Materials Chemistry and Physics, 23 (1989) 464–472

DETERMINATION OF THE ELASTIC PROPERTIES OF CERAMIC Al:YIG SYSTEMS BY ULTRASONIC TECHNIQUES

G. SOCINO

Dipartimento di Fisica, Università di Perugia (Italy)

N. SPARVIERI

Selenia Direzione Ricerche, Via Tiburtina km 12.4, Rome (Italy)

F. TREQUATTRINI, E. VERONA

CNR, Istituto di Acustica, Via Cassia, 1216 - I-00189 Rome (Italy).

ABSTRACT

The elastic properties of polycrystalline garnets have been analyzed by means of an acoustic investigation technique. The method relies on measurement of the phase velocity of both the Lamb and Love modes propagating along a sample having the shape of a plate. Because of the structure of the acoustic modes, each consisting of a different combination of longitudinal and shear partial waves, the information obtained permits an evaluation of the elastic constants of the material. Measurements performed on a ceramic YIG plate , enabled us to determine the two independent constants c_{11} and c_{44} of the material. An analysis of ceramic garnets with different percentages of Al^{3+} ions in the tetrahedral sites of Fe in the basic structure of YIG, has shown a strong dependence of the elastic constants on the concentration of the substitutional ions.

INTRODUCTION

A large amount of work has been done in recent years on the technology of production and on the investigation of physical properties of magnetic garnets for microwave applications. The importance of these materials lies on their magnetic properties and low electrical conductivity which allow electromagnetic waves to propagate in the medium with characteristics which depend on its magnetization state. As this can be varied by means of an external bias magnetic field, magnetic garnets are suitable for applications to microwave devices such as tunable delay lines, phasers, magnetic field sensors and nonreciprocal devices [1-6].

0254-0584/89/$3.50

The magnetic properties of these garnets can be widely changed because of their capacity to selectively incorporate a large number of ions in crystal sites which depend on the radius of the substitutional ions. This paper presents the results of an investigation of the elastic properties of ceramic $Y_3\,Al_x\,Fe_{5-x}\,O_{12}$ for different concentrations of Al^{3+} ions. The mechanical properties of these ceramic materials differ from those of the single crystal and can be highly affected by the process of their production, so that a direct characterization of these materials is of great importance. The experimental method used for determining the elastic constants relies on measurement of the phase velocity of acoustic modes propagating along the sample under investigation. Both Lamb and Love modes were analyzed in order to determine the two independent elastic constants c_{11}, and c_{44}. The experimental results show a strong dependence of these constants on the concentration of substitutional Al^{3+} ions.

MAGNETOELASTIC WAVES IN THIN PLATES

The structure under investigation consists of an elastically isotropic ferrimagnetic plate of thickness h, magnetized beyond its saturation magnetization $\overline{M_s}$ by a uniform bias magnetic field $\overline{H}_o$ parallel to the surface of the plate. A rectangular Cartesian coordinate system (xyz) is chosen, with the z-axis along the magnetic field direction and the y-axis along the normal to the faces of the plate. Because of the magnetoelastic coupling , the characteristics of the acoustic modes propagating along the plate are affected by the presence of the magnetic field and depend on the relative direction between the field itself and the acoustic wavevector $\overline{\beta}$.

We assume that the acoustic frequencies of interest lie in the low megahertz range, so that exchange-free conditions are satisfied and, moreover, the quasistatic approximation can

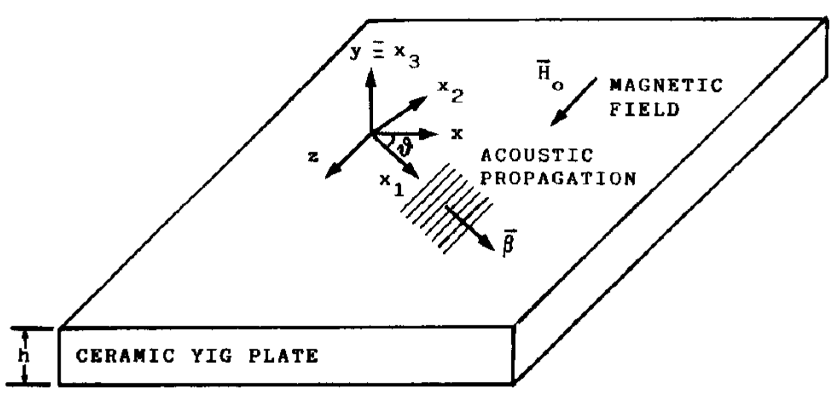

Fig. 1. Schematic of the magnetoelastic structure under investigation.

apply. With these approximations, the complete set of coupled particle motion, spin motion and Maxwell equations, for a small dynamic field superposed on a large static bias magnetic field is given by [7-10]:

$$
\begin{aligned}
\rho\ddot{u}_x &= c_{11}(u_{x,xx} + u_{y,yx} + u_{z,zx}) + c_{44}(u_{x,yy} + u_{x,zz} - u_{y,yx} - u_{z,zx}) + 2M_s b_{44} m_{x,z} - M_s\phi_{,zx} \\
\rho\ddot{u}_y &= c_{11}(u_{x,xy} + u_{y,yy} + u_{z,zy}) + c_{44}(u_{y,xx} + u_{y,zz} - u_{x,xy} - u_{z,zy}) + 2M_s b_{44} m_{y,z} - M_s\phi_{,yz} \\
\rho\ddot{u}_z &= c_{11}(u_{x,xz} + u_{y,yz} + u_{z,zz}) + c_{44}(u_{z,xx} + u_{z,yy} - u_{x,xz} - u_{y,yz}) + 2M_s b_{44}(m_{x,x} + m_{y,y}) + \\
&\quad -M_s\phi_{,zz} \qquad (1) \\
-\dot{m}_x/\gamma &= H_o m_y + 2M_s^2 b_{44}(u_{y,z} + u_{z,y}) + M_s\phi_{,y} \\
-\dot{m}_y/\gamma &= -H_o m_x - 2M_s^2 b_{44}(u_{x,z} + u_{z,x}) - M_s\phi_{,x} \\
\nabla^2\phi &\quad -4\pi(m_{x,x} + m_{y,y}) + 4\pi M_s(u_{x,xz} + u_{y,zy} + u_{z,zz}) = 0
\end{aligned}
$$

The six variables in the differential equations 1 are the components of the displacement vector $\overline{u}$, the two transverse components of the dynamic magnetization vector $\overline{m}$ and the magnetic potential ϕ. ρ, c_{ij}, b_{44} and γ are the mass density, the elastic and magnetostrictive constants and the gyromagnetic ratio of the material, respectively. A comma followed by a letter denotes a derivative with respect to the corresponding spatial coordinate.

We consider magnetoelastic modes that propagate along the plate at an angle θ from the x-axis. Each mode consists, in the more general case, of a linear combination of twelve partial waves. This number is lower when some of the partial waves uncouple from the others because of symmetry conditions in the coupled eqns. 1. On referring to the laboratory coordinate system x_i shown in Fig. 1, with the x_1-axis along the acoustic propagation direction and the x_3-axis along the normal to the plate , the particle displacement components can be written in the form:

$$u_i = \sum_{p=1}^{12} A_p a_i^{(p)} \exp i\beta b^{(p)} x_3 \exp i(\beta x_1 - \omega t) \qquad (2)$$

where β is the acoustic wavenumber of the mode, $\beta b^{(p)}$ the propagation constant along the normal to the plate of the p'th partial wave, whose amplitude and mechanical polarization are given by A_p and $a_i^{(p)}$, respectively. Similar expressions can be written for the magnetic quantities associated with the acoustic field. These acoustic modes must satisfy both the differential equations 1 and the mechanical and electromagnetic boundary conditions at the free surfaces of the plate [8] . This implies that the modes are dispersive since the wavenumber component $\beta b^{(p)}$ must satisfy the transverse resonance conditions. The magnetoelastic coupling is fairly strong at the crossover points of the dispersion curves, where the uncoupled spin and elastic waves have the same frequency and wavenumber [9-12]. For frequencies far away from the crossover values, the acoustic and magnetic waves are still coupled but with a predominant elastic or magnetic character.

ELASTIC CONSTANTS EVALUATION

The elastic properties of ceramic garnets have been studied by operating in a range of frequencies where the acoustic modes are almost exclusively elastic. Under these conditions, the propagation medium can be considered purely elastic and isotropic. Two types of acoustic modes can propagate along the plate : Lamb and Love modes [13]. Lamb modes are polarized in the sagittal plane $(x_1 x_3)$ and consist of two longitudinal and two shear vertical partial waves coupled together. The dispersion relations $v(h/\lambda)$, depending on both c_{11} and c_{44}, can be expressed in the form:

$$\frac{\tan\left[\pi\frac{h}{\lambda}\sqrt{v^2\frac{\rho}{c_{44}}-1}\right]}{\tan\left[\pi\frac{h}{\lambda}\sqrt{v^2\frac{\rho}{c_{11}}-1}\right]} = -\left(\frac{\frac{4}{v^2}\frac{c_{44}}{\rho}\sqrt{1-\frac{1}{v^2}\frac{c_{44}}{\rho}}\sqrt{\frac{c_{44}}{c_{11}}-\frac{1}{v^2}\frac{c_{44}}{\rho}}}{\left(\frac{2}{v^2}\frac{c_{44}}{\rho}-1\right)^2}\right)^{\pm 1} \tag{3}$$

where the plus or minus sign of the exponent on the right hand side of eqn. 3 refers to symmetric or antisymmetric modes, respectively. Love modes, polarized along the x_2 direction, consist of two shear horizontal partial waves. Their phase velocity is related to the elastic constant c_{44} by the dispersion relations:

$$\frac{\rho}{c_{44}} = \frac{1}{v^2}\left(1+\frac{n}{2\frac{h}{\lambda}}\right)^2 \tag{4}$$

with $n = 0, 1, 2, \ldots$

Equation 4 can be solved analytically while eqn. 3 requires the use of a numerical computation technique. The dispersion curves relative to Love and Lamb modes propagating along an undoped YIG ceramic plate, are shown in Fig. 2. These curves were calculated by using the effective elastic constants of the ceramic garnet as determined from measurements of the phase velocity of a number of acoustic modes. The procedure followed is based on an iterative computation technique, exploiting the linear regression method. The values of the elastic constants are those which minimize the standard deviation of the experimental values from the theoretical ones.

RESULTS

The material under investigation is ceramic yttrium iron garnet with different concentrations of Al^{3+} substitutional ions: $Y_3Al_xFe_{5-x}O_{12}$. Its preparation followed the standard

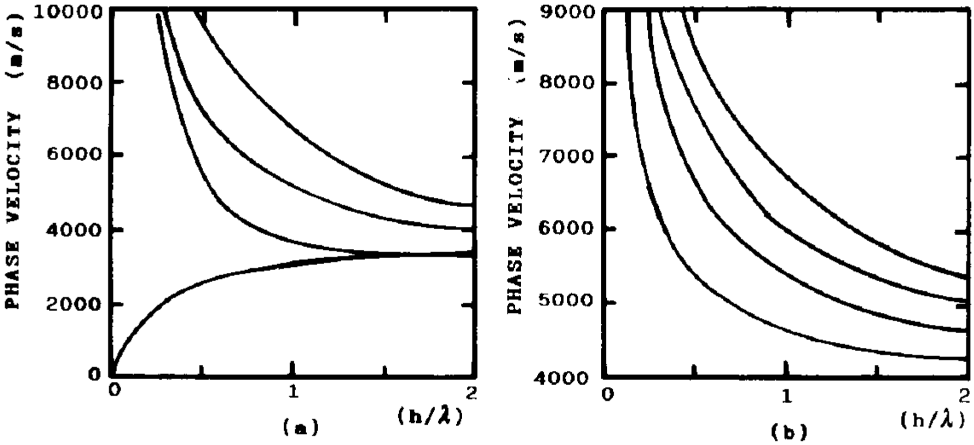

Fig. 2. Dispersion curves for (a) Lamb and (b) Love modes propagating along an undoped YIG ceramic plate.

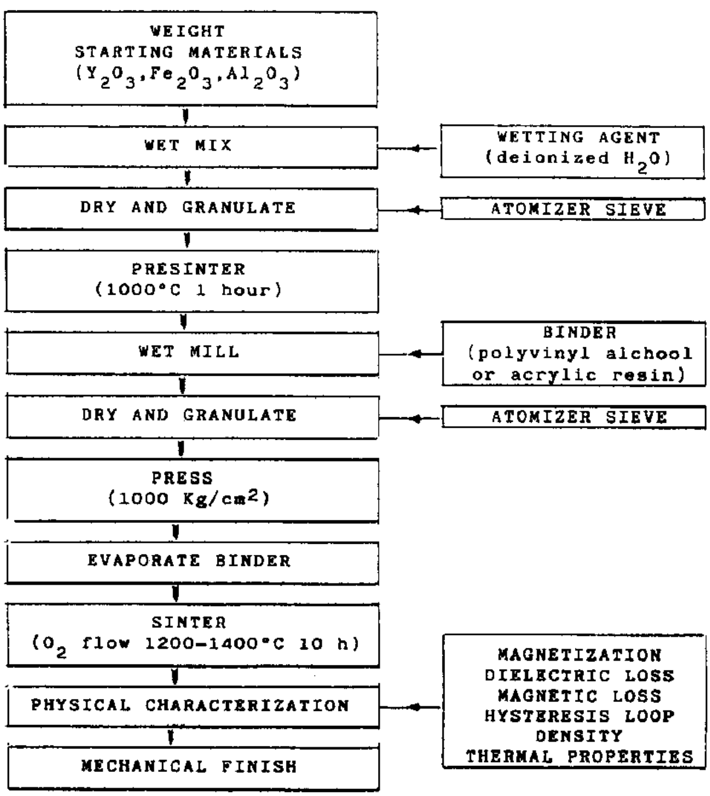

Fig. 3. Schematic diagram of the procedure followed for preparing the ceramic garnets.

ceramic technology as schematized in Fig. 3. Four different concentrations of Al^{3+} ions were investigated, corresponding to $x = 0, 0.4, 0.8$ and 1.1. The specimens were shaped as thin plates, 1 mm thick, with the two surfaces parallel and well finished. Acoustic waves were generated and detected by means of meanderline transducers, configured by standard photolithographic techniques. The transducers consist of 11 meanders with a spatial periodicity λ=0.6 mm and an electrode length of 4mm. Two transducers, 24 mm apart were implemented on each sample, so to configure an acoustic delay line. Meanderline transducers are effective in generating and detecting both Lamb and Love waves, provided that the bias magnetic field is parallel or orthogonal to the acoustic propagation direction, respectively (see Fig. 4) [14,15]. All the modes having a wavelength λ equal to the period of the transducer can be generated and detected. The corresponding phase velocity is given by the intersection in the $(v, h/\lambda)$ plane of Fig. 2, between the dispersion curve and a straight vertical line at a value (h/λ) corresponding to the specific experimental conditions. The relation between the phase velocity and frequency f of the mode is given by: $v = \lambda f$.

The two independent elastic constants of the material to be determined, are c_{11} and c_{44}. They are related to the wavelength and velocity of the acoustic modes, by the dispersion relations given in eqns. 3 and 4. The mass density ρ, which also enters into these equations, was measured by means of a pycnometer. Its value $\rho = (5.08 \pm 0.02)10^3 Kg/m^3$ turned out to be almost independent of the Al^{3+} concentration within the experimental error. Measurements

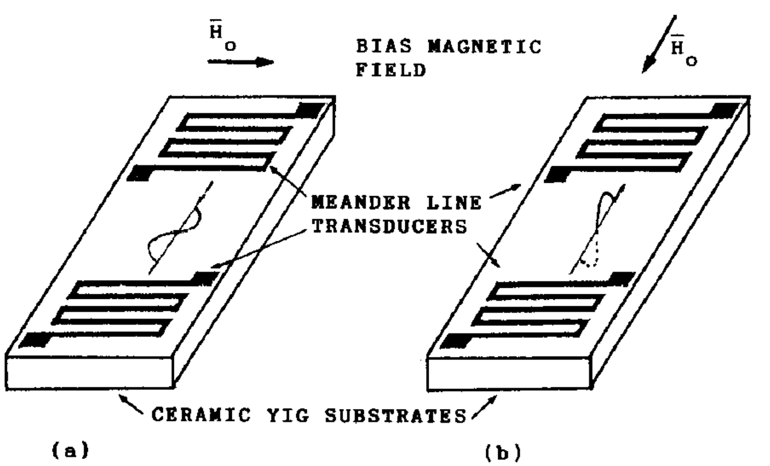

Fig. 4 Schematic of the acoustic delay lines used for investigating (a) Love and (b) Lamb waves.

Table I. Elastic constants c_{11} and c_{44} of the four samples analyzed with different concentrations of substitutional Al^{3+} ions.

ceramic material	elastic constants (10^{11} N/m^2)	
	c_{11}	c_{44}
$Y_3Fe_5O_{12}$	1.486	0.738
$Y_3Al_{0.4}Fe_{4.6}O_{12}$	1.492	0.798
$Y_3Al_{0.8}Fe_{4.2}O_{12}$	1.513	0.825
$Y_3Al_{1.1}Fe_{3.9}O_{12}$	1.549	0.863

of the frequency of the acoustic modes were performed by means of an HP 8753A network analyzer. Love modes were analyzed at first, in order to evaluate the c_{44} constant. The frequency corresponding to the first three modes was measured for each sample, and the experimental data processed according to the procedure outlined in the previous section, in order to minimize the experimental error. A symilar analysis, performed on the first three Lamb modes, allowed us the evaluation of the c_{11} constant. The measured elastic constants c_{11} and c_{44} of the four samples analyzed are reported in Table I. The values relative to undoped YIG ceramic are in a fairly good agreement with those calculated by the single crystal constants [16] on using the procedure outlined in [17] ($c_{11} = 1.61$, $c_{44} = 0.79$). The behaviour of the elastic stiffness versus per cent substitutions of Al^{3+} in Fe can be seen in Fig. 5. An almost linear increase of both the constants with Al^{3+} concentration is seen. An increase of about 5.6% and 16.5% was observed for the c_{11} and c_{44} constants, respectively, between undoped

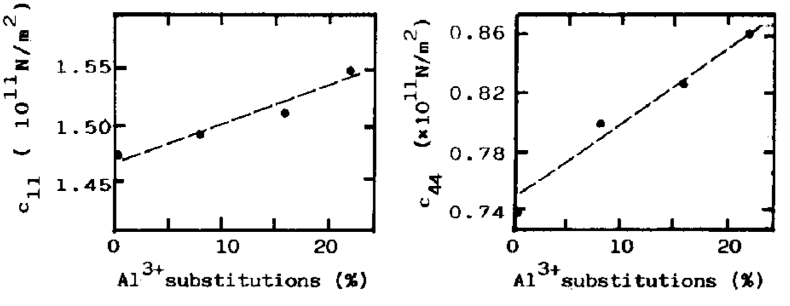

Fig. 5. Elastic constants c_{11} and c_{44} of $Y_3Al_xFe_{5-x}O_{12}$ versus Al^{3+} concentration.

and 22% Al^{3+} doped YIG. In order to evaluate the dependence of the these constants on the process of production of the ceramic, measurements were performed on different samples having the same concentration of substitutional Al^{3+} ions. The values of the elastic constants turned out to differ by amounts not larger than 2.5%.

CONCLUSIONS

In summary, an ultrasonic technique has been exploited for the evaluation of the elastic constants of ceramic garnets. The experimental method relies on measurement of the phase velocity of a number of acoustic modes propagating along a sample having the shape of a thin plate. Measurements were performed on ceramic Al:YIG systems, for different concentrations of substitutional Al^{3+} ions. The two independent elastic constants c_{11} and c_{44} of the material turned out to be strongly dependent on the concentration of substitutional ions. An almost linear increase of both the constants with Al^{3+} substitutions was observed. This behaviour is bound to the decrease of the lattice parameter with Al^{3+} concentration, that implies an increase of the cohesive force and, consequently, a stiffening of the material.

REFERENCES

1 B. Lax and K. J. Button, Microwave ferrites and ferrimagnetics, McGraw-Hill, New York, 1962.

2 F.F.Y.Wang (ed.), Treatise on materials science and technology, Vol. 9, Ceramic fabrication processes, Academic Press, New York, 1976.

3 G. Y. Onoda and L. L. Hench, Ceramic processing before firing, Wiley, New York, 1978. York, 1978.

4 M.S.Sodha and N.C.Srivastava, Microwave propagation in ferrimagnetics, Plenum press, New York, 1981.

5 G.Winkler, Magnetic garnets, Friedr. Vieweg, Braunschweig-Wiesbaden, 1981.

6 M.Massani, N.Sparvieri, Ceramurgia,XVIII (1988) 208.

7 E.Schlemann, J. Appl. Phys., 31 (1960) 1647.

8 H.F.Tiersten, J. Appl. Phys., 36 (1965) 2250.

9 W.Strauss, in W.P.Mason (ed.), Physical Acoustics, Vol.4, Part B, Academic Press, New York, 1968, p. 211.

10 J. P. Parek and H. L. Bertoni, J. Appl. Phys., 44 (1973) 2866.

11 R. Q. Scott and D. L. Mills, Phys. Rev. B, 15 (1977) 3545.

12 R.E.Camley, J. Appl. Phys., 50 (1979) 5272.

13 G.W.Farnell, in W.P.Mason and R.N.Thurston (eds.), Physical Acoustics, Vol. 6, Academic Press, New York, 1970, Ch. 3, p. 109.

14 R.B.Thompson, IEEE Trans. on Son. and Ultrason.,SU-25 (1978) 7.

15 R. B. Thompson, in J. de Klerk and B. R. McAvoy (eds.) Proc. 1978 IEEE Ultrason. Symp., Cheng Hill, N.Y., 25-27 Sept. 1978, p.374.

16 A. E. Clark and R. E. Strakna, J. Appl. Phys. 32 (1961) 1172.

17 O.L.Anderson, in W.P.Mason (ed.), Physical Acoustics, Vol. 3, Part B, Academic Press, N.Y., 1965, Ch. 2, p. 43.