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Microwave magnetoelectric particles: An experimental study of oscillating spectrums

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One of the ways to uncover the nature of the microwave magnetoelectric (ME) effect, recently observed in small ferrite resonators with special-form surface metallizations, is a comparative analysis of oscillating spectrums excited by different type rf external fields. Experimental results of the ME coupling in different types of ferrite resonators and different types of surface electrodes are reported and some important conclusions are drawn observing the oscillating spectrums of those particles. A special interest in spectral properties of point ME particles should be found in the field of microwave artificial composite materials-bianisotropic materials.

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I. INTRODUCTION

The fact that, due to constitutive relations in a medium, one has an additional (with respect to macroscopic Maxwell equations) coupling between the electric and magnetic fields, promises, it seems, to give very attractive fundamental problems and applications [1,2]. Artificial chiral media were developed to demonstrate the phenomenon of electromagnetic activity at microwave frequencies, analogous to optical activity. As a further generalization of such media, artificial bianisotropic media based on a composition of helices or omega particles were introduced as well [2,3]. Up to now, however, the notion ''condensed bianisotropic media'' bears a formal character. Nobody has defined constitutive parameters of these media from microscopic analysis similar to quantum-mechanical analysis and laws of quantum statistics used to obtain constitutive parameters of nonbianisotropic condensed media. For this reason, the main aspects of electrodynamics of bianisotropic media are far from completion. In many problems, one can meet a strong divergence of views [4].

Fundamental principles of macroscopic electrodynamics of bianisotropic media should arise from the microscopic point of view. It means that such media should be composed by point magnetoelectric (ME) particles with energy-eigenstate spectrum of ME oscillations. In this case, one may use the Hamiltonian formalism and consider an interaction with the external rf quasistatic fields by the interaction Hamiltonian (the perturbation of energy eigenstates by the external fields) [4]. Recently, an idea that small ferromagnetic (quasimagnetostatic) resonators with special-form surface metallizations may exhibit in microwaves the properties of a local (point) particle with an internal ME coupling, was put forth [5,6]. Experimental investigations have verified the quasistatic microwave ME effect that is characterized by a spectrum of ME oscillations excited by the external uniform rf electric and magnetic fields [7–9]. The multiresonance oscillating spectrum demonstrates that ME modes may actually diagonalize the total electric and magnetic energies of the external fields. Such point ME particles (which one may consider, in some cases, by a simple model of ''glued'' electric and magnetic dipoles), being artificial particles, do not have any analogs in nature.

An analysis of oscillating spectrums of local ME particles plays a very important role for future problems of artificial-bianisotropic-material composed structures. In this paper, we give a comparative analysis of experimental ME oscillating spectrums for different types of ferrite ME particles. One should distinguish the cases of regular and irregular oscillating spectrums. For regular spectrums, certain parameters (such, for example, as polarizability coefficients) may be introduced to characterize a particle. The main purpose of the paper is to trace the spectrum transformations when configurations of ferrite resonators and surface metallizations are changed. It will be shown that, for certain cases, simple models to describe the particle properties may be introduced.

II. POLARIZATION PROPERTIES OF SMALL FERRITE RESONATORS

Because of essential temporal dispersion of permeability, the so-called magnetostatic (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 [10]. 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 a MS potential function ψ: $\vec{H}=-\nabla\psi$. The second-order differential equation—the Walker equation [11]—describes the MS potential function ψ inside a ferrite resonator, while the Laplace equation is used for the MS potential distribution outside a ferrite. Effect of excitation of MS oscillations in

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ferrite resonators by the external rf magnetic fields is a subject of many publications over more than the last 40 years. Necessary conditions for the excitation of multiple oscillating MS modes in a small ferrite *sphere* are those that the exciting rf magnetic field at the sample be essentially nonuniform. In this case, however, one may just see only a few absorption peaks in a spectrum [12]. A striking difference in the picture of absorption spectrums can be observed in a case of small ferrite *disks* [13,14]. There is really a surprising fact that in these spectrums (as it was shown by Dillon [13]), the experimental oscillating modes were distinguishable out to number 55 in a very simple (homogeneous) configuration of the external rf magnetic field. The transition from a spherical to a disk form of a ferrite resonator leads to absolutely another physical picture of the observed oscillations.

In a ferrite spheroid, an analytical solution for MS modes was obtained [11]. It was shown that these modes are mutually orthogonal [11,15]. Based on this orthogonality relation, the electromagnetic theory of excitation of MS oscillations was developed [15,16]. This theory, may certainly be applied for the observed two-, three-resonance spectrums in a ferrite sphere but cannot be accepted, however, as an adequate basis for a proper explanation of experimental *multiresonance* spectrums one may observe in a ferrite disk. Really, in a general linear theory of excitation of electromagnetic resonators, the field distribution of an excited resonance mode is assumed to be practically the same as the field distribution of an eigenmode and the role of a source is merely to support an amplitude of an eigenoscillation [17]. So such a theory may hardly be applicable to explain excitation of, for example, the 10th or, moreover, the 50th resonance mode. Certain attempts to explain the reason of the ''illegal'' (with almost zero quantity of the excitation integral) high-order peaks in the spectrum with use of the coupled-mode theory [16] do not clarify the question. In some papers [14,18,19], the main accent was made to show that the multiresonance MS oscillations could chiefly be observed due to the nonuniform DC magnetic field in disk-shaped samples. This fact, however, cannot be accepted as the main reason to explain the multiresonance nature of the spectrum. In numerous spectral problems—quantum mechanical or integrated-optics (see, for example, [20] and [21])—one cannot reveal the fact that nonhomogeneity of a potential well (in quantum mechanics) or nonhomogeneity of refractive index (in optics) lead to a *striking difference* in a picture of oscillating spectrums.

Are there any factors that can be used to explain these experimental results? Reach oscillating spectrums (clearly distinguishable out to the number of tens), one may see in the atomic dynamical structures, but not in electromagnetic resonators. Concerning this problem, it is important to keep in mind the fact that when in classical electrodynamics structures, the spectral problems are characterized by *wave numbers* and *frequencies* as spectral parameters, in quantum-mechanical structures there are *energy eigenstates* as spectral parameters. So the question inevitably comes to mind: Could MS oscillations in a ferrite resonator be characterized by *energy eigenstates*? A positive answer to this question was given in [22]. It was shown that in a ferrite disk resonator, the MS potential function may be considered as a probability distribution function. The average (on the rf period) MS energy of a normally magnetized ferrite disk of thickness h may be defined as [22]

$$\overline{W}=\frac{\omega\mu_0}{4}\int_Q\left[X^{(D)}\left(\int_{-\infty}^{0}\psi\psi^*dz+\int_h^{\infty}\psi\psi^*dz\right)+X^{(F)}\int_0^h\psi\psi^*dz\right]dQ, \tag{2.1}$$

where $X^{(D)}$ and $X^{(F)}$ are coefficients characterizing wave processes in dielectric (D) and ferrite (F) regions, Q is a square of an ''in-plane'' cross section of an open ferrite disk. Coefficients X are found from the equations

$$-\frac{i}{X}\nabla_{\parallel}^2\psi=\frac{\partial\psi}{\partial t}. \tag{2.2}$$

Here, $\nabla_{\parallel}^2$ is the longitudinal part of the Laplace operator. In a disk ferrite resonator with a small thickness/diameter ratio, the MS potential ψ is represented as

$$\phi=\sum_{p,q}A_{p,q}\tilde{\xi}_p(z)\tilde{\varphi}_q(\rho,\alpha), \tag{2.3}$$

where $A_{p,q}$ is a MS mode amplitude, $\tilde{\xi}_p(z)$ and $\tilde{\varphi}_q(\rho,\alpha)$ are dimensionless functions describing, respectively, p ''thickness'' and q ''in-plane'' MS mode. The ''in-plane'' mode index q is composed, in its turn, by the azimuth number ν and the radial mode index r. For resonance frequency ω_{pq}, one has [22]

$$X_{pq}^{(D)}=\frac{(\beta_{pq}^{(D)})^2}{\omega_{pq}},\quad X_{pq}^{(F)}=-\mu_{pq}\frac{(\beta_{pq}^{(D)})^2}{\omega_{pq}}, \tag{2.4}$$

where μ is a diagonal component of the permeability tensor and β is the propagation constant for MS waves. Here, we denoted $\mu\equiv\mu(\omega_{pq})$ and $\beta_{pq}^{(D,F)}\equiv\beta^{(D,F)}(\omega_{pq})$. MS oscillations in a ferrite disk resonator are characterized by a normalized spectrum of energy eigenstates. The energy orthonormality is described as

$$(E_{pq}-E_{pq'})\int_Q\tilde{\varphi}_q\tilde{\varphi}_{q'}^*dQ=0. \tag{2.5}$$

The normalized energy of MS oscillations E_{pq} is an eigenvalue of a differential equation

$$\hat{F}_{\perp}\tilde{\varphi}_q=E_{pq}\tilde{\varphi}_q, \tag{2.6}$$

where $\hat{F}_{\perp}$ is a two-dimensional (''in-plane'') differential operator: $\hat{F}_{\perp}=(g\mu_0/4)\nabla_{\perp}^2$, containing $\nabla_{\perp}^2$ as the two-dimensional (''in-plane'') Laplace operator, μ_0 is the vacuum permeability, and g is the unit-dimensional (with the dimension of the square of MS potential) coefficient. For a disk resonator with a unit characteristic volume, the normalized energy of MS oscillations is defined as [22]

$$E_{pq}=\frac{g\mu_0}{4}(\beta_{pq}^{(D)})^2=-\frac{g\mu_0}{4}\frac{(\beta_{pq}^{(F)})^2}{\mu_{pq}}. \tag{2.7}$$

These results show that MS oscillations may actually diagonalize the magnetic energy in a ferrite disk resonator. We have a *discrete absorption spectrum of quasistatic magnetic energy*. Excitation of these oscillations by the RF magnetic field should be considered as a time-dependent perturbation [22]. Experimental results in [13,14] 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.

A process of MS oscillations is characterized by a strong predominance of the rf magnetic energy over the rf electric energy (the last one takes place due to a small curl electric field that accompanies the MS-wave process). In our experiments [7–9] with ferrite ME particles—small ferrite resonators with surface electrodes—we observed the multiresonance absorption spectrum in the external rf electric field. It was proven experimentally that in the region much less than the free-space electromagnetic wavelength, the quasielectrostatic energy absorbed by a small specimen is effectively transformed to the magnetostatic energy of this specimen. In other words, in a small (in comparison with the free-space electromagnetic wavelength) free-space region, we have some object that effectively transforms the energy of the electric polarization to the energy of magnetization (of a whole ferrite body). At the same time, we know that in accordance with the Maxwell theory, the space scale of electric energy—magnetic energy transformation is about a free-space wavelength. A metal electrode in our specimen is not a free-space dipolar antenna. Also, a ferrite specimen is not a free-space reradiating element. We have discrete absorption spectrums of quasistatic electric energy and quasistatic magnetic energy. The quasistatic electric energy absorbed by a ME particle in the external rf electric field, is going partially to increase a quasistatic magnetic energy of a ferrite body. In other words, to magnetize the whole ferrite resonator. It can be dipole, or quadrupole or, in general, multipole magnetic polarization of a sample. On the other hand, the quasistatic magnetic energy absorbed by a ME particle in the external rf magnetic field may go partially to electric polarization (dipole, quadrupole, or, in general, multipole) of the surface metallization region. One of the ways to uncover the nature of the observed microwave ME effect is a comparative analysis of oscillating spectrums exciting in different type RF external fields. We will classify the observed oscillations in ferrite resonators with surface electrodes as ME oscillations and MS oscillations. In a case of ME oscillations, we have linear surface electric currents terminated with electric charges on the border of the metallization. Figures 1(a) and 1(b) illustrate such current distributions on a two-dimensional electrode for dipole and quadrupole electric polarizations, respectively. Oscillations with ''closed-loop'' surface electric current on a two-dimensional electrode [Fig. 1(c)] we will call as modified MS oscillations (compared to ''pure'' MS oscillations in a ferrite resonator without surface metallization).

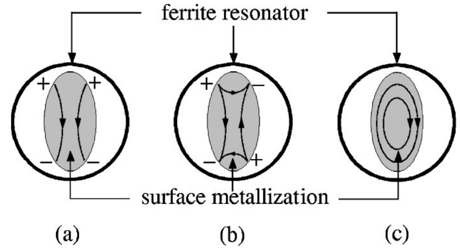

FIG. 1. Possible induced surface current distributions in the two-dimensional surface electrode of a disk-type ME particle. Current distributions for (a) dipole electric polarization, (b) quadrupole electric polarization, and (c) closed-loop surface current.

III. TYPES OF FERRITE ME PARTICLES

With the use of different forms of ferromagnetic resonant bodies and surface metallic electrodes, one may create different types of ferrite ME particles. We will distinguish straight-edge (square- or rectangular-form) and disk-form thin-film ferromagnetic resonators. The straight-edge ferrite resonators have evident technological advantage compared to disk-form samples. At the same time, disk-form resonators have regular multiresonance absorbing spectrums (in terms of magnitude and mutual spacing) [13,14] while the spectrums of straight-edge samples are irregular [23]. Surface metallic electrodes are separated as one-dimensional (wire form) and two-dimensional ones. In the latter case, we will distinguish different configurations of the continuous type (C-type) and hollow type (H-type) surface metallizations.

In our first experiments, the straight-edge ferrite resonators with one-dimensional (wire form) surface electrodes were used [7,8]. These types of ME particles are shown in Figs. 2(a) and 2(b). Some of the experimental results of works [7,8] will be used in this paper for comparison with oscillating spectrums obtained for types of ME particles. Some of these particles are shown in Fig. 3 (straight-edge ferrite resonators with C-type elliptic metallization and two configurations of H-type elliptic metallizations) and in Fig. 4 (disk-form ferrite resonator with a wire-form, C-type, and H-type elliptic and two H-type rectangular/square metallizations). Other types of ME particles used in our study, are shown as insertions to the corresponding spectral pictures. YIG film ($4\pi M_S=1780$ G, film thickness$=0.10$ mm) specimens had ''in-plane'' sizes: 5.0×5.0 mm for square-form straight-edge resonators, 4.0×3.0 mm for rectangular-form straight-edge resonators and diameter 5.0 mm for disk-form resonators. Wire-form surface electrodes had diameter of a wire 0.1 mm. The length was 7.0 mm for a rectangular-

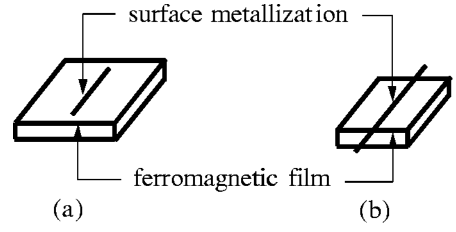

FIG. 2. ME particles as straight-edge ferrite resonators with one-dimensional (wire-form) electrodes.

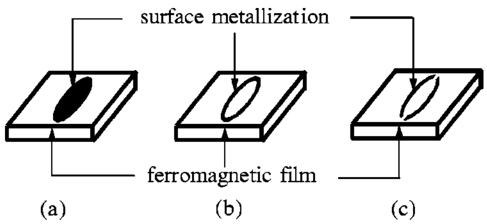

FIG. 3. ME particles as straight-edge ferrite resonators with two-dimensional electrodes.

form ferrite resonator and 5.0 mm for square-and disk-form ferrite resonators. The sizes of the two-dimensional surface metallizations are the following. Major axis = 4 mm and minor axis = 2 mm for elliptic electrode, diameter = 4 mm for circular electrode, length = 4 mm, and width = 2 mm for rectangular electrode and length = width = 4 mm for square electrode.

IV. EXPERIMENTAL ARRANGEMENT

The experimental arrangement is shown in Fig. 5. Different structures of the exciting rf fields are ensured by placing the normally magnetized ferrite ME particles at three positions in a rectangular cavity resonant in the TE_{101} mode at 4.02 GHz. Position 1 corresponds to the maximum of the exciting rf electric-field E_y. Position 3 corresponds to the maximum of the exciting rf magnetic-field H_z. In a case of position 2, we have a combined excitation due to mutually perpendicular electric-E_y and magnetic-H_z fields. Because of sizes of ferrite specimens used in our experiments, the observed oscillations may be described based on the magnetostatic-wave assumption. We do not have pure electromagnetic oscillations and do not have exchange oscillations as well [11–16].

V. ELECTRIC-FIELD EXCITATION

A physical phenomenon of quasielectrostatic to quasimagnetostatic energy transformation discussed in Sec. II of the paper, becomes evident in a case of the rf electric field excitation. For all types of ME particles, we observed strong responses when the particles were placed in the uniform rf electric field. These responses are characterized by multiresonance (regular or irregular) spectrums or by high-quality single-resonance spectrums. A large variety of these spectrums for different types of particles, placed in position 1 of the cavity, are shown in Fig. 6. Types of ME particles and orientation of the rf electric field are depicted in insertions. It is clear that one has these spectrums due to *surface-electric-charge resonances* on metallic electrodes excited by the rf external electric field. But the question arises about the nature of these numerous high-quality resonances. Evidently, the structure cannot be considered just as a section of an electric line based on a substrate with a frequency-dependent permeability. In magnetostatic-wave YIG-film devices, the linear electric-current transducers are used. There are, however, no data of a multiresonance spectrum of a magnetostatic-wave radiation resistance due to longitudinal variations of a linear electric current [13,14]. The only explanation of the spectrums shown in Fig. 6 can be based on an assumption that we have spectrums of ME (combined) oscillations. These oscillations should be characterized by a process when variations of magnetostatic potential in a ferrite body are accompanied with the surface-electric-charge variations on a special-form metallic electrode. These oscillations of a combined nature cannot, however, be considered as a coupled process of ''magnetic-subsystem oscillations'' and ''electric-subsystem oscillations.'' In other words, the particle cannot be considered just as a mechanical combination of two resonant structures: a ferrite body and a surface electrode. These aspects were preliminarily discussed in the theoretical work [4]. Now we have experimental results that may uncover the nature of ME oscillations.

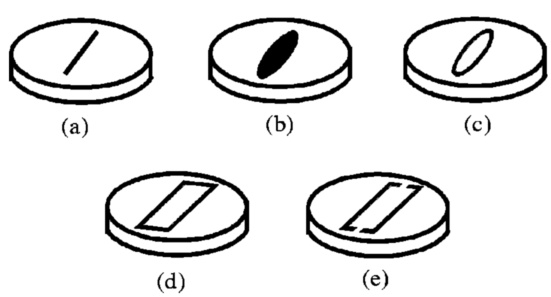

FIG. 4. ME particles as disk-form ferrite resonators with one-dimensional (wire-form) and two-dimensional electrodes.

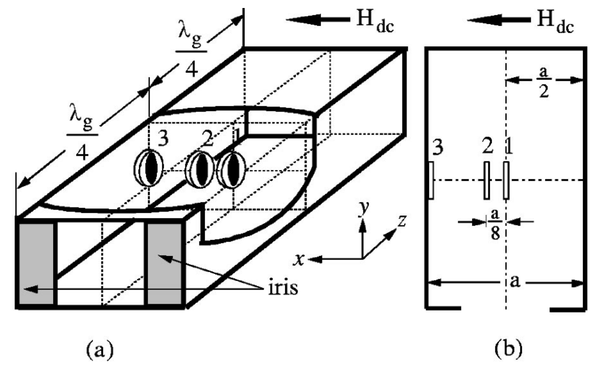

FIG. 5. Experimental arrangement. (a) Rough Sketching, (b) top view.

The oscillations shown in Fig. 6 are responses of the ''electric parts'' of ME spectrums in the external rf electric field. Certain regularities may be revealed in these pictures of spectrums. First of all, we have to note that for any type of ferrite resonators (rectangular and square straight edge or disk form) we have regular multiresonance spectrums for wire-form surface electrodes [see Figs. 6(a), 6(b), and 6(c)]. Evidently, these resonances excited by an external rf electric field, should be correlated with oscillations of linear electric current in a surface wire-form electrode. In other words, such ferrite ME particles, being placed in the rf electric field, clearly exhibit properties of a small (with sizes essentially much less than the external-field electromagnetic wavelength) electric dipole with a multiresonance spectrum. When particles were oriented so that the exciting electric field was perpendicular to a wire-form electrode, no responses were observed.

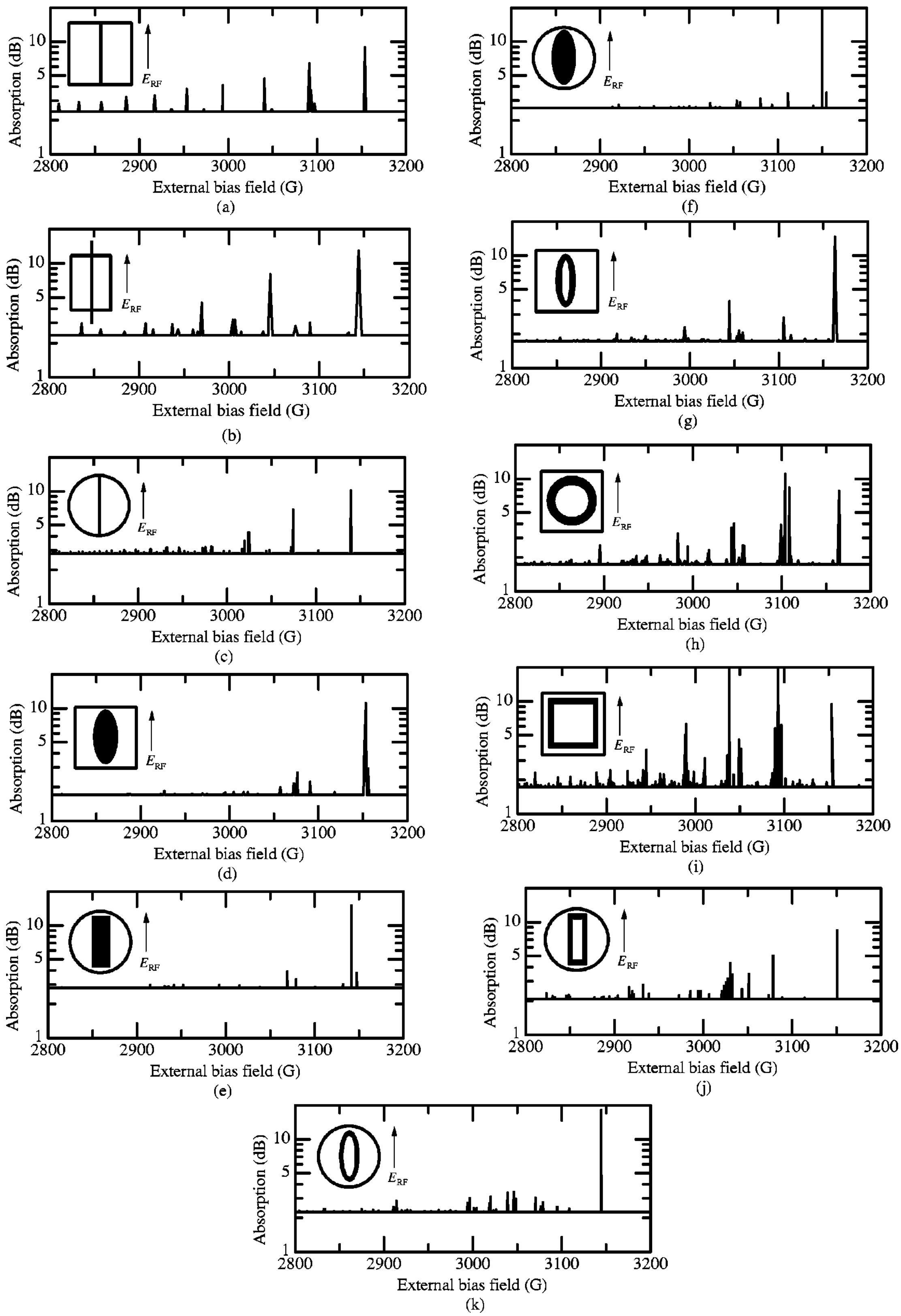

FIG. 6. Absorption spectrums of different types of ME particles when excited with only an electric field.

In a case of *C*-type surface electrodes we have chiefly one-resonance responses in the external rf electric field [see Figs. 6(d), 6(e), and 6(f)]. It is clear that for two-dimensional surface metallizations, we have a combination of electric dipole terms with multipole (quadrupole, etc.) terms. At the same time, in the homogeneous rf electric field we can excite only electric-dipole terms. The one-resonance responses shown in Figs. 6(d), 6(e), and 6(f) characterize the one-resonance properties of an electric dipole that one has for *C*-type metallizations.

For different variants of *H*-type surface electrodes, shown in Fig. 6, one can see rich but irregular spectrums in the external rf electric field. Such complex-form surface metallizations give complex spectrums of responses. At the same time, as we discussed above, these should be electric-dipole-term responses. For this reason, we may advance a supposition that for *H*-type surface electrodes, shown in Fig. 6, we have compositions of two parallel electric dipoles mutually connected in lower and upper points (these points are placed on an axis of symmetry of a region of metallization that is oriented in the direction of the exciting electric field). In these lower and upper points, surface electric current is equal to zero. To prove this two-parallel-dipole model (TPD model) we slightly changed forms of *H*-type electrodes making small gaps in *H* metallizations in the lower and upper points. Since we suppose that in these points electric current should be equal to zero, we should obtain the same picture of absorption peaks for *H*-type electrodes (of the same geometry) with and without gaps. Our experiments give a good confirmation that the proposed TPD-model really works. In Figs. 7(a), 7(b), 7(c), 7(d), and 7(e), one may see absorption spectrums for *H*-type electrodes with gaps that are very similar to pictures of spectrums shown for *H*-metallizations of the same geometry without gaps [see, respectively, spectrums in Figs. 6(g), 6(h), 6(i), 6(j), and 6(k)]. The main aspect of this similarity should be envisaged from the peak positions in the spectrums.

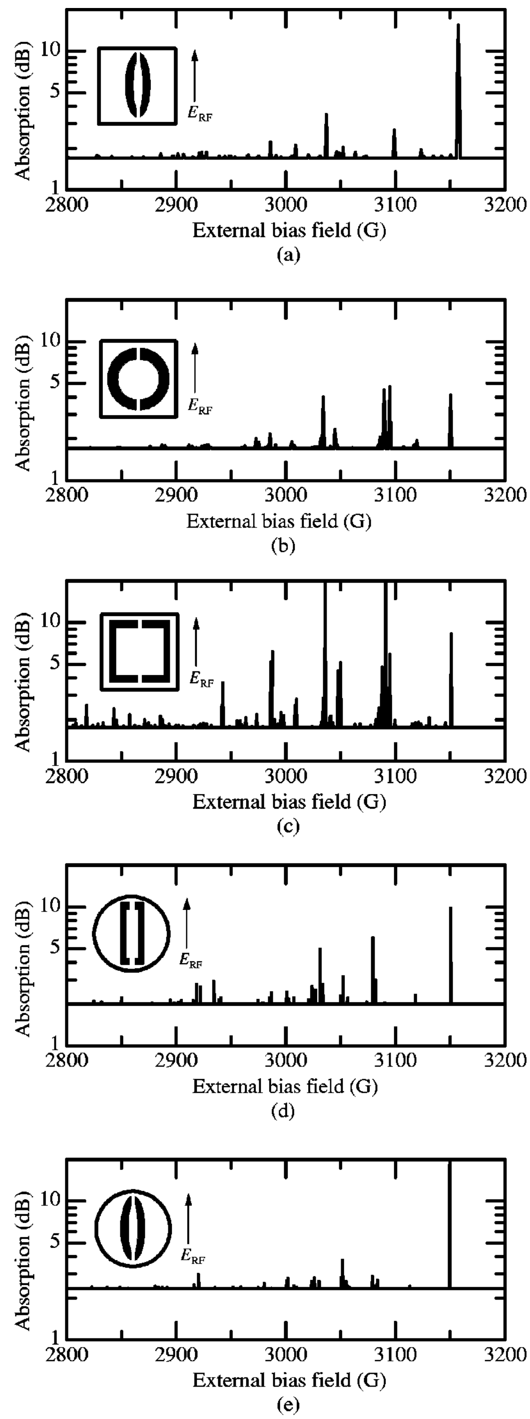

FIG. 7. Absorption spectrums of different types of ME particles with TPD-type surface electrodes when excited with electric field.

VI. MAGNETIC AND COMBINED (ELECTRIC- AND MAGNETIC-FIELD) EXCITATIONS

Our initial supposition (adduced in preceding section) that oscillating spectrums of ferrite resonators with special-form surface metallization observed in exciting electric field are spectrums of ME (combined) oscillations, may find further development when magnetic or combined (electric and magnetic) excitations take place. One should understand, however, that together with ME oscillations, usual magnetostatic (MS) oscillations may also exist. These MS oscillations in ME particles are not accompanied with surface-electric-charge resonances, but are, certainly, transformed with respect to MS oscillations in ‘‘pure’’ (without surface electrodes) ferrite resonators.

In position 3 (see Fig. 5), the particles are excited by the uniform rf magnetic field. Spectrums of straight-edge and disk-form ferrite resonators without surface electrodes excited by uniform magnetic field are well known [13,14,23]. In our case of ferrite resonators with surface electrodes, one has a specific interest to compare absorption spectrums obtained in external rf magnetic field with such spectrums as those excited by rf electric field (see Fig. 6). This comparison shows that almost for all types of ME particles, the spectrums in the magnetic field are strongly different from those that were observed in the electric field. In Fig. 8, one can see some examples of pictures obtained for particles excited by uniform magnetic field. Two kinds of excitations were used: the rf magnetic field is perpendicular or parallel to longitudinal axes of surface electrodes. Types of particles are shown in insertions. One may compare spectrums in Fig. 8 with corresponding (for the same type of a ME particle) spectrums in Fig. 6.

It becomes clear that for particles shown in insertions of Figs. 8 we have strong peaks of ‘‘new’’ responses together with some ‘‘old’’ responses for the electric-field excitation. These ‘‘new’’ peaks should correspond to the MS oscillations excited by the uniform rf magnetic field. So for these

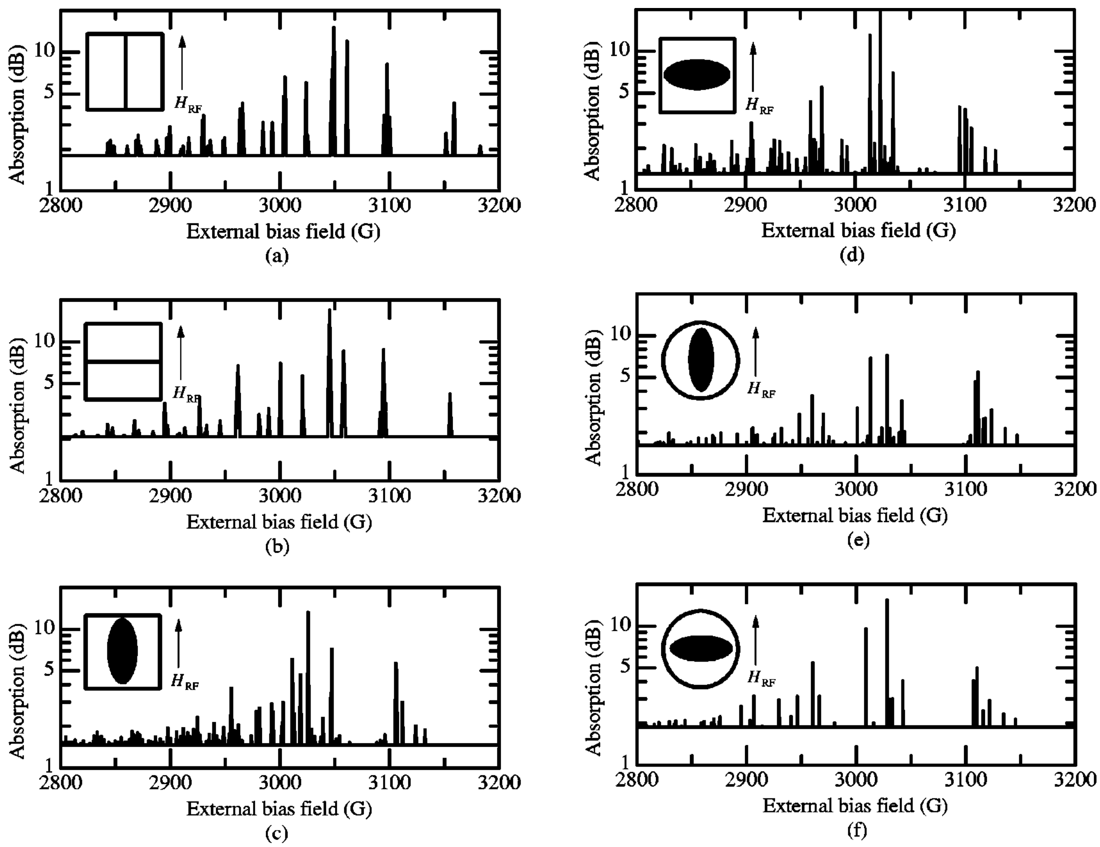

FIG. 8. Absorption spectrums of different types of ME particles when subjected to magnetic-field excitation.

particles, the entire spectral picture cannot be classified as the responses of magnetic dipoles coupled with corresponding electric dipoles. In other words, in these cases, we do not have an excitation of the spectrum of the unified system of ME eigenoscillating modes. Completely another situation, one can see in a case of a ME particle based on a disk-form ferrite resonator with a wire-form surface electrode. The corresponding spectrums (for two orientations of magnetic field with respect to a surface electrode) are shown in Fig. 9. Evidently, positions of main resonance peaks are regular and are the same as in a case of the electric-field excitation [see Fig. 6(c)]. Some small parasitic peaks do not alter the entire spectral picture. The only difference is in amplitudes of the main peaks. This takes place because of the different effectiveness of peak excitations by different (external rf electric-field or external rf magnetic-field) sources.

In a case of combined (electric and magnetic) exciting fields, we may have an excitation of combined (MS+ME) oscillations or pure ME oscillations. To obtain such a type of excitation, we placed our particle in position 2 in the cavity (see Fig. 5). Figure 10 shows the absorption spectrums for some particles excited by combined fields. Almost for all types of ME particles, the pictures of spectrums are strongly different in comparison with the pictures shown in Figs. 6 and 8. The only exception, again, is for a particle based on a disk-form ferrite resonator with a wire-form surface electrode. We see that positions of main resonance peaks are regular and are the same as in cases of the electric-field excitation [Fig. 6(c)] and the magnetic-field excitation (Fig. 9). One may, certainly, conclude that for a disk+wire particle, we have a set of unified ME oscillating modes, but for other types of particles, there are mainly superpositions of MS oscillations and ME oscillations (MS+ME oscillations). It is clear that electric-field and the magnetic-field components of the combined exciting field should be in a certain phase correlation to provide a maximum of potential energy of a

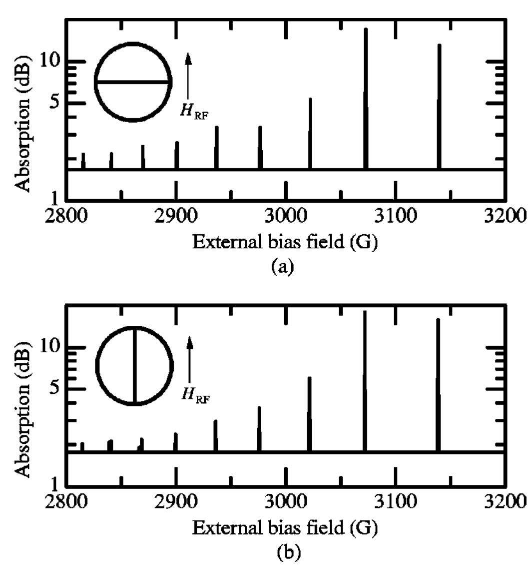

FIG. 9. Absorption spectrums of disk+wire ME particles when subjected to magnetic-field excitation.

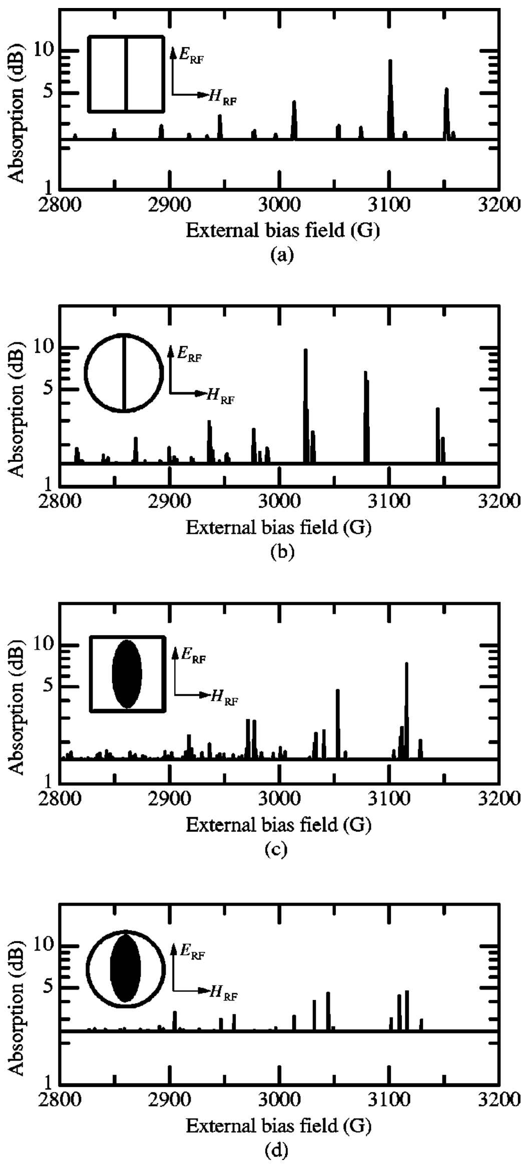

FIG. 10. Absorption spectrums of different types of ME particles when excited with combined structure of electric and magnetic fields.

disk + wire ME particle. The problem of this phase correlation is a reason why amplitudes of main peaks observed in Fig. 10(b) are different from amplitudes of peaks shown in Figs. 6(c) and 9.

VII. DISCUSSION

Our experiments show that for different types of ME particles, one has discrete multi-resonance absorption spectrum of quasistatic electric energy. The quasielectrostatic energy absorbed by a small particle is effectively transformed to the magnetostatic energy of this specimen (the energy of magnetization of a whole ferrite body). Mainly, we have the multipole magnetic polarization of a sample.

A detailed analysis of absorption spectrums obtained for different types of ME particles and different types of the exciting fields leads us to a very important conclusion that only for ME particles based on disk-form ferrite resonators with wire-form surface electrodes, one has a spectrum of the unified ME oscillating modes. One may note that all the spectrums shown in Figs. 6(c), 9(a), and 9(b), and 10(b) have the same positions of main oscillation peaks with the only distinction of magnitudes. It should mean that different types of fields ($\vec{E}$, $\vec{H}$, and $\vec{E}+\vec{H}$ fields) excite the same spectrum of ME oscillation modes. However, effectiveness of excitation of different ME modes in the spectrum (mode amplitudes) depends on the type of exciting fields. Since different types of the exciting fields produce the same oscillation spectrum, a system is characterized by a set of parameters with certain spectral properties. This fact gives us a possibility to represent a disk-type ME particle as a particle characterized by two (electric $\vec{p}_e$ and magnetic $\vec{p}_m$) moments. The moments are related to external $\vec{E}$ and $\vec{H}$ fields as

$$\vec{p}_e = \overleftrightarrow{\alpha}_{ee}\cdot\vec{E} + \overleftrightarrow{\alpha}_{em}\cdot\vec{H},$$
$$\vec{p}_m = \overleftrightarrow{\alpha}_{me}\cdot\vec{E} + \overleftrightarrow{\alpha}_{mm}\cdot\vec{H}, \tag{7.1}$$

where dyadic polarizabilities $\overleftrightarrow{\alpha}_{ee}$, $\overleftrightarrow{\alpha}_{em}$, $\overleftrightarrow{\alpha}_{me}$, and $\overleftrightarrow{\alpha}_{mm}$ are defined from ferrite material properties and geometry of a disktype ME particle. These polarizabilities are parameters of a system characterized by certain spectral properties (certain positions of poles and zeros with respect to frequency or bias magnetic field). Because of these spectral properties, one may talk about *the unified process of ME oscillations*. The disk + wire ME particles may be considered as ''glued pairs'' of two (electric and magnetic) small dipoles and, therefore, may be used as structural elements for bianisotropic composite materials [4–6]. For this reason (and to distinguish these ME particles from other types of ferrite ME particles analyzed, in particular, in this paper) we will call the disk + wire particles as bianisotropic particles (the BAP's). Also, because of the dipole character (electric + magnetic dipoles) of ME oscillations, we will classify such oscillations in BAP's as magnetoelectric dipole (MED) oscillations.

ME particles with wire-form electrodes play a special role in our experiments. The oscillations excited in a ferrite disk resonator with a wire-form electrode are characterized by the same positions of peaks as oscillations excited by the external rf magnetic field in such resonators without surface electrodes. So we can conclude that the observed MED oscillations have degenerated peak positions with respect to MS oscillations in a ''pure'' (without a surface electrode) ferrite disk resonator.

VIII. CONCLUSION

The effect of local magnetoelectric coupling, which becomes apparent in small ferrite resonators with a special-form surface electrodes, is an effect in microwaves. In this paper, we carried out a wide range of experimental investigations of different types of ferrite ME particles. The results show that proposed ferromagnetic particles, being placed in different structures of the external rf fields, are strongly excited by the rf electric, magnetic, and combined (electric

(electric+magnetic) fields. The particle responses are characterized by multiresonance spectrums of absorption peaks. One may classify these spectrums as ME spectrums, MS spectrums, and superposed (ME+MS) spectrums. For some types of complex-form (two-dimensional) surface electrodes, the so-called TPD model may be successfully used to describe the particle responses in the exciting rf electric field. In a special case (for disk+wire ME particles), we have BAP's with the unified spectrum of ME oscillations—the MED oscillations.

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