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The field symmetry breaking effects in microwave-vortex structures originated by ferrite disks in a cavity

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For a microwave resonator with an enclosed ferrite disk, one has the electromagnetic resonant fields which are not the fields of standing waves. This leads to very specific topological-phase characteristics. In such a nonintegrable system with time-reversal symmetry breaking, one obtains the Poynting-vector microwave vortices and intensive field localization in a region of a disk. The purpose of this paper is to give detailed explanations of physics of the electromagnetic-vortex phenomena shown in our recently published paper [E. O. Kamenetskii et al., Phys. Rev. E 74, 0366620 (2006)]. Based on numerical simulation, we show that for a thin ferrite disk with positive permeability parameters and negligibly small material losses, the Poynting-vector microwave vortices in a cavity are accompanied with topological magnetic currents and topological magnetic charges. Such topological sources create very unique field structures with evident symmetry breaking properties. The observed vortex phenomena open an exciting prospect in novel applications of ferrite-based microwave devices. © 2008 American Institute of Physics.

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I. INTRODUCTION

The main objective of this paper is to determine the structure of electromagnetic fields in a system of a microwave resonator with an enclosed ferrite disk. The studies do not concern any aspects of intrinsic magnetic oscillations (magnetization fluctuations) in ferrite samples in the proximity of the ferromagnetic resonance (FMR).1,2

Analyses of the electromagnetic-field scattering by a dc magnetized ferromagnetic sample in microwave waveguides and cavities are a subject of numerous investigations.2,3 Specifically, in questions of microwave theory and techniques, an interest in such systems was devoted to development of general and rigorous formulations of the problem and an analysis of properties of the scattering matrix.4 The unitary condition on the scattering matrix is guaranteed for lossless ferrite inclusions—the obvious fact in a view of fundamental formulations of the reciprocity relationships for gyrotropic media.5 At the same time, the studies of quadratic relations will be complex, even in the absence of dissipative losses. It means that the fields of eigenoscillations are not the fields of standing waves inside a cavity. When, however, microwave resonators contain enclosed gyrotropic-medium samples, the electromagnetic-field eigenfunctions will be complex, even in the absence of dissipative losses. It means that the fields of eigenoscillations are not the fields of standing waves in spite of the fact that the eigenfrequencies of a cavity with gyrotropic-medium samples are real.5 Very specific field phase characteristics of microwave resonators with ferrite inclusions become evident from the reflection features of electromagnetic waves at a dielectric-ferrite interface. In the case of ferrite inclusions acting in the proximity of the FMR, the phase of the wave reflected from the ferrite boundary depends on the direction of the incident wave. For a given direction of a bias magnetic field, one can distinguish the right-hand and left-hand rays of electromagnetic waves. This fact, arising from special boundary conditions for the tangential components of the fields on the dielectric-ferrite interface, leads to the time-reversal symmetry breaking effect in microwave resonators with inserted ferrite samples.6–8

Microwave resonators with the time-reversal symmetry breaking effects give an example of a nonintegrable system. The concept of nonintegrable, i.e., path dependent, phase factors is one of the fundamental concepts of electromagnetism. Presently, different nonintegrable systems are the subject for intensive numerical and experimental studies in microwave and optical resonator systems.6–11 Among a rich variety of such resonators, there is an interesting class of dielectric nonintegrable systems where the boundary manifests itself by a change in the index of refraction. The interplay of reflection and transmission at the different interfaces gives rise to unique properties of wave phenomena.11 Ferrite inclusions are also characterized by non-hard-wall boundary conditions with the interplay of reflection and transmission at the interfaces. At the same time, these properties are combined with the time-reversal symmetry breaking effect.

The time-reversal symmetry breaking effect leads to creation of the Poynting-vector vortices in a vacuum region of the TE polarized microwave resonators with enclosed lossless ferrite samples. In a vacuum region of a cavity, the vortex behavior can be easily understood from an analysis of the field structure.7,12 For TE polarized (with respect to the y direction) electromagnetic waves in vacuum, the singular features of the complex electric field component \( E_y(x, z) \) can

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be related to those that will subsequently appear in the associated two-dimensional time-averaged real-valued Poynting-vector field $\mathbf{S}(x,z)$. For such electromagnetic fields, the Poynting vector is represented as $(\mathbf{S})=(e^2/8\pi)\text{Im}(E_y \nabla E_x)$, where $E_x$ is a complex vector of the $y$ component of the electric field: $E_x=(E_x)e^{i\text{atan}}$. The fact that for electromagnetic fields invariant with respect to a certain coordinate, a time-average part of the Poynting vector can be approximated by a scalar wave function, allows the analysis of the vortex phenomena. For a TE polarized field, we can write $E_y(x,z)=\psi(x,z)e^{i\chi(x,z)}$, where $\psi$ is an amplitude and $\chi$ is a phase of a scalar wave function $\psi$. This allows rewriting the Poynting-vector expression as $(\mathbf{S})=\rho(x,z)^2\nabla \cdot \chi(x,z)$. Such a representation of the Poynting vector in a quasi-two-dimensional system gives possibility to define a phase singularity as a point $(x,z)$, where the amplitude $\rho$ is zero and, hence, the phase $\chi$ is undefined. These singular points of $E_y(x,z)$ correspond to vortices of the power flow $\mathbf{S}$, around which the power flow circulates. A center is referred to as a (positive or negative) topological charge. Since such a center occurs in free space without energy absorption, it is evident that $\nabla \cdot (\mathbf{S})=0$.

The singular points of $(\mathbf{S})$ (the vortex cores) can be directly related to the zero-electric-field topological features in a vacuum region of the cavity space but not inside a ferrite region where one cannot express the Poynting vector only by the $E$-field vector. Moreover, there could be a special interest in an analysis of microwave vortices generated by a ferrite sample placed in a cavity region of a maximal field $E_y(x,z)$. In our recent paper,\cite{12} we studied the Poynting-vector microwave vortices in a three-dimensional system of a TE polarized rectangular-waveguide resonator with an inserted thin ferrite disk based on full Maxwell-equation numerical solutions of the problem. It was shown that a ferrite sample acts as a topological defect causing induced vortices. In the rectangular-waveguide cavity, the Poynting-vector vortex rotation direction is not invariant with respect to a combined symmetry operation: mirror reflection and time reversal.\cite{12} This is a distinctive feature regarding the known reciprocity-theorem relationships for gyrotropic media.\cite{5}

For a microwave resonator with an enclosed ferrite sample, the fact that the electromagnetic resonant fields are not the fields of standing waves may give very specific topological-phase characteristics. The purpose of this paper is to show that for a ferrite disk with positive permeability parameters and negligibly small material losses, the Poynting-vector microwave vortices in a cavity are accompanied with topological magnetic currents and topological magnetic charges. Such topological sources, caused by the symmetry breaking effects, create very unique field structures. This gives necessary explanations of physics of the electromagnetic-vortex phenomena shown in Ref.\cite{12}. Since the nonintegrable nature of the problem precludes exact analytical results for the eigenvalues and eigenfunctions, numerical approaches are required. We use the HFSS (the software based on FEM method produced by Ansoft Company) CAD simulation programs for three-dimensional (3D) numerical modeling of Maxwell equations. In our numerical experiments, both modulus and phase of the fields are determined. It is worth noting that an analysis allows the study of the main role of the magnetic gyrotropy and geometrical factors in a cavity but cannot show the scattered fields from a ferrite sample with intrinsic magnetic-dipolar-mode oscillations. These oscillations appear in the region of negative permeability parameters and are characterized by strong multiresonance interactions with the cavity electromagnetic fields.\cite{13} A detailed analysis of such interactions demands development of special methods and is beyond the frames of the present work.

II. REFLECTION SYMMETRY BREAKING IN THE CAVITY-FERRITE-DISK SYSTEM

A key aspect of the behavior of the cavity-ferrite-disk configuration is reflection and refraction of waves at ferritedielectric interfaces. In a general case of oblique incidence on a single ferrite/dielectric interface, apparently different situations arise by changing the directions of incident waves and bias and incident side of the interface. For example, four cases of reflection at a single ferrite-dielectric interface shown in Fig. 1 correspond to different physical situations. This fact becomes evident when one analyzes the reflection and transmission coefficients obtained from Maxwell equations and the electromagnetic boundary conditions at the ferrite-dielectric interfaces. The solutions obtained for different electromagnetic problems of ferrite-dielectric structures\cite{6,8,12,14,15} show the time-reversal symmetry breaking effect.

The TE (or TM) waveguide mode propagation has a clear interpretation when viewed as a pair of two bouncing plane waves. When a ferrite sample is placed in a waveguide, the points on the ferrite-vacuum interfaces become the symmetry breaking places. Figure 2 illustrates this phenomenon for a general case of a ferrite disk magnetized in an arbitrary direction. The waves incident symmetrically from the waveguide-wall points to the ferrite-disk points are strongly different. While the ray trajectory 1o is identical with the ray trajectory $1’o$ and the ray trajectory $2f$ is identical with the ray trajectory $2’f$, there are no identities between the ray trajectories $1b$ and $1’b$, $1c$ and $1’d$, $2c$ and $2’d$, and $2e$ and $2’e$. Also, there are no identities between the ray trajectories...
FIG. 2. Illustration of the reflection symmetry breaking in the cavity-ferrite-disk system.

1c and 2c and between 1’d and 2’d. Our analysis shows that such a symmetry breaking effect for the ray trajectories in the cavity-ferrite-disk configuration leads to the field singularities which result in effective magnetic charges and effective magnetic currents.

In the ferromagnetic resonance, depending on a quantity of a bias magnetic field and (or) frequency, one has the regions with positive or negative permeability parameters. For homogeneous plane wave propagating in an infinite ferrite medium perpendicular to the direction of a bias magnetic field, ferrite is characterized by the effective permeability parameter,

\[
\mu_{\text{eff}} = \mu_0 \frac{\mu^2 - \mu_g^2}{\mu},
\]

where \(\mu\) and \(\mu_g\) are, respectively, the diagonal and off-diagonal components of the permeability tensor. This effective-medium parameter can also be used for characterization of the fields inside a ferrite slab and a ferrite cylinder magnetized in the direction perpendicular to the wave propagation in a waveguide.\(^{2,4,16}\)

On the other hand, for electromagnetic wave propagating in a ferrite medium along a bias magnetic field, there are two effective permeability parameters characterizing the waves with right-hand and left-hand circular polarizations,\(^{2}\)

\[
\mu_{\text{eff}+} = \mu_0 (\mu + \mu_d), \quad \mu_{\text{eff}-} = \mu_0 (\mu - \mu_d). \tag{2}
\]

Only for the right-hand circularly polarized wave, one can distinguish two behaviors: \(\mu_{\text{eff}+} > 0\) and \(\mu_{\text{eff}-} < 0\). The quantity \(\mu_{\text{eff}-}\) is always positive.\(^2\)

In a cavity with enclosed ferrite samples, the field structures are strongly dependent on signs of the permeability parameters and so, there should be fundamentally different conditions for generation of microwave vortices in the positive- and negative-parameter regions. Primarily, it may concern the role of losses in a ferrite material in forming microwave vortices. For negative permeability parameters, microwave vortices appear only when the material properties of a disk are characterized by big losses.\(^{17}\) Similar situation takes place for a plasmon-resonance nanoparticle illuminated by the electromagnetic field, where the spiral energy flow line trajectories appear for a lossy sample.\(^{18}\) Contrary, in the case of positive permeability parameters, the losses play an indirect role in forming microwave vortices.\(^{12,17}\)

We consider a situation when a thin normally magnetized ferrite disk (being oriented so that its axis is perpendicular to a wide wall of a waveguide) is placed in the middle of the waveguide height. An example of such a configuration is shown in Fig. 2 in Ref. 12. We study the field structures for two cases: (a) a disk center is located in a point of a maximal cavity magnetic field \((l = \lambda_c/2\), where \(\lambda_c\) is a waveguide wavelength\)) and (b) a disk center is located in a point of a maximal cavity electric field \((l = \lambda_c/4\). Since the fields inside a ferrite sample may have variations in all three directions, the regions of positive and negative permeability parameters will be determined by combination of three factors: bias magnetic field \(H_0\), frequency \(f\), and geometry of the sample. Necessarily, the condition for positive permeability parameters in a ferrite disk is the condition when simultaneously \(\mu_{\text{eff}+} > 0\) and \(\mu_{\text{eff}-} > 0\). In our studies, the ferrite-disk parameters are diameter \(D = 6\) mm, thickness \(t = 0.5\) mm, saturation magnetization \(4\pi M_s = 1880\) G, and permittivity \(\varepsilon_r = 15\). A bias magnetic field \(H_0 = 5030\) Oe and the

FIG. 3. (Color online) Top views of an internal magnetic field for a ferrite disk placed in a maximal cavity electric field.
cavity resonance frequency $f=8.7$ GHz correspond to the ferromagnetic resonance conditions: a diagonal component of the permeability tensor is $\mu/\mu_0=23.85$ and an off-diagonal component is equal to $\mu_{\parallel}/\mu_0=22.55$. This, evidently, provides us with positive permeability parameters: $\mu_{\text{eff}}>0$ and $\mu_{\text{eff}}'=0$. To stress the role of a combined effect of magnetic gyrotropy and geometrical factors we ignore any material losses in a ferrite disk (we assume that $\Delta H=0$ and $\tan \hat{\beta}=0$). The only losses taken into account in our numerical simulations are the losses in cavity walls; the cavity walls are made from copper.

It was shown in Ref. 12 that for the above behavior of a normally magnetized ferrite disk ($H_0=5030$ Oe, $f=8.7$ GHz corresponding to $\mu/\mu_0=23.85$ and $\mu_{\parallel}/\mu_0=22.55$), there are the vortex-type Poynting-vector rotation effects both internal, inside a ferrite disk, and external, in the neighboring vicinity of a ferrite disk. For a disk located in a maximal cavity electric field ($I=\lambda_0/4$) and in a maximal cavity magnetic field ($I=\lambda_0/2$), the pictures of the power flow distributions clearly show the presence of topological singularities in a region of a ferrite disk (see, respectively, Figs. 4 and 12 in Ref. 12). The observed Poynting-vector singularities give evidence for 3D field localizations and should presume unique structures of the fields near the ferrite-disk surfaces.

III. TOPOLOGICAL-PHASE CHARACTERISTICS OF THE FIELDS FOR A FERRITE DISK PLACED IN A MAXIMAL CAVITY ELECTRIC FIELD

The nature of the Poynting-vector singularity for a ferrite disk can be clarified from an analysis of the internal fields (the fields inside a ferrite sample) and the external fields (the fields outside and immediately close to a ferrite disk). The pictures of these fields reveal very unique topological structures.

For a case when a ferrite disk is placed in a maximal cavity electric field, there is a very interesting fact that in every given point of a disk, the internal magnetic field is elliptically polarized and is rotating clockwise in the plane of a disk. Figure 3 gives top views of the magnetic field inside a ferrite disk for different time phases. It is worth noting that the observed clockwise rotation of the internal magnetic field is opposite to the direction of the eigenmagnetization precession in a ferromagnet. Figure 4 gives top views of the external magnetic field immediately above a ferrite disk. The pictures correspond to the time phases $\omega t=90^\circ$ and $270^\circ$. It becomes evident that at phase $\omega t=90^\circ$, a disk center behaves as a singular drain point for an external magnetic field, while the points on a lateral surface behave similar to magnetic-field sources. Contrary, at phase $\omega t=270^\circ$, a disk center behaves as a singular source point of the external magnetic field, while the points on a lateral surface behave similar to drains. An analysis of the external-magnetic-field structures allows coming to conclusion that the points on a lateral surface of a ferrite disk behave similar to north or south magnetic poles, while a disk core region behaves as a topological magnetic charge (positive or negative). It is very important to note that a magnetic field outside a ferrite disk has the helical-like distribution. These features of the external-magnetic-field structure are clearly illustrated by Fig. 5 giving the perspective (top and side) views for phase $\omega t=270^\circ$.

When one compares the pictures of the internal, in Fig. 3, and external, in Fig. 4, magnetic fields at phases $\omega t=90^\circ$ and $270^\circ$, one sees that directions of the radial components of these fields are mutually opposite. There should not be, certainly, discontinuities of the radial components of the magnetic flux density on a disk lateral surface. Based on the known permeability tensor written for our configuration as

$$
\begin{align*}
\mu_{\parallel} & = \mu_0 + \frac{1}{2} \chi, \\
\mu_{\perp} & = \mu_0 - \frac{1}{2} \chi,
\end{align*}
$$

FIG. 5. (Color online) Perspective (top and side) views of an external magnetic field.
and the known internal-magnetic-field structure, one obtains the magnetic flux density $\mathbf{B}$ inside a ferrite disk. It can be shown that internal $\mathbf{B}$ field rotates counterclockwise, oppositely to the internal $\mathbf{H}$ field rotation. Evidently, the inside and outside radial components of the magnetic flux density on a disk lateral surface are on the same directions. Based on the results of the numerical analysis, we can reproduce a schematic picture of an entire magnetic flux density distribution in our structure. Such cross-section pictures are shown in Fig. 6. One can see that the out-of-plane magnetic field has the freedom to spread over the top and bottom disk planes.

Figure 7 shows the time evolutions of a tangential electric field on an upper surface of a ferrite disk. In this case, in every point on a disk surface, the tangential electric field vector is elliptically polarized with the counterclockwise rotation. From Fig. 8, giving the perspective view of an electric field on an upper plane of a ferrite disk and in the air region near a ferrite disk,

$$\mathbf{\mu} = \begin{bmatrix} \mu_0 & 0 & -j\mu_0 \\ 0 & 1 & 0 \\ j\mu_0 & 0 & \mu \end{bmatrix}$$

a specific spiral structure of a tangential electric field in a ferrite disk shown in Figs. 7 and 8 becomes evident when one compares such pictures with the electric field distributions on surfaces of a dielectric disk. We suppose that a dielectric disk having the same permittivity $\varepsilon_r = 15$ and the same geometry as a ferrite disk is placed in a maximal $E_y$ cavity electric field. Orientation of a dielectric disk in a cavity is the same as the orientation of a ferrite disk. Typical structures of the electric field on upper and lower plane surfaces of a dielectric disk are shown in Fig. 9 for a certain time phase. Evidently, the vectors of the tangential electric field are oppositely directed on the upper and lower plane surfaces. For any other time phase, a character of the electric field structure will be the same, as shown in Fig. 9.

The plane surfaces of a dielectric disk behave as concentration regions for tangential components of the electric field.
Since the disk thickness is much smaller than a waveguide height, the perturbation of the cavity electric field by an enclosed dielectric disk (in the near-field region of a disk) can be described by effective surface magnetic currents which are perceived as a result of effective discontinuities for the tangential electric field at the disk surface. The notion of the effective magnetic currents is widely used in different excitation problems of waveguides and cavities (see, e.g., Ref. 19). Usually, equivalent surface magnetic currents are introduced as a formal result of discontinuity of tangential components of an electric field,

\[ i^n = n \times (E_{t1} - E_{t2}), \]

where \( E_{t1} \) and \( E_{t2} \) are tangential fields near the interface and \( n \) is a normal to the interface. It is evident that for a dielectric disk, there are only close-loop surface magnetic currents.

Now, we come back to an analysis of a ferrite disk. In the case of a ferrite disk, there is also a structure with pronounced tangential components of the electric field vectors on the upper and lower planes of a disk. There are no tangential components of the external electric field in the vicinity of a ferrite disk. Similar to a dielectric disk, this tangential electric field can be represented by an effective surface magnetic current. In this case, however, a character of a tangential electric field distribution (and, therefore, a picture of a surface magnetic current) evaluates with respect to time phases. One can observe a spiral-like character of the surface magnetic current. The surface magnetic current distributions on a plane of a ferrite disk placed in a maximal cavity electric field were studied in Ref. 20. An analysis gives an evidence for topological magnetic charges. The topological magnetic charges appear at the phases of extreme dynamical symmetry breaking when circulations of surface magnetic currents are maximal. It is also important to note that at the phases \( \omega t = 0^\circ \) and 180°, there are maximal discontinuities of azimuth components of the electric fields on a lateral surface of a ferrite disk. This provides maximal \( y \)-directed magnetic currents on the disk lateral surface at \( \omega t = 0^\circ \) and 180°. These lateral-surface currents, being directed oppositely from the upper and lower disk planes, create “magnetic charges” on a lateral surface at \( \omega t = 90^\circ \) and 270° (see a side-view picture in Fig. 5).

The external-magnetic-field singularities shown in Figs. 4 and 5 appear as a result of sharp fractures of the field lines on scales much less than the waveguide characteristic sizes. These singularities are described as alternative magnetic charges and so should be correlated with certain surface magnetic currents. While the appearance of magnetic charges is exhibited as evident concentration regions for normal components of the magnetic flux density (the Gauss law for magnetic charges 21), magnetic currents should appear as evi-
dent concentration regions for tangential components of the electric field (the Ampere law for magnetic currents).

IV. TOPOLOGICAL-PHASE CHARACTERISTICS OF THE FIELDS FOR A FERRITE DISK PLACED IN A MAXIMAL CAVITY MAGNETIC FIELD

We now analyze the nature of the Poynting-vector singularity for a ferrite disk placed in a maximal cavity magnetic field. For a ferrite disk placed in a maximal cavity magnetic field, we clearly observe magnetic dipoles with “positive” and “negative” effective magnetic charges located at diametrically opposite regions on a lateral surface of a disk. Figure 10 gives the top views of the magnetic field inside a ferrite disk for different time phases. In every given point of a disk, the internal magnetic field is rotating clockwise in the $x,z$ plane, but a character of this rotation is different from the rotation shown in Fig. 3. The top and side views of the magnetic field outside a ferrite disk for different time phases are shown in Fig. 11. It becomes evident that at the time phases $\omega t=0^\circ$ and $180^\circ$, the disk behaves similar to a magnetic dipole. The dipole is oriented along the $z$ axis. Based on the known internal-magnetic-field structure and the permeability tensor $\varepsilon$, one obtains the magnetic flux density $B$ inside a ferrite disk. The cross-section schematic pictures of an entire magnetic flux density distribution for phases $\omega t=0^\circ$ and $180^\circ$ are shown in Fig. 12.

Figure 13 gives general top-view pictures of magnetic fields inside a cavity at different time phases. One clearly sees the magnetic-dipole field structure at $\omega t=0^\circ$, while at $\omega t=90^\circ$, the top-view picture of the cavity magnetic field remains unperturbed. Figures 14(a) and 14(b) show the $xy$-plane side views of the cavity magnetic and electric field distributions at $\omega t=90^\circ$. In Fig. 14(b), one clearly observes the electric field rotation caused by a maximal linear magnetic current (directed along the $z$ axis) which appears at $\omega t=90^\circ$, when the magnetic-dipole polarization is equal to zero.

V. DISCUSSION AND CONCLUSION

Our analysis shows that the magnetic fields of a thin ferrite disk located in a microwave cavity are the fields origi-
nated from magnetic charges. There are the potential-like fields with respect to the curl cavity magnetic fields. A structure of the entire, electric and magnetic ferrite-disk field (FDF) is strongly different from a structure of the cavity electromagnetic field. In comparison with the cavity electromagnetic fields, the FDFs are characterized by evident symmetry breaking. The potential-like nature of the FDFs is a result of the 3D confinement effect.

The observed magnetic charges are not the usual demagnetizing-field magnetic charges which one can expect to find when a ferrite disk is placed in the rf cavity magnetic field. In the case of a ferrite disk placed in a maximal cavity electric field, one has, as a result, such a mechanism of interaction of precessing electrons in a thin ferrite disk with the cavity magnetic field.

It has been shown theoretically that in a case of a ferrite disk placed in a maximal cavity magnetic field, one has, as a result, such a mechanism of interaction of precessing electrons in a thin ferrite disk with the cavity electric field and in a maximal cavity magnetic field.

One has linear-type magnetic dipoles but oriented perpendicular to the cavity magnetic field. It becomes evident that the method of perturbation of waveguides and resonators by gyrotrropic samples cannot lead us to appearance of the induced chiral magnetic currents and topological magnetic charges. Such sources arise from the dynamical symmetry breaking processes and cannot be considered as sources in an ordinary theory of the waveguide and cavity mode excitation.

In both cases, when a ferrite disk is placed in a maximal cavity electric field and in a maximal cavity magnetic field, one has the clockwise rotation of the internal magnetic field, which is opposite to the direction of the eigenmagnetization precession in a ferromagnet. Because of a special mechanism of interaction of precessing electrons in a thin ferrite disk with the cavity magnetic field, one has, as a result, such unique effects as field localization in a region of a disk, special-symmetry near-field structure, and appearance of magnetic charges. It has been shown theoretically that in dipolar excitonic condensates realized in a quasi-two-dimensional semiconductor bilayer, planar-type magnetic charges can be observed. There are topological defects, which play the roles of positive and negative magnetic charges and can emit quantized radial magnetic fluxes. It is very interesting to note that for a thin ferrite disk placed in a maximal cavity electric field, a schematic picture of a magnetic flux density configuration (see Figs. 6) is quite similar to the field configuration for a dipolar excitonic condensate with a vortex shown in Ref.

One can expect opening a very exciting prospect in the electromagnetic-vortex applications. Recently, a new interesting phenomenon of relationships between the near-field phase singularities (vortices) in a slit-metal-plate structure and the features of the far-field radiation pattern has been observed. The question of new types of microwave devices based on the considered above ferrite-disk vortex structures may appear as a subject of a great future interest. Some examples of proper applications of the vortex concept in design of the ferrite-based microwave devices can be found in Ref. 24. It is shown, in particular, that for a microwave patch antenna with an enclosed ferrite disk, the “vortex quality” is strongly correlated with the far-field antenna characteristics.

3P. S. Epstein, Rev. Mod. Phys. 28, 3 (1956).