Functional Materials 14, No.2 (2007)

Parametric interaction in the Terfenol-D based magnetostrictive composite and nickel ferrite

V.V.Rudenko, V.N.Berzhansky, S.N.Polulyakh, P.Pernod*, V.L.Preobrazhensky**

Taurida National University, Simferopol, Ukraine
*Institute d'Electronique, de Micro-electronique et de Nanotechnologie
(IEMN-DOAE-UMR CNRS 8520), Ecole Centrale de Lille,
Villeneuve d'Acsq, France
**Wave Research Center, A.Prokhorov Institute of General Physics,
Russian Academy of Sciences, Moscow, Russia

Received March 10, 2007

The parametric interaction between electromagnetic pumping field and magnetoelastic oscillations in the Terfenol-D based composite has been studied. An original high-sensitivity experimental technique to study the the pulse pumping influence on the decay of magnetoelastic oscillations in the sub-threshold parametric mode is described. The results obtained for the Terfenol-D based composite are compared with data for the polycrystalline nickel ferrite.

Исследовано параметрическое взаимодействие магнитоупругих колебаний с полем электромагнитной накачки в композите на основе Терфенола-D. Описывается оригинальная импульсная экспериментальная методика, позволяющая с высокой чувствительностью регистрировать влияние накачки на декремент затухания магнитоупругих колебаний в подпороговом параметрическом режиме. Результаты приводятся в сравнении с данными, полученными на поликристаллическом никелевом феррите.

Last years, the acoustic time reversal systems based on parametric wave phase conjugation (WPC) of ultrasound in magnetically ordered media are developed extensively for acoustic imaging and nondestructive quality control (see review [1] and references therein). The functionality of WPC systems is defined essentially by the properties of parametrically active medium of a phase conjugator. In medical and hydro-acoustic applications, the acoustic impedance matching between the active medium and water or biological tissues is required in addition to the requirements of effective sound speed control by AC magnetic field. To satisfy these requirements, the composite materials with variable elastic and magneto-elastic properties are of interest as prospective ones. The rare-earth intermetallic compound $Tb_{0.3}Dy_{0.7}Fe_2$ (Terfenol-D) can be considered as a basic component of such kind of composites due to its giant magnetostriction as well as the compensated magnetic anisotropy in the room-temperature range [2]. The magnetoelastic coupling coefficient for this compound reaches 80 % [3] and is accompanied by strong dependence of linear [4] and non-linear [5] elastic moduli on the applied magnetic field. On the other hand, the metallic conductivity of the Terfenol-D limits its application area by quasi-static and low-frequency range due to the skin-effect which hinders penetration of AC magnetic field into the sample bulk. Preparation of composite which contains magnetostrictive material as small (from ten to hundred micrometers in size) particles placed into an

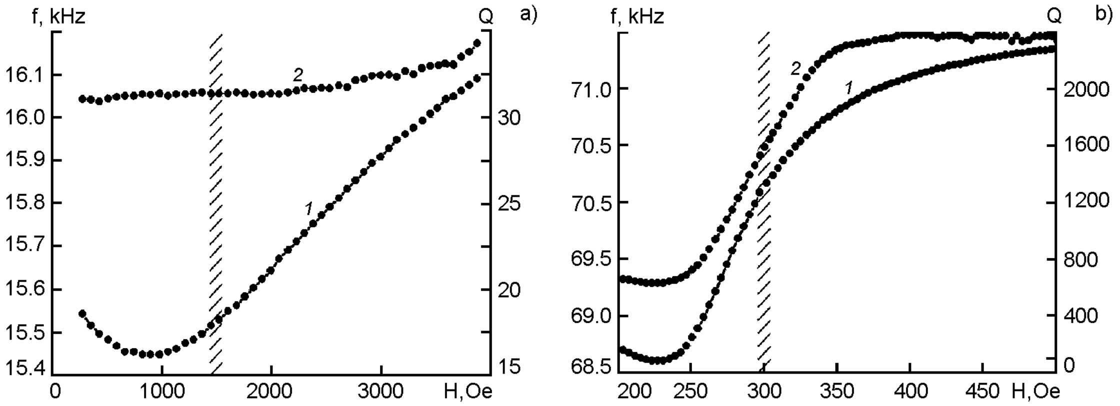

Fig. 1. Dependences of fundamental mode frequency (*1*) and Q-factor (*2*) on the DC magnetic field for the composite (a) and ferrite (b) samples.

insulating matrix was already proposed as an approach to extend the applicability area into the high-frequency range [6–8]. Such composites demonstrate workable magnetostriction at frequencies up to 1 MHz. The last experiments [9] have revealed the influence of external magnetic field on the ultrasound speed in the composites, that is a reason to investigate parametric phenomena in the discussed material.

In this paper, described are the results of first experimental study of parametric interactions between magnetoelastic oscillations and external AC magnetic field in the Terfenol-D based composites.

The studied samples of composite materials have been made as Terfenol-D powder homogenously distributed in a solidified epoxy resin matrix. The powder particles are of 60 to 90 μm size and the active material takes about 45 % of sample volume. The samples were shaped as parallelepipeds of $50.5\times10.1\pm4.5$ mm^3 size. The measurements give the magnetostriction about $5\cdot10^{-4}$ in the external DC fields up to 4 kOe. The reference measurements have been made using the sample of polycrystalline nickel ferrite $Fe_{2.026}Ni_{0.95}Co_{0.024}O_4$ prepared as a $42\times13.5\times13.5$ mm^3 parallelepiped. The saturation magnetostriction of ferrite sample has been determined to be $4.2\cdot10^{-5}$.

A copper wire coil of 130 turns was placed along the longest side of the sample. This coil was used to excite and to detect magnetoelastic oscillations using inductive technique. We have used a HP4195A analyzer to observe and to analyze the resonance line at the fundamental mode frequency of longitudinal oscillations along the sample longest side. The dependences of the resonance frequency and Q-factor for this mode on the external DC magnetic field for both studied samples are presented in Fig. 1. The measured resonance frequencies correspond to the maximal speed of the longitudinal elastic wave V_{max} = 5999.6 m/s for the ferrite and V_{max} = 1626.6 m/s for composite samples.

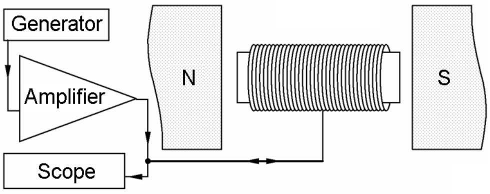

Fig. 2. Experimental scheme.

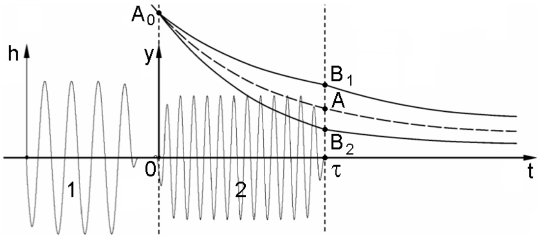

Fig. 3. Time diagram of the experiment: *1*, exciting pulse at resonance frequency; *2*, parametric pumping pulse at double frequency; h, pulse amplitude; y, oscillation amplitude; A_0, oscillation amplitude after the first pulse; A, free decay amplitude at time moment τ; B_1, B_2, decay amplitudes at time moment τ under parametric pumping; τ, parametric pumping pulse duration.

Fig. 2 presents the experimental scheme for the study of parametric interaction efficiency between magnetoelastic oscillations and longitudinal AC external magnetic field. In Fig. 3, the details of experiment are shown. A sequence of two radio-frequency (RF) pulses is applied to a coil. Dur-

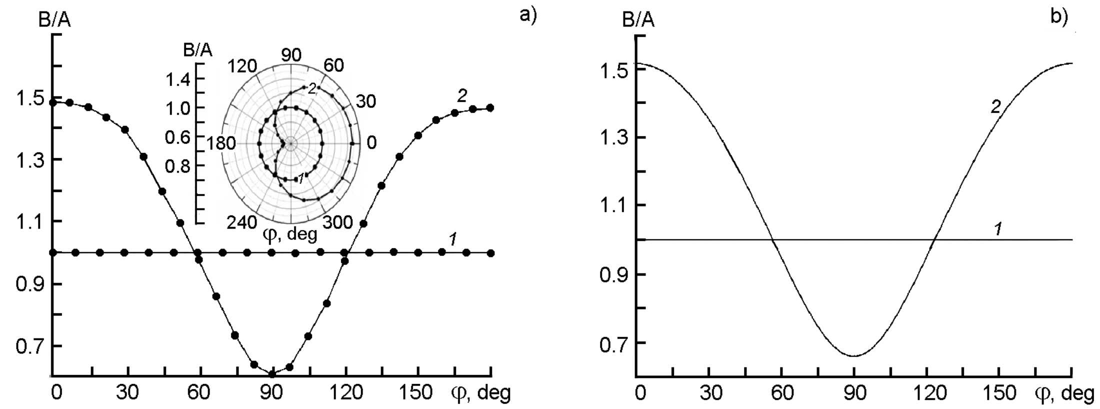

Fig. 4. Experimental (a) and calculated (b) oscillation amplitudes in the composite sample. Pumping duration $\tau = 1.3$ ms. Pumping field amplitude, Oe: $h = 0$ (*1*), $h = 253$ (*2*). The inset presents the data in polar diagram.

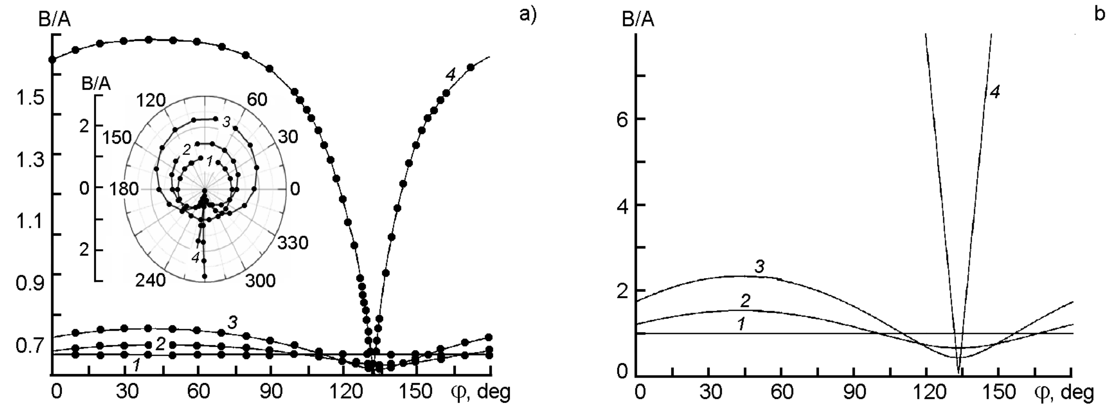

Fig. 5. Experimental (a) and calculated (b) oscillation amplitudes in the ferrite sample. Pumping duration $\tau = 4.7$ ms. Pumping field amplitude, Oe: $h = 0$ (*1*), $h = 0.5h_C$ (*2*), $h = h_C$ (*3*), $h = 4h_C$ (*4*). h_C is the threshold pumping field amplitude. The inset presents the data in polar diagram.

ing the first pulse, the RF oscillation frequency corresponds to the resonance frequency of the mode being studied. The second RF pulse at double frequency is applied just after the first pulse and provides parametric pumping. If the second pulse is absent, the free decay of oscillations induces a signal presented schematically by A_0A curve in Fig. 3. The parametric amplification (curve A_0B_1 in Fig. 3) and parametric damping (curve A_0B_2 in Fig. 3) of oscillations caused by second pulse depends on the phase shift between oscillations in the excited pulses. The oscillation amplitude measurement after the second pulse makes it possible to determine the deviations in the damping parameter caused by amplitude and phase of parametric pumping and to estimate the longitudinal sound speed modulation depth by AC magnetic field.

The dependences of the magnetoelastic oscillation normalized amplitude on the phase and amplitude of pumping pulse are shown in Fig. 4 and Fig. 5 for composite and ferrite samples, respectively. The pumping pulses of 4.7 ms and 1.3 ms duration were used for composite and ferrite samples, respectively. The amplitude of AC pumping field was varied from zero to 15 Oe for the ferrite and from zero to 253 Oe for the composite samples. The specified parameters are sufficient to detect the changes in the damping parameter for the sub-threshold pumping in composite and to detect sub-threshold as well as over-threshold phenomena in ferrite sample.

The parametric interaction in an acoustic resonator is described under the quasi-linear approximation by the system of equations for the amplitude and phase of elastic displacement

$$\frac{\partial B}{\partial t} + \left(\delta - \frac{1}{2} m\omega \sin(2\varphi)\right) B = 0 \qquad (1)$$
$$\frac{\partial \varphi}{\partial t} - \frac{1}{2} m\omega \cos(2\varphi) = 0 \ ,$$

here ω and δ are frequency and damping parameters of the magnetoelastic mode; B, the elastic displacement amplitude; φ, phase shift of displacement with respect to the pumping at the frequency 2ω; m, modulation depth of the resonance frequency.

The solution of system (1), which gives displacement amplitude after pumping pulse of duration τ can be written as:

$$B = \qquad (2)$$
$$= A_0 \exp\left\{-\delta\tau + \Gamma \int_0^{\tau} \cos\left[2 \operatorname{arctg}(\operatorname{tg}\Psi_0 e^{(-2\Gamma t)})\right] dt\right\},$$

where $\psi_0 = \varphi_0 - \pi/4$; A_0 and φ_0 are initial amplitude and phase shift for displacement; $\Gamma = m\omega/2$ is the parametric amplification increment.

The relationship (2) together with experimental data shown in Fig. 4a and 5a allow to calculate the relation between oscillation amplitudes $B(\tau)/A(\tau)$, where $B(\tau)$ corresponds to the pumping case and $A(\tau) = A_0\exp(-\delta\tau)$ is the amplitude in the pumping-free case. The modulation depth can be determined, too.

Fig. 5b presents calculated results for oscillation amplitude and modulation depth obtained for ferrite sample with the pumping pulse of duration τ = 4.7 ms. Taking into account the resonator parameters measured in the DC field of H = 300 Oe (Fig. 1b), one can calculate the threshold increment value $\Gamma_C = \delta = \omega/2Q$. The calculated value $\Gamma_C = 0.18 \cdot 10^3$ s^{-1} corresponds to the critical modulation depth $m_C = 0.86 \cdot 10^{-3}$. Experimental and calculated dependences of normalized oscillation amplitude on phase shift obtained at threshold pumping level are shown in Fig. 5 (curves *3*). The calculated dependences agree with experimental data at both threshold and sub-threshold modulation levels. The non-linear mechanisms of limitations define the oscillation amplitude in the over-threshold mode. The critical modulation depth obtained for h_C = 3 Oe agrees well with the experimental dependences of resonance frequency on the external DC magnetic field (Fig. 1b): $m_C = h_C(\omega^{-1}\, \partial\omega/\partial H) = 0.84 \cdot 10^{-3}$. The corresponding sensitivity of sound speed to the magnetic field variations is about 0.28 Oe^{-1}.

Fig. 5 presents a comparison between experimental dependence from Fig. 4a and calculations according to Eq.(2) for composite sample at pumping amplitude 250 Oe and duration 1.3 ms. This comparison results in amplification increment $\Gamma = 0.32 \cdot 10^3$ s^{-1} that corresponds to the modulation depth of $m = 6.6 \cdot 10^{-3}$ at resonance frequency. The obtained modulation depth defines the sound speed sensitivity to the AC magnetic field as 2.6 %/kOe for the studied com-posite. It is to note that the calculations based on the results of measurements with static magnetic fields yields a lower value of $m = 3.8 \cdot 10^{-3}$ at the same pumping amplitude. The difference between the results is caused by the difference in influence of high-frequency and static magnetic fields on the magnetic state of a sample.

In particular, unlike the case of magnetization in a static field, at high-frequency modulation of a constant field, the magnetostrictive stresses have no enough time to relax to equilibrium and may noticeably be manifested in a composite with giant magnetostriction. The difference between static and dynamic results may also be caused by the difference between the static and dynamic demagnetization fields. The latter is due to the difference of the static and high frequency longitudinal magnetic susceptibilities. While for ferrite in the bias field range above 200 Oe the reversible magnetization rotation processes take place that equalize static and dynamic magnetic susceptibilities, the dynamic magnetization of composite occurs by particular hysteretic cycles in all ranges of bias fields used in our experiments.

To conclude, using the pulse technique proposed in this work, we have measured the rate of sound speed modulation caused by parametric AC magnetic field pumping in the composite magnetostrictive material. The obtained experimental results confirm the influence of AC magnetic field on relative sound speed of the order of 0.026 kOe^{-1} in Terfenol-D based composite material. It follows from the measurements of the gain factor that the increasing of the acoustic Q-factor up to Q = 150 may be sufficient to reach the parametric instability level in real experiments. It is technologically available to reach the required Q-factor value. Taking into account close values of sound speed in composites and in water, one can consider the Terfenol-D based composites as perspective materials for medical and hydro-acoustic applications.

Acknowledgments. This work has been carried out under International projects ECO NET 2006-2007 and INTERREG IIIa-198 and under support of Ecole Centrale de Lille (France). The authors thank Dr.S.C.Busbridge who has offered the composite sample.

References

1. V.L.Preobrazhensky, *Uspekhi Phys.Nauk*, **176**, 98 (2006).
2. A.E.Clark., in: Ferromagnetic Materials, v.1, ed. by E.P.Wohlfarth, North-Holland, Amsterdam (1980).
3. E.du Tremolet de Lacheisserie, Magnetostriction, Theory &Applications of Magnetoelasticity, CRC Press, London, Tokyo (1993).
4. E.Clark, H.T.Savage, *IEEE Trans. on Sonics and Ultrasonics*, **SU-22(1)**, 50 (1975).
5. V.Preobrazhensky, A.M.Zaikin, in: Abstr. of 19th All-Union Conf. on Phys. of Magnet. Phenomena, Part.1, C1B20, Tashkent (1991), p.87.
6. L.Sandlund, M.Fahlander, T.Cedell et al., *J. Appl.Phys.*, **75**, 5656 (1994).
7. J.Hudson, S.C.Busbridge, A.R.Piercy, *Ferroelectrics*, **228**, 283 (1999).
8. L.Garcia-Gancedo, S.C.Busbridge, P.Pernod et al., *J.Magn.& Magn.Mater.*, **310**, 2627 (2007).
9. L.Krutyansky, S.Busbridge, P.Pernod, V.Preobrazhensky, in: Abstr. of Int. Conf. on Functional Materials, Partenit (2005), p.195.

Параметрична взаємодія у магнітострикційних композитах на основі Терфенолу-D та фериті нікелю

В.В.Руденко, В.Н.Бержанський, С.Н.Полулях, П.Перно, В.Л.Преображенський

Експериментально досліджено параметричну взаємодію магнітопружних коливань з полем електромагнітної накачки у композиті на основі Терфенолу-D. Описується оригінальна імпульсна експериментальна методика, яка дозволяє з високою чутливістю реєструвати вплив накачки на декремент згасання магнітопружних коливань у підпороговому параметричному режимі. Результати приведено у порівнянні з даними, які отримані на полікристалічному нікелевому фериті.