Journal of Magnetism and Magnetic Materials 449 (2018) 505–509

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Research articles

Nonlinear magnetoelectric effects in a composite ferromagnetic-piezoelectric structure under harmonic and noise magnetic pumping

D.A. Burdin [a], D.V. Chashin [a], N.A. Ekonomov [a], Y.K. Fetisov [a,*], A. Stashkevich [b]

[a] Moscow Technological University (MIREA), 119454 Moscow, Vernadskogo pr. 78, Russia
[b] LSPM, (CNRS-UPR 3407), Université Paris 13, Sorbonne Paris Cité, 93430 Villetaneuse, France

ARTICLE INFO

Article history:
Received 7 August 2017
Received in revised form 6 October 2017
Accepted 24 October 2017

Keywords:
Magnetoelectric effect
Magnetostriction
Noise pumping
Frequency mixing

ABSTRACT

Low-frequency nonlinear magnetoelectric effects in a composite structure comprised of a piezoelectric langatate slab sandwiched between two Metglas amorphous alloy magnetostrictive layers under simultaneous harmonic and noise magnetic pumping have been investigated. It is shown that the frequency f_p of harmonic pumping is linearly reproduced in the piezoelectric voltage spectrum accompanied by its higher harmonics. Similarly, narrow-band magnetic noise with a central frequency f_N is present in the output piezoelectric voltage along with two noise peaks in the vicinity of a double $2f_N$ and zero frequency. Simultaneous application of harmonic and noise magnetic fields produces a noticeably more complex output voltage spectrum containing additional noise satellite lines at frequencies $f_p \pm f_N$, $2f_p \pm f_N$ etc. as well as a noise "pedestal". Amplitudes of voltage spectral components depend on the applied constant bias magnetic field, scaling as magnetostriction derivatives with respect to this field. The effects observed are well described by the theory of magnetic field mixing in magnetoelectric composites with nonlinear dependence of magnetostriction on applied fields.

1. Introduction

Magnetoelectric (ME) effects in composite planar structures containing mechanically coupled ferromagnetic (FM) and piezoelectric (PE) layers result from the combination of magnetostriction of the FM layer and piezoelectricity of the PE layer [1–3]. As the strength of magnetic field H acting on the structure increases, the nonlinearity in the dependence of the magnetostriction of the FM layer λ on the field H leads to the appearance of nonlinear ME effects [4]. It has been shown that if such a structure is exposed to harmonic magnetic field pumping $h(f)$ together with a constant bias magnetic field H the PE layer generates a voltage $u(f)$ at the pumping frequency and its multiples with growing efficiency under pumping with increasing amplitude [5–8]. In the case of two harmonic magnetic fields applied to the system the output voltage contains additional spectral lines at the sum and difference frequencies [9–11]. Harmonic magnetic pumping of high amplitude induces a static deformation of the structure [12]. High efficiency of nonlinear ME effects allows for creation of a new generation of advanced magnetic detectors such as highly sensitive sensors of low frequency alternating magnetic fields [13,14], sensors of dc magnetic fields [15,16], tunable wideband sensors of low-frequency fields [17] and «zero-biased» sensors of alternating fields [18].

So far studies of nonlinear ME effects focused on the case of purely harmonic pumping. At the same time, creation of high-performance magnetic field ME sensors and weak radio signal processing devices is impossible without knowledge of the characteristic features demonstrated by ME structures in the presence of magnetic noise. It has already been shown that it is exactly the magnetic noise in the FM layer that limits the sensitivity of ME low-frequency magnetic field sensors [19,20]. Moreover, typically the structure is exposed to exterior magnetic various noise fields of technogenic nature with various spectral characteristics. Thus, in this paper we address the important issue of nonlinear effects in composite structures under simultaneous harmonic and noise magnetic pumping.

The plan of the paper is as follows. In the first section will be outlined the sample preparation and the measuring techniques used in the experiment including formation of magnetic field with noise spectrum. The next section is dedicated to description of the experimentally observed effects both under harmonic pumping, noise pumping, and combined «harmonic plus noise» one. The paper concludes with a discussion based on theoretical analysis and backed with numerical simulations with a short summary of major results given in its final part.

* Corresponding author.
E-mail address: fetisov@mirea.ru (Y.K. Fetisov).

https://doi.org/10.1016/j.jmmm.2017.10.096
0304-8853/© 2017 Published by Elsevier B.V.

2. Sample preparation and experimental arrangement

A schematic of the composite structure utilized in the experiment is given in the inset in Fig. 1. It is comprised of a slab of piezoelectric langatate $La_3Ga_{5.5}Ta_{0.5}O_{14}$ (LGT) sandwiched between two layers of a magnetostrictive amorphous alloy having the following composition FeBSiC (Metglas 260551A) [21]. The layers were glued together with epoxy glue. The dimensions of the Metglas layers were 20 mm × 5 mm and had a thickness of 20 μm and saturation magnetostriction $\lambda_S \approx 20$ ppm in saturating fields $H_S \sim 60$ Oe. The LGT slab (provided by FOMOS Materials, Moscow, Russia) having the same dimensions was 0.5 mm thick, its dielectric permittivity and piezoelectric modulus were equal to ε = 20, d_{11} = 5.2 pm/V [22].

The structure was placed inside a solenoid generating a uniform excitation magnetic field $h(f)$. To create harmonic pumping $h_P\cos(2\pi f_P t)$ with an amplitude h_p = 0–5 Oe and frequency f_P = 1–50 kHz the solenoid was fed by the AKIP-3409/5 generator. To produce magnetic pumping with a noise spectrum the solenoid was connected to an Agilent 33210a noise generator followed by a band-pass filter and a wideband current amplifier. Such a circuit allowed for generation of a magnetic field with a noise spectrum whose shape is close to rectangular with a central frequency f_N in the range from 0.5 to 20 kHz, bandwidth Δ from 0.5 to10 kHz, edge steepness of 115 dB/decade, and a spectral density of up to h_N = 80 mOe/$\sqrt{}$Hz. When the solenoid is fed from both a harmonic current generator and a noise current generator the structure is simultaneously exposed to a noise and sinusoidal magnetic field. To minimize the interference between the structure and the coil a special screen made of thin copper foil was added (not shown in Fig. 1). A homogeneous dc magnetic field was created by a pair of Helmholtz coils.

Frequency spectra of the pumping magnetic field $h(f)$ and those of the voltage generated by the ME structure $u(f)$ were recorded with a SR770 spectrum analyzer at different amplitudes of the excitation field h and different values of the dc magnetic field H. The measurements were carried out in a non-resonant regime, the magnetic field frequency being well below the frequencies of acoustic resonances of the structure. No bending oscillations have been excited due to the symmetry of the structure. The magnetostriction of the Metglas layer has been measured by a strain-gauge technique using a sample of the above-mentioned dimensions magnetized along its longest axis.

3. Experimental results

Fig. 1 shows a frequency spectrum of the pumping magnetic field together with a corresponding spectrum of the ME voltage $u(f)$, generated by the PE layer due to the nonlinear ME effect. The pumping field frequency and amplitude were f_p = 15 kHz and h_p = 1 Oe, while the bias dc field was H = 0.1 Oe. Nonlinearity leads to generation of voltage at the pumping frequency f_p as well as higher harmonics with frequencies $2f_p$, $3f_p$ and amplitudes u_1, u_2, and u_3, respectively. Relative amplitudes, as shown in [6], depend on the pumping field amplitude h_p and the magnitude of the bias field H.

In Fig. 2 is given a frequency spectrum of the magnetic noise $h_N(f)$ along with that of the ME generated voltage $u(f)$ under magnetic noise pumping. The noise spectrum had a shape close to rectangular with a central frequency f_N = 4 kHz, bandwidth $\Delta = f_2 - f_1 \approx 2$ kHz and height h_N. In this case, one can observe in the ME voltage spectrum a peak in the vicinity of the noise central frequency f_N having a width of ∼Δ and height $u_N(f_N)$ accompanied by another peak at a double central frequency $2f_N$ approximately ∼2Δ wide and having a height of $u_N(2f_N)$. Moreover, contrary to the case of harmonic pumping there appears an additional noise-like peak close to the zero frequency having a width of ∼Δ and height $u_N(0)$. The height of this peak is comparable to that of the noise-like one at $2f_N$. The mechanisms of the formation of spectral components will be considered below.

Fig. 3 reproduces a typical spectrum of the ME voltage generated by the composite structure under the combined action of harmonic pumping at a frequency f_P = 15 kHz and magnetic noise with a central frequency $f_N \approx 4$ kHz and bandwidth $\Delta \approx 2$ kHz. It can be seen that the spectrum contains the main pumping frequency and its higher harmonics with frequencies f_P, $2f_P$, $3f_P$, noise-like peaks with a width of ∼Δ close to the zero point and around f_N, and a noise-like ∼2Δ-wide peak around $2f_N$. Besides, there appear in the spectrum additional noise-like peaks with central frequencies $f_p \pm f_N$, $2f_P \pm f_N$, $3f_P \pm f_N$, $f_P \pm 2f_N$, etc. Also should be mentioned the noise-like «pedestals» appearing at the frequency f_P and its second harmonic $2f_P$. The appearance of additional noise-like peaks below and above the harmonic frequencies attest to the efficiency of the nonlinear interaction between the harmonic signal and magnetic noise. When the frequency of the harmonic pumping is being swept from 5 kHz to 30 kHz or the central frequency of the

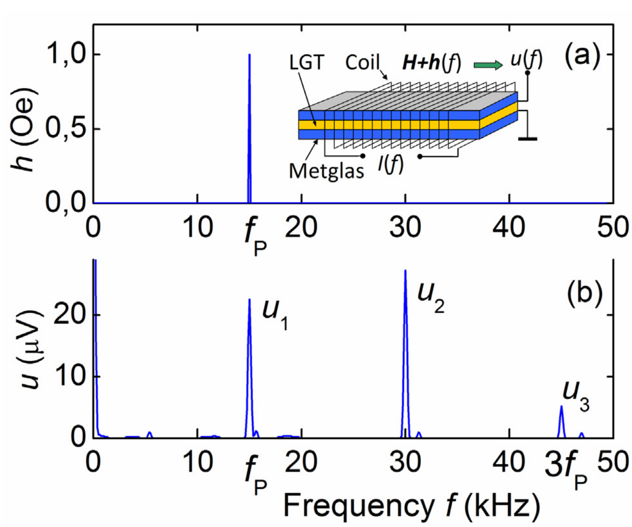

Fig. 1. Frequency spectra of pumping field (a) and ME voltage (b) under harmonic pumping. In the inset is given the geometry of the Metglas-LGT-Metglas structure.

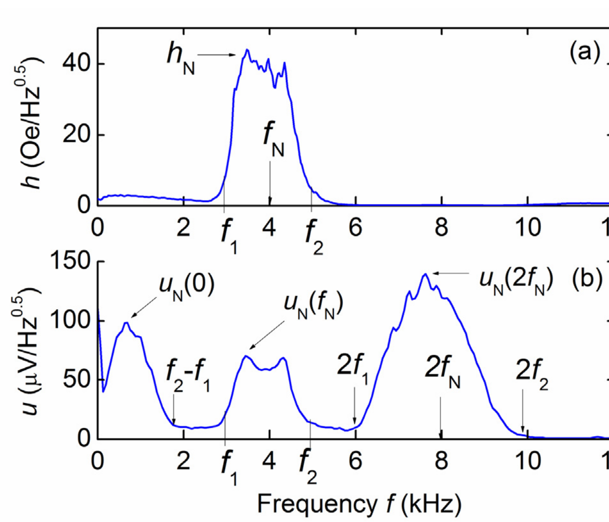

Fig. 2. Frequency spectra of pumping field (a) and ME voltage (b) under noise pumping.