THE PROBLEMS OF LOCAL COUPLING BETWEEN ELECTRICAL AND MAGNETIC POLARIZATIONS IN MICROWAVES: EXPERIMENTS AND THEORY.

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ABSTRACT

The question about local coupling of electric and magnetic polarizations [magnetoelectric (ME) coupling] arises in a subject of new artificial microwave materials. In classical electromagnetic theory of such complex media one becomes faced with serious contradictions. One cannot consider (classical electrodynamically) two coupled electric and magnetic dipoles - the ME particles - as point sources of the electromagnetic field. One cannot construct a classical model of duality symmetry in points with local sources. In nature, such duality symmetry appears to be spoiled by the fact that one can observe point electric charges, but not magnetic ones. Based on these aspects we should come to the following conclusion: the unified ME fields originated by ME particles may exist with the symmetry properties distinguished from that of the electromagnetic fields.

INTRODUCTION

Heras discussed the fact that duality symmetry is presented in classical electrodynamics of *dipoles* since the external-field lines of the electric dipole cannot be distinguished from those due to a magnetic dipole [1]. This, certainly, touches upon a question about coupling the electric and magnetic polarizations - the problem arising in artificial chiral and bianisotropic media [2,3].

Can one consider (classical electrodynamically) two small, i.e. quasistatic (with sizes much less than the electromagnetic wavelength) coupled electric and magnetic dipoles – magnetoelectric (ME) particles – as *point sources*? A point ME particle should be presented as a certain microscopic physical object, which has quasistatic energy of electric and magnetic polarizations and quasistatic energy of the internal ME coupling in a small (in comparison with the free-space electromagnetic wave) free space region. “The internal ME coupling” means that energy of the induced electric polarization of a whole particle can partially be transformed to energy of the magnetic polarization of a whole specimen and, conversely, energy of the induced magnetic polarization can partially be transformed to the electric polarization energy.

The physical ground for such point sources – the ME particles – has been found in small ferromagnetic resonant specimens where short-wavelength [so-called *magnetostatic (MS*)] oscillations take place. The properties of a multi-resonance spectrum of MS oscillations underlie the conception of ferrite quasistatic ME particles - small ferrite resonators with special-form surface electrodes [4,5]. The validity of ME coupling in such specimens has been proved in recent experiments where the multi-resonance spectrums of ME oscillations (excited by the external RF electric and magnetic fields and their combinations) were observed [6-8]. This is a new effect in microwaves. It was shown that the *unified quasistatic ME fields* originated by point sources - the quasistatic ME particles - can exist with the symmetry properties distinguishing from that of the electromagnetic fields [8,9].

EXPERIMENTS

Our experiments [6-8] give an evidence that in the quasistatic free-space region (the region much less than the free-space electromagnetic wavelength) one has an effective transformation of energy of electric polarization to energy of magnetization or, in other words, the effective transformation of the quasielectrostatic energy to the quasimagnetostatic energy. In this paper we demonstrate further experimental results of spectral properties of quasistatic ME particles based on small ferrite resonators with linear-form surface electrodes. In the presented experimental study, an essential attention is paid to uncover the main physics of such effective *quasielectrostatic to quasimagnetostatic energy transformation*. For this purpose we made a comparative analysis of different oscillating ME spectrums obtained for particles with different forms and sizes of ferrite resonators and different lengths of linear electrodes. It was found, as a very important fact, that small additional capacitative terminals of the linear electrodes might strongly increase the effect of ME coupling. For some ME particles, our experiments show that we have a clear picture of two locally coupled electric and magnetic dipoles. This model becomes evident as a result of a careful comparison of different absorption spectrums obtained in small (quasistatic) regions of the RF electric and magnetic fields. To emphasize the fact that just the quasistatic dipole properties play the main role in the effective electric-field excitation, we analyzed spectrums for different particles with a successive reduction of a ferrite disk diameter. The experimental arrangement is shown in Fig. 1. Different structures of the exciting RF fields are ensured by placing the *normally magnetized* ferrite ME particles at two positions (positions 1 and 2 in Fig. 1) in a rectangular cavity resonant in the TE_{101} mode at 4.02 GHz. Because of the cavity frequency and sizes of ferrite specimens used in our experiments, the observed oscillations can be described based on the MS assumption. We do not have pure electromagnetic oscillations and do not have exchange oscillations as well. Some examples of the observed oscillating spectrums are shown in Figs.2,3. Fig.2 shows absorption spectrums of a flat disk (disk diameter 5 mm, thickness 0.10 mm) ME particle with a strip (strip sizes 4 mm $\times$ 0.10 mm) metallization, in the cavity position 1. (a) RF magnetic field is perpendicular to the strip; (b) RF magnetic field is parallel to the strip. Fig. 3 demonstrates absorption spectrums of a flat disk (disk diameter 5 mm, thickness 0.10 mm) ME particle with a strip metallization, in the cavity position 2, when RF electric field is parallel to a strip. (a) the strip (strip sizes 4 mm $\times$ 0.10 mm) is at the central position; (b) the strip (strip sizes 5 mm $\times$ 0.10 mm) is upward shifted by 1.5 mm; (c) the strip (strip sizes 4 mm $\times$ 0.10 mm) is shifted 1mm far from the resonator axis.

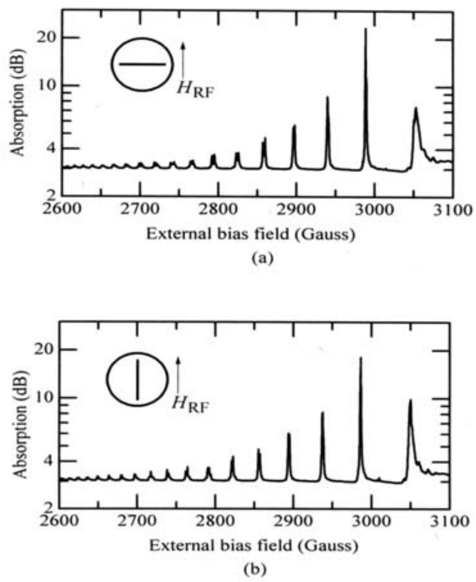

Fig. 1. Experimental arrangement. (a) rough sketching (b) top view

Fig. 2. Absorption spectrums of a ferrite-disk ME particle with a strip metallization, in the cavity position 1.
(a) RF magnetic field is perpendicular to the strip; (b) RF magnetic field is parallel to the strip.

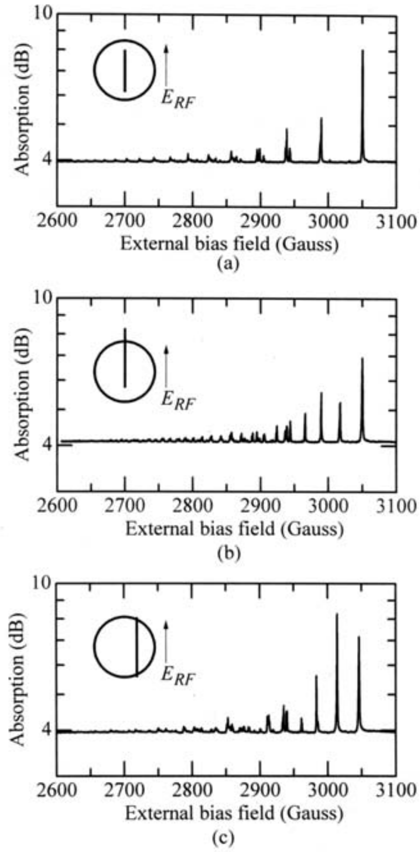

Fig. 3. Absorption spectrums of a ferrite-disk ME particle with a strip metallization, in the cavity position 2, when RF electric field is parallel to a strip. (a) the strip is at the central position; (b) the strip is upward shifted by 1.5 mm; (c) the strip is shifted 1mm far from the resonator axis.

THEORY

To understand the processes in point ME particles, one should be based on an analysis of the properties of MS multi-resonance oscillations in small ferromagnetic resonant specimens. Because of essential temporal dispersion of permeability, MS oscillations take place in ferromagnetic bodies with sizes much less than the electromagnetic wavelength in a microwave region but much more than the characteristic length of the exchange interaction. It can be supposed that the MS oscillations are well described by the Maxwell equations in neglect of the electric displacement current. In this case, the magnetic field is characterized by MS potential function. The second-order differential equation – the Walker equation – describes the MS potential function inside a ferrite resonator, while the Laplace equation is used for the MS potential distribution outside a ferrite. It is necessary to note that the MS potential function is a pseudoscalar quantity. In a normally magnetized thin ferrite resonator, a MS potential is a *complex order* parameter with the properties of the "macroscopic wave function". The one-dimensional wave equation contains a second derivative with respect to a space coordinate and a first derivative with respect to time [10]:

$$-\frac{i}{X^{(D,F)}}\nabla_{\parallel}^{2}\,\psi=\frac{\partial\psi}{\partial t}\,, \tag{1}$$

where $X^{(D)}$ and $X^{(F)}$ are coefficients characterizing wave processes in dielectric and ferrite regions, $\nabla_{\parallel}^{2}$ is a longitudinal part of the Laplace operator. Based on this Schrodinger-like wave equation, we have shown that MS oscillations in such a resonator can be characterized by a *normalized spectrum of energy eigenstates* [10]. The energy orthonormality is described as

$$(E_{pq} - E_{pq'}) \int_Q \tilde{\varphi}_q \tilde{\varphi}^*_{q'} ds = 0 \quad (2)$$

where Q is a square of "in-plane" cross section of an open ferrite disk. The normalized energy of MS oscillations E_{pq} is an eigenvalue of a differential equation:

$$\hat{F}_\perp \tilde{\varphi}_q = E_{pq} \tilde{\varphi}_q \quad (3)$$

where $\hat{F}_\perp$ is a two-dimensional ("in-plane") differential operator.

Because of full quantization in all three dimensions, MS oscillations can actually diagonalize the magnetic energy in a disk ferrite resonator. We have *discrete absorption spectrum of quasistatic magnetic energy*. Excitation of these oscillations by the RF magnetic field should be considered as a time-dependent perturbation of the energy spectrum, similar to the quantum mechanical problem. Experimental results clearly verify this fact and demonstrate that a small ferrite disk resonator is a particle, an "*artificial atom*", or, in other words, a lumped oscillating element *quasistatically* interacting with the external RF magnetic fields.

The oscillation spectrum of a ME particle should be characterized by a *discrete set of eigen energies.* In accordance with the boundary conditions in a ferrite disk resonator, one can distinguish the "left" and "right" states of MS-potential functions. This fact leads to the properties of eigen-electric-moment oscillations in ferrite disk resonators, recently observed experimentally [11] and analyzed theoretically [12]. The energy-eigenstate spectrums as well as the spectrums of eigen-electric-moment oscillations underlie the nature of the observed local (quasistatic) coupling between the electric and magnetic polarizations in ferrite ME particles.

CONCLUSION

Our studies of experimental spectrums show that in a case of a symmetrical position of a linear electrode with respect to a disk resonator, one has *the unified process of ME oscillations.* Because of the spectral properties (*characterized by certain regular positions of poles and zeros with respect to frequency or bias magnetic field*), the particle can be described by the polarizability parameters. The particle can be considered as a "glued pair" of two (electric and magnetic) *point* dipoles and, therefore, can be used as structural elements for bianisotropic composite materials.

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