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High Frequency Ultrasonic Transducer on Base of Yttrium Iron Garnet (YIG) Films

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Abstract

The purpose of the present work is to investigate efficiency of ultrasound excitation by thin YIG films depending on value and the direction of an external magnetic field, geometric sizes of ~~a~~ films, and ultrasound frequency, and to interpret the received results.

Keywords: ultrasonic oscillations, yttrium iron garnet, magnetoelastic interaction, domain structure.

Introduction

In the present paper we propose a new type ultrasonic transducer for excitation longitudinal and shear waves on base of yttrium iron garnet thin films. Ultrasonic transducers based on magnetostrictive materials are widely used in different spheres of science and technology. Mainly they are applied for impacting the matter (cavitation, device cleaning, micrograin crystallization of metals, nanostructure fabrication, fragmentation, etc.) with excitation of longitudinal oscillations. High conductivity of well-known ferromagnetic (iron, cobalt, nickel and alloys based on them) limits the frequency range of their appliance as ultrasound emitters and receivers due to significant losses caused by Foucault current on frequencies higher than 100 kHz and some construction features [1-2]. Dynamic magnetostriction constants rare-earth metals which define the efficiency of transduction are in order of magnitude lower than the ones of well-known high-frequency ferrites: manganese zinc spinel (MZS), yttrium iron garnet (YIG) and magnetite (Fe_3O_4) with different admixtures. Our research of these ferrites magnetostrictive parameters revealed prospective of their usage in 10-100 MHz frequency range due to absence of losses on Foucault current, strong magnetoelastic coupling and small ultrasound attenuation on these frequencies. Additional advantage of magnetostrictive high-frequency transducers in comparison with traditionally used piezoelectric ones is capability to generate and receive longitudinal and transverse oscillations using the same transducer by changing bias field intensity and direction. The method of generation and registration of high-frequency ultrasonic oscillations (from units to hundreds MHz) by ferrite powders under superposition of constant and alternating magnetic field was described by us in [3]. It was discovered that during parallel orientation of applied fields the effective generation of longitudinal wave takes place and during perpendicular orientation the generation of transverse wave with polarization vector collinear with constant magnetic field direction become effective.

The system of an iron-yttrium garnet film on a substrate gallium - gadolinium garnet (GGG) is widely applied in radio electronic. Owing to high values of magneto elastic interaction and small attenuation of ultrasound it is an ideally coordinated system for excitement and registration of high-frequency ultrasonic oscillations.

In this work we present the results of researches of electromagnetic excitement efficiency of ultrasound on the basis of measurements of amplitude A of ultrasonic oscillations by a YIG film placed in a combination of variable and constant magnetic fields.

Experimental Setup and Samples For Researches

The measurement technique is described in detail in work [4]. If the angle between the directions of fields equals zero, the longitudinal ultrasonic wave is exited effectively extending along an axis of a ultrasonic delay line at the end face of which a YIG film settles down. If the angle equals 90 degrees, a shear wave with the vector of polarization coinciding with the direction of a constant magnetic field is exited. Yttrium iron garnet was chosen because of significant value of magnetoelastic coupling and very low losses in high frequency range. These losses are evaluated by width of ferromagnetic resonance line, which for YIG is the thinnest of all analyzed ferrites and is 0.2 Oe. YIG films acquired using the liquid-phase epitaxy method contain very little defects and dislocation, especially when they were grown of gadolinium gallium garnet substrate. The last fact is due to close values of lattice distance of YIG and GGG. Film growth rate in liquid-phase epitaxy method is about one micrometer per minute which is quite acceptable for growing plates up to 100 micrometers thick. Researched construction of high-frequency oscillations transducer based on YIG plates includes thin YIG film (4,5 – 83 micrometer thick) grown on GGG substrate 0.5 mm thick acoustically connected with acoustic line delay made of fused quartz. Acoustic line delay is made in shape of cylinder 15 mm in diameter and 30 mm long with polished faces. Precision of faces procession is 0.2 micrometers. Acoustic line delay is meant to form the sound beam and transmit it into researched object. In addition, a coil with several winds of copper wire is put on the line delay close to YIG film for excitation of alternating magnetic field pulse.

The experiments were carried out in a pulse mode at the room temperature. The thickness of YIG films was equal 83, 64, 16, 10 and 4.5 micrometer on GGG 500 micron thick substrate a plane of which is perpendicular to the crystallographic direction [111]. The shape of samples is a square with the sides L equal 6 mm, thickness of a film d is much less than L.

The magnitude of a constant magnetic field from 0 to 2000 Oe was varied by means of an electromagnet with a diameter of pole tips 120 mm in a gap of 50 mm. Ultrasonic oscillations of corresponding polarization were detected by piezoelectric transducers at a frequency of 36 MHz and 16 MHz The samples studied might be subdivided into two types: thin ones (with a thickness of 4.5, 10 and 16 micron) and thick (with a thickness of 64 and 83 micrometer). Fig.1 illustrates efficiency of excitation of ultrasonic oscillations by a YIG film.

Results

For the 64 and 83 micron films, field dependence of the size A represents a monotonous curve with saturation in the field of the 1200 Oe both for longitudinal and shear oscillations. We found that the thin films show a resonant character of excitation efficiency of longitudinal ultrasonic oscillations depending on a magnetizing field with the characteristic maxima in the field H_{max} . The arrangement of maxima depends on thickness of a film and ultrasound frequency.

The results of the research of efficiency of longitudinal ultrasonic oscillations excitation in a uniform magnetic field by YIG films of different thickness are shown in Fig.2

The most significant influence of domain structure is found to be in field dependence of longitudinal wave generation efficiency in non–uniform magnetic field by thin YIG films (4.5 - 16 micrometers). For receiving a non-uniform magnetic field the film YIG on the substrate GGG and the acoustic delay line were shifted to different distances X from an electromagnet center in the direction perpendicular to the bias field direction. During such movement a magnetic field component tangent to film plane appeared. In Fig.3 resonance-like maxima can be easily seen. With the increase of X distance from 0 to 40 mm the maxima move to a low field range, Q-factor of "resonance" curve and maximum magnitude increases. The observed dependencies were theoretically predicted in the paper [5] and are explained by the fact that domain borders take part in sound generation. The domain structure of YIG films and its dynamics upon application of a weak magnetic field in the film plane were studied using the Faraday effect with the aid of a POLAM P – 312 polarization microscope In addition to a labyrinth structure (Fig. 4a), the samples exhibited a regular strip structure (Fig. 4b), with a domain width (2 -16 micrometer) dependent on the film thickness and magnetic field. It should be noted that we couldn't excite ultrasonic oscillations in films with labyrinth structure of domains owing to considerable scattering of ultrasound.

Discussion

We assume that resonant and dimensional nature of behavior of A and H_{max} value (Fig. 2 and Fig. 3) can be defined by formation of band domain structure in thin YIG samples. In ferromagnetic under temperature lower than Curie point in absence of outer magnetic field and under low intensity fields (in comparison with saturation field) the appearance of different domain structures is possible such as strip domains, labyrinth structure and cylindrical magnetic domains. Between domains there are regions in which M vector orientation changes from one equilibrium orientation to another (domain borders). In experiments on electromagnetic excitation of ultrasonic oscillations constant magnetic field H_0 is modulated by alternating high frequency magnetic field H_1 . Thus, the domain borders are affected by alternating force which leads in presence of magnetoelastic interaction to excitation of acoustic oscillations. Oscillating system of domain borders can be described using Dering's model [6] by differential equation

$$m\frac{d^2x}{dt^2} + C\frac{dx}{dt} + Dx = M(H_0 + H_1 sin\omega t) \qquad (1)$$

where *X* is domain border shift, m and D is its effective mass and quasi-elastic constant respectively, *C* is friction ratio, H_1 is alternating magnetic field intensity, *M* is unit volume magnetization. Considering magnetic properties of YIG [6] and applied magnetic field, resonance frequency of domain borders oscillations is 25-75 MHz which corresponds with longitudinal oscillations frequency used in our experiments.

Conclusion

Losses on double transduction when using YIG-based film transducer are in order of magnitude higher comparatively to widely used piezo-electric transducers [7] , but this drawback is compensated by following advantages.

a) researcher obtains a capability to change transduction efficiency and emitted ultrasonic wave polarization by changing magnetic field intensity and direction;
b) a capability of resonance excitation of domain borders oscillation by applying magnetic field tangent to plate plane appears [8];
c) there is capability to excite longitudinal and transverse ultrasonic oscillation simultaneously and separate them when receiving by changing the angle between alternating and constant magnetic field components direction

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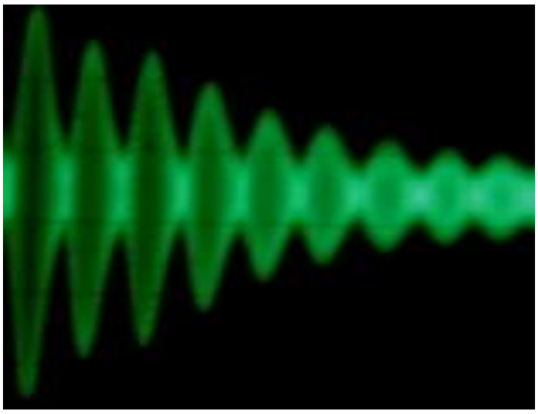

Figure 1: Sequence of echo pulses of longitudinal ultrasonic oscillations with 36 MHz Frequency generated by YIG and multiply reflected in the acoustic delay line. The pulse duration is equal to 1 microsecond

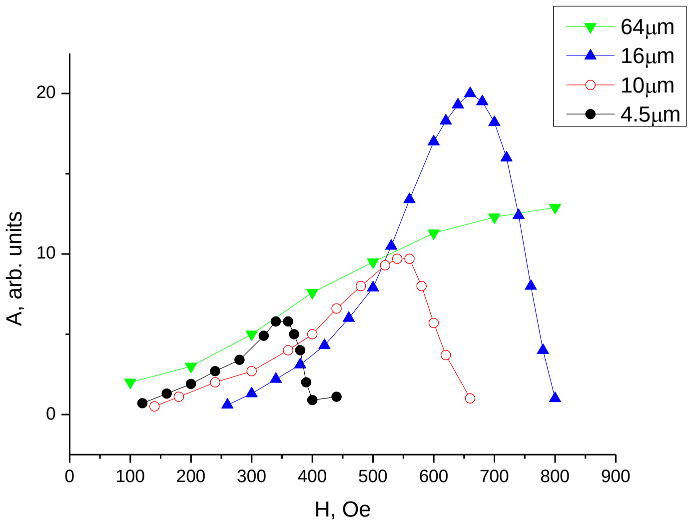

Figure 2: Field dependence of efficiency longitudinal ultrasonic waves excitement by YIG film of different thickness. Frequency of oscillations is 36 MHz

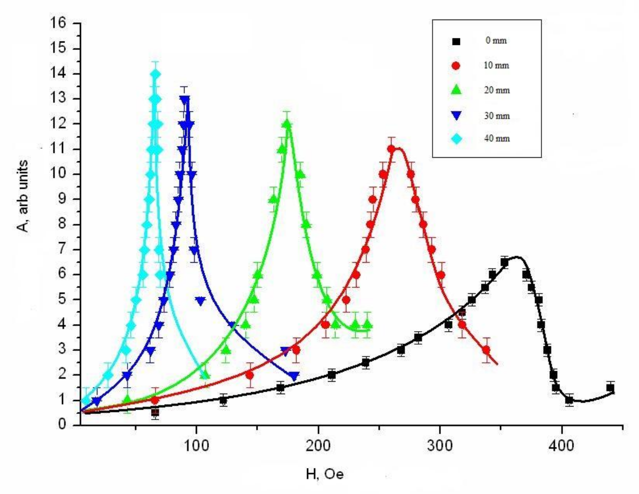

Figure 3: Dependence of longitudinal ultrasonic waves amplitude on magnetic field intensity for different shifts X from center of magnet. Ultrasonic wave at 36 MHz frequency generated by YIG film of 4,5 micrometer thickness

Figure 4 A): Strip Domain Structure YIG Film of 4.5 Micrometer Thickness

Figure 4 b): labyrinth domain structure YIG film of 12.7 micrometer thickness

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