa_l^2-C_{13}k^2\right)sh\left(\frac{\kappa_{t,l}h}{2}\right)ch\left(\frac{\kappa_{t,l}h}{2}\right)=0 \quad (1)$$

where C_{ij} – elastic constants, k – projection of the wave vector along axis x, κ_l and κ_t – projections of the wave vector along z. The first index with κ corresponds to antisymmetric, the second – to symmetric waves.

For further calculations, let's introduce the following notations:

$$s_1^2=\frac{C_{11}}{\rho},\quad s_2^2=\frac{C_{13}}{\rho},\quad s_3^2=\frac{C_{33}}{\rho},\quad s_4^2=\frac{2C_{44}}{\rho},\quad (2)$$

where ρ is density.

With consideration for numerical values of elastic constants for iron borate [8], $s_1 \approx 10{,}2\cdot10^5$ cm/s, $s_2 \approx 5{,}7\cdot10^5$ cm/s, $s_3 \approx 8{,}4\cdot10^5$ cm/s, $s_4 \approx 6{,}7\cdot10^5$ cm/s.

The solution has two couples of dispersive relations $\kappa_t(k)$ and $\kappa_l(k)$ corresponding to the sets of normal plate waves. Further given are calculations for the first set, for which κ_t and κ_l are determined according to formulae:

$$\kappa_l^2=\frac{k^2\left(s_1^2-\nu^2\right)}{s_2^2+2s_4^2};\qquad \kappa_t^2=\frac{k^2\left(s_{t1}^2-\nu^2\right)}{s_4^2},\quad (3)$$

where $s_{t1}=\sqrt{s_1^2-s_2^2-s_4^2}\approx 5.2\cdot10^5\text{cm/s}$, $\upsilon = \omega/k$ – phase velocity.

Fig. 1 shows spectra of phase υ and group $\upsilon_{gr} = d\omega/dk$ velocities for 16-th mode s_{16} of symmetric Lamb waves in a 0.01 cm-thickness plate of $FeBO_3$ calculated according to equations (1).

Dashed lines correspond to phase velocity, solid – to group one. Dashed straight lines correspond to velocities s_{t1} and s_l.

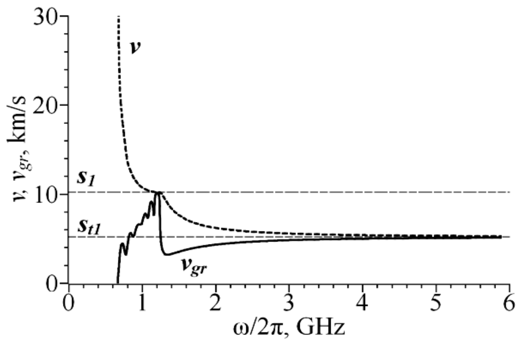

Fig. 1 – Mutual disposition of $\upsilon(\omega)$ and $\upsilon_{gr}(\omega)$ curves for s_{16} mode in a $FeBO_3$ plate

It is seen from Fig. 1 that the phase and group velocities for each mode come closer at different frequencies, which should result in DW retardation at relevant velocities.

According to [11], the dissipative function that describes the energy transfer of DW to the acoustic subsystem is proportional to function $\Delta(\omega) = (v - v_{gr})^{-1}$. The maximum energy transfer must correspond to regions with a linear dispersion law where the condition fulfills

$$v_{гр} \approx v. \quad (4)$$

In this case, acoustic modes will be generated at frequencies depending on the DW velocity. Depicted in Fig. 2 is the dependence of the main maximum $\Delta(\omega)$ for the first 60 symmetrical (*S*) and antisymmetrical (*A*) modes of frequency. The modes are enumerated from the left. When the number of modes increases, the frequency corresponding to the primary maximum $\Delta(\omega)$ also increases. The relevant phase velocities approach s_1.

This dependence can be used to generate hypersonic waves with a desired frequency that is dependent on the source velocity, the role of which can be played by not only DW. The estimation reveals that the frequency value of the generated waves amounts to several terahertz.

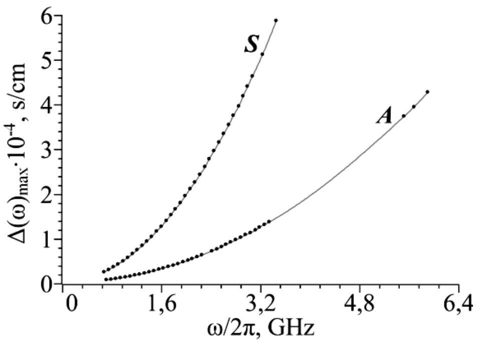

Fig. 2 – Primary maximum of function $\Delta(\omega)$ for symmetrical (*S*) and antisymmetrical (*A*) waves as a function of frequency

3. EXPERIMENTAL. THE INFLUENCE OF ELASTIC VIBRATION ON THE DOMAIN STRUCTURE OF IRON BORATE

The interaction of the acoustic subsystem with DW can not only result in the sound generation but also produce the DW motion, which was theoretically described in [6] for an easy-plane ferromagnet.

To experimentally support conclusions of [6], a plate of $FeBO_3$ was used with a thickness of 40 μm. The domain structure was visualized with the Faraday effect according to the procedure described in [1, 9]. The sample studied was fixed at the piezoelectric element surface, with which flexural vibration was generated. The vibration amplitude was measured by the deflection of a laser beam from the sample surface [10].

Equilibrated domain structure of $FeBO_3$ presents a set of domains in several layers parallel to the plate plane (Fig. 3). When the sample vibrates, it was observed that the domain structure was spreading, which indicated its vibrational motion. Fig. 4 demonstrates an image of the domain structure at vibration frequency $f = 34.3$ kHz.

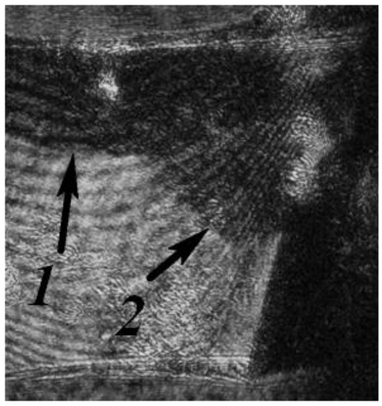

Fig. 3 – Domain structure of $FeBO_3$ in a free state 1 and 2 are boundaries of the domains in various layers

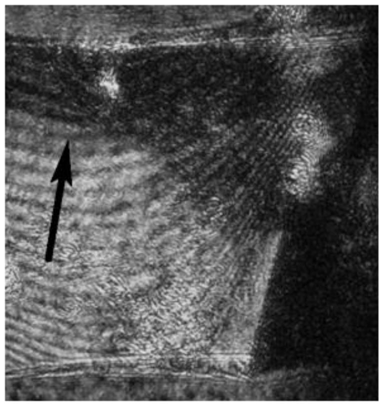

Fig. 4 – Shift of the domain structure in the sample at a vibration frequency $f = 34.3$ kHz

These images make it possible to roughly estimate the maximum velocity of DW motion. The smearing of DW in Fig. 4 corresponds to its amplitude of 0.03 mm. The amplitude of the DW velocity was estimated according to formula $V_m = 2\pi f A_m$, where A_m is the amplitude of the DW shift. For such parameters, this value reached 6 m/s.

The DW vibration causes the change in the intensity of the luminous flux going through the sample, which was recorded with a photodiode. Demonstrated in Fig. 5.is the relevant dependence of the DW vibration amplitude on the vibration amplitude of the sample at a frequency of 49 kHz.

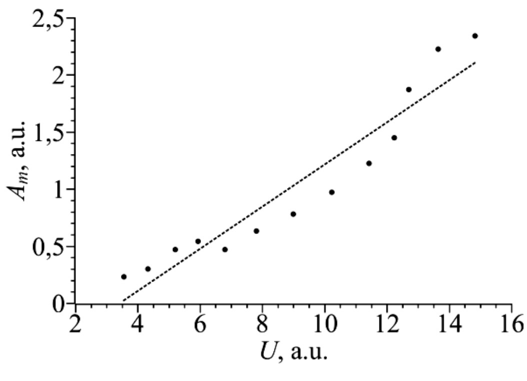

Fig. 5 – The dependence of the DW vibration amplitude on the vibration amplitude of the sample at a frequency of 49 kHz

4. CONCLUSIONS

Dispersive dependencies of the Lamb waves in an iron borate plate were calculated. From them, one can conclude about the retardation velocities of DW and the potential of creating a tunable source of hypersonic waves up to terahertz frequency. In this case, the wavelength proves to be in the nanometer range.

Forced vibrations of DWs in $FeBO_3$ crystals in the elastic wave field are found. The numerical estimate of the velocity and the shift of DW in the field are given.

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