Magnetoelectric gradient structures

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Abstract. This work is a comprehensive theoretical study of a new class of structures – magnetoelectric gradient structures, which are a product of the integration of magnetoelectric multiferroic layered structures and an artificial dielectric. In this paper, a mathematical model of the behaviour of a layered multiferroic structure in inhomogeneous electric and magnetic fields is built on the basis of solving Maxwell’s equations, taken in the magnetostatic approximation, and the equation of motion of the magnetization. Based on the constructed mathematical model, the influence on the spectrum of eigenwaves of stationary magnetic and electric fields, as well as the values of the dielectric constant of an artificial dielectric layer, are analysed. The results of the study confirm the possibility of designing a new class of electronically controlled microwave devices with a triple control mechanism: magnetic field – electric field – artificial distribution of dielectric constant.

1. Introduction
In recent decades, there has been a trend to combine the physical principles underlying the control of microwave devices. In many respects, this was facilitated by the emergence of a new class of materials – multiferroics, which are characterized by the presence of several types of orderings: magnetic, electrical and mechanical. The class of multiferroics with the presence of a magnetoelectric (ME) interaction, which consist in the induction of magnetization when the material is exposed to an electromagnetic field, deserves special attention.

The first works in the field of practical application of ME materials belonging to a scientific group led by prof. Bichurin’s M.I. In the early 1980s, the group carried out a number of studies on the resonance ME effect in paramagnetic and magnetically ordered crystals that do not have an electrically ordered structure in the microwave range [1]. Scientific group led by prof. Bichurin’s M.I. a phenomenological theory of the low-frequency and resonant ME effect in para-, antiferro- and ferromagnetic crystals is constructed. Explicit expressions are obtained for the shifts of resonance lines in an external electric field. Comparison of the result of theory with experiment was carried out [2, 3].

On the other hand, the processes occurring in multiferroic composites are studies from the point of view of the wave interaction of surface magnetostatic (spin) waves (SMSW) and electromagnetic waves (EMW). It was shown in [4, 5], that mutual hybrid electromagnetic-spin waves propagate in layered ferromagnetic-ferroelectric structures. Later built a theoretical model was used in the development of phase shifters and resonators with the implementation of double control: 1) magnetic, due to the dependence of the frequency of ferromagnetic resonance of ferromagnetic on the magnitude of external magnetic field; 2) electric, due to the dependence of the dielectric constant of the ferroelectric on the magnitude of the external electric field [6-8]. In [9], the possibility of creating controlled microwave devices was shown due to above effects, however, the external controlled action was determined by one electric field.
In turn, artificial dielectrics (AD) have more than half a century of application history. AD are large-scale models of real-life dielectrics and constructively are set of metal particles, usually disk-shaped, interspersed with a given spatial distribution into a dielectric medium. Under the action of an external electric field, the charges on each of the conducting plates are displaced, thereby imitation the behavior of dipoles in an ordinary dielectric [10]. AD found their application in microwave, as substrates, in which an artificial increase in the dielectric constant made it possible to proceed to the design of compact microwave resonators [11]. In addition, AD substrate have found their application in the design of antennas [12] (figure 1), high impedance surfaces, and antireflection coatings [13].

![Figure 1. AD lens antenna prototype: structure of a 32 layers with a diameter of 50 mm and a thickness of 5.9 mm.](image)

Thus, the above areas of research have a significant theoretical and experimental basis, which made in possible to proceed to the study of a new type of multiferroic structures – magnetoelectric gradient microwave structures, which are a product of the integration of ME multiferroics and artificial dielectrics. This merger will qualitatively expand the possibilities of electronic control of the wave properties of these structures: add to the generalized mechanism described in [14] through the control action of the electric field, an artificial gradient setting of the dielectric constant of one of the dielectric layers of the structure.

In this work, on the basis of the constructed mathematical model of the behavior of layered multiferroic structure in inhomogeneous electric and magnetic fields, the possibility of creating electronically controlled microwave devices based on magnetoelectric gradient microwave structures is investigated.

2. Electrodynamics of magnetoelectric gradient structures

Initially, a search was carried out for a unified wave solution for a layered multiferroic structure, which would take into account both the different nature of the oscillations and the effects arisen from the application of electric and magnetic fields. This problem is solved based on the theory of plane waves, according to which the procedure for finding the spectrum of eigenwaves is based on the joint solution of Maxwell’s equations, taken in the magnetostatic approximation, and the equation of motion of magnetization. Further, the solution is found in the form of an expansion in plane waves. In the course of the solution, a characteristic equation of the sixth order is obtained. This equation connects the frequency of the eigenwaves of the structure with the tangential component of the wave vector at a certain value of the transverse wave number.

Consider a four-layer structure (figure 2). An atypical structure was chosen for the study, since, on the one hand, it allows quite simply to make the transition to the classical multiferroic metal-ferroelectric-ferromagnetic-dielectric-metal (MFFDM) structure at zero thickness of the second layer, on the other hand, provided an opportunity to study a new type of structures with an integrated artificial dielectric.
Let layer 3 – ferromagnetic plate of thickness s magnetized to saturation with a tangential homogeneous magnetic field $H_0$ and is characterized by a relative permittivity $\varepsilon_3$. The ferromagnetic plate is characterized by the $\mu_3$ magnetic permeability tensor of the form:

$$
\begin{pmatrix}
\mu & i\nu & 0 \\
-i\nu & \mu & 0 \\
0 & 0 & 1
\end{pmatrix},
\quad \mu = 1 + \frac{\omega M_0}{\omega^2 - \omega^2_0},
\quad \nu = \frac{\omega M_0}{\omega^2 - \omega^2_0},
$$

(1)

where, $\omega = 2\pi f$, $\gamma$ – gyromagnetic constant, $M_0$ – ferromagnetic saturation magnetization, $f$ – electromagnetic frequency, $\mu_0 = 4\pi \times 10^{-7}$ H/m – magnetic constant. Dielectric layers 1, 2 and 4 have, respectively, thickness $d_1$, $d_2$ and $w$, relative dielectric constants $\varepsilon_1$, $\varepsilon_2$ and $\varepsilon_4$ and magnetic permeability $\mu_1$, $\mu_2$ and $\mu_4$.

In the case of plane waves, there are no extraneous currents, and the system of Maxwell’s for complex amplitudes in each of the media has the following form:

$$
\text{rot} \mathbf{h}_j = i\omega \varepsilon_0 \mathbf{e}_j,
\quad \text{rot} \mathbf{e}_j = -i\omega \mu_0 \mathbf{h}_j,
$$

(2)

where, $\mathbf{h}_j$ and $\mathbf{e}_j$ – complex amplitude of vectors of intensity of electric and magnetic fields, for dielectric layers $\mathbf{\mu}_j = \mu_0 \mathbf{\mu}_j$, $\mathbf{e}_j$ and $\mathbf{\mu}_j$ – layers parameters (i.e. $j = 1$, 2, 3 or 4), $\varepsilon_0 = 8.854 \times 10^{-12}$ – electrical constant.

When waves propagate along the $y$-axis, we can assume that the problem is homogeneous along the $z$-axis and $\partial / \partial z = 0$. Then, using the expression for the rotor in the Cartesian coordinate system, based on the system of equations (2), the following system was obtained for dielectric layers:

$$
\begin{align*}
\mathbf{e}_j &= 1_x \frac{1}{i \omega \varepsilon_0 \mathbf{e}_j} \frac{\partial \mathbf{h}_j}{\partial y} - 1_y \frac{1}{i \omega \varepsilon_0 \mathbf{e}_j} \frac{\partial \mathbf{h}_j}{\partial x} + 1_z \frac{1}{i \omega \varepsilon_0 \mathbf{e}_j} \left( \frac{\partial \mathbf{h}_j}{\partial x} - \frac{\partial \mathbf{h}_j}{\partial y} \right), \\
\mathbf{h}_j &= -1_x \frac{1}{i \omega \mu_0 \mathbf{\mu}_j} \frac{\partial \mathbf{e}_j}{\partial x} + 1_y \frac{1}{i \omega \mu_0 \mathbf{\mu}_j} \frac{\partial \mathbf{e}_j}{\partial y} - 1_z \frac{1}{i \omega \mu_0 \mathbf{\mu}_j} \left( \frac{\partial \mathbf{e}_j}{\partial x} - \frac{\partial \mathbf{e}_j}{\partial y} \right),
\end{align*}
$$

(3)

For the ferromagnetic layer, taking into account:

$$
\mathbf{\mu}_3 \mathbf{h}_3 = 1_x \mu_0 \left( \mu_3 h_{3x} + i \nu h_{3y} \right) + 1_y \mu_0 \left( -i \nu h_{3x} + \mu h_{3y} \right) + 1_z \mu_0 h_{3z},
$$

(4)

the system of equations was as follows:

$$
\begin{align*}
\mathbf{e}_3 &= 1_x \frac{1}{i \omega \varepsilon_0 \mathbf{e}_3} \frac{\partial \mathbf{h}_3}{\partial y} - 1_y \frac{1}{i \omega \varepsilon_0 \mathbf{e}_3} \frac{\partial \mathbf{h}_3}{\partial x} + 1_z \frac{1}{i \omega \varepsilon_0 \mathbf{e}_3} \left( \frac{\partial \mathbf{h}_3}{\partial x} - \frac{\partial \mathbf{h}_3}{\partial y} \right), \\
\mathbf{h}_3 &= -1_x \frac{1}{i \omega \mu_0 \mathbf{\mu}_3} \frac{\partial \mathbf{e}_3}{\partial x} + 1_y \frac{1}{i \omega \mu_0 \mathbf{\mu}_3} \left( l \frac{\nu \partial \mathbf{e}_3}{\mu} - \frac{\partial \mathbf{e}_3}{\partial y} \right) - 1_z \frac{1}{i \omega \mu_0 \mathbf{\mu}_3} \left( \frac{\partial \mathbf{e}_3}{\partial x} - \frac{\partial \mathbf{e}_3}{\partial y} \right),
\end{align*}
$$

(5)

where, $\mu_\perp = (\mu^2 - \nu^2) / \mu$. 

![Figure 2. Investigated structure.](image-url)
For the case of plane waves, systems of equations (3) and (5) split into two subsystems describing TM-wave (or E-wave) – \((e_x, e_y, h_z)\) and TE-wave (or H-wave) – \((h_x, h_y, e_z)\). To begin with, consider the expansion for the ferromagnetic layer (5) into subsystems of above waves:

\[
\begin{align*}
e_{3x} &= -\frac{i}{\omega_\varepsilon e_3} \frac{\partial h_{3z}}{\partial y}, \\
e_{3y} &= \frac{i}{\omega_\varepsilon e_3} \frac{\partial h_{3z}}{\partial x}, \\
h_{3z} &= \frac{i}{\omega_\mu_0} \left( \frac{\partial e_{3x}}{\partial y} - \frac{\partial e_{3y}}{\partial x} \right),
\end{align*}
\]

\[
\begin{align*}
h_{3x} &= \frac{i}{\omega_\mu_0 \mu_1} \left( \frac{\partial e_{3z}}{\partial y} + i \frac{\nu}{\mu} \frac{\partial e_{3z}}{\partial x} \right), \\
h_{3y} &= \frac{i}{\omega_\mu_0 \mu_1} \left( i \frac{\nu}{\mu} \frac{\partial e_{3z}}{\partial y} - \frac{\partial e_{3z}}{\partial x} \right), \\
e_{3z} &= -\frac{i}{\omega_\varepsilon e_3} \left( \frac{\partial h_{3x}}{\partial y} - \frac{\partial h_{3y}}{\partial x} \right),
\end{align*}
\]

(6)

It is seen that the components \(\mu\) and \(\nu\) are not included in the system for the TM-wave; therefore, these solutions are similar to waves in an ordinary dielectric. In other words, at certain spatial arrangements of the magnetic components of the microwave field relative to the magnetic axes of the ferromagnetic (z-axis), there is no precession of the magnetic moments, i.e., the condition of ferromagnetic resonance are not met. Therefore, solutions of the TM-wave type cannot describe magnetostatic (spin) waves and are not of interest for this study. Further, solutions were considered only for TE-waves.

The subsystems for TE-waves in dielectric layers will have the following form:

\[
\begin{align*}
h_{jx} &= \frac{i}{\omega_\mu_0 \mu_j} \frac{\partial e_{jz}}{\partial y}, \\
h_{jy} &= -\frac{i}{\omega_\mu_0 \mu_j} \frac{\partial e_{jz}}{\partial x}, \\
e_{jz} &= -\frac{i}{\omega_\varepsilon e_j} \left( \frac{\partial h_{jx}}{\partial y} - \frac{\partial h_{jy}}{\partial x} \right),
\end{align*}
\]

(7)

After transformation the systems of equations for TE-waves (6) and (7), taking into account \(k_0^2 = \omega^2/c_0^2 = \omega^2 \varepsilon_0 \mu_0\) (\(c_0\) is the speed of light in vacuum) took the following form:

\[
\begin{align*}
h_{jx} &= \frac{i}{\omega_\mu_0 \mu_j} \frac{\partial e_{jz}}{\partial y}, \\
h_{jy} &= -\frac{i}{\omega_\mu_0 \mu_j} \frac{\partial e_{jz}}{\partial x}, \\
\frac{\partial^2 e_{jz}}{\partial x^2} + \frac{\partial^2 e_{jz}}{\partial y^2} + \varepsilon_{j} k_j^2 e_{jz} &= 0,
\end{align*}
\]

(8)

As can be seen, for each of the layers the component \(e_z\) satisfied the Helmholtz equation:

\[
\frac{\partial^2 e_{jz}}{\partial x^2} + \frac{\partial^2 e_{jz}}{\partial y^2} + q_j^2 e_{jz} = 0,
\]

(9)

where, \(q_1^2 = \varepsilon_1 \mu_1 k_0^2, q_2^2 = \varepsilon_2 \mu_2 k_0^2, q_3^2 = \varepsilon_3 \mu_3 k_0^2, q_4^2 = \varepsilon_4 \mu_4 k_0^2\), the solution of which will be consider in the form:

\[
\begin{align*}
e_{1z} &= \exp(-ik_y y) \left( H \exp(k_{1x} x) + P \exp(-k_{1x} x) \right), \\
e_{2z} &= \exp(-ik_y y) \left( C \exp(k_{2x} x) + D \exp(-k_{2x} x) \right), \\
e_{3z} &= \exp(-ik_y y) \left( A \exp(k_{3x} x) + B \exp(-k_{3x} x) \right), \\
e_{4z} &= \exp(-ik_y y) \left( F \exp(k_{4x} x) + G \exp(-k_{4x} x) \right),
\end{align*}
\]

(10)

where, \(A, B, C, D, F, G, H\) and \(P\) are arbitrary constants, \(k_{1x}\) and \(k_{2x}\) – projections of the wave vector.

Substitution expressions (10) into (9), we obtained expressions connecting the projections of the wave vector in the layers of the structure:
\[
\begin{align*}
\frac{k_{1x}^2}{\varepsilon_1\mu_1} &= \frac{k_{2x}^2}{\varepsilon_2\mu_2} - \varepsilon_1\mu_1 k_0^2, \\
\frac{k_{2x}^2}{\varepsilon_3\mu_3} &= \frac{k_{2x}^2}{\varepsilon_4\mu_4} - \varepsilon_3\mu_3 k_0^2, \\
\frac{k_{3x}^2}{\varepsilon_5\mu_5} &= \frac{k_{2x}^2}{\varepsilon_6\mu_6} - \varepsilon_5\mu_5 k_0^2, \\
\frac{k_{4x}^2}{\varepsilon_7\mu_7} &= \frac{k_{2x}^2}{\varepsilon_8\mu_8} - \varepsilon_7\mu_7 k_0^2.
\end{align*}
\] (11)

Further substitution of (10) into systems of equations (8) made it possible to obtain the components of the magnetic field for each of the layers \(h_{1x}\) and \(h_{2y}\). Then, the boundary conditions were applied, assuming the continuity of the tangential components \(h_j\) and \(e_j\) at the boundaries \(x = -w, x = 0, x = s, x = l, x = a\) and the presence of conducting walls on the surfaces \(x = -w\) and \(x = a\). As a result, a system of eight equations was obtained, the subsequent transformation of which led to the wave dispersion of the investigated four-layer structure:

\[
k_{ya} - \frac{N_1 y_a}{N_2} k_{yb} \exp(2k_{3x}s) + \frac{k_{4x}\mu_4}{\mu_4} \coth(k_{4x}w) - \frac{N_1 k_{4x}\mu_4}{N_2} \exp(2k_{3x}s) \coth(k_{4x}w) = 0.
\] (12)

where:

\[
\begin{align*}
k_{ya} &= \frac{\varepsilon_1 k_y - k_{3x}}{\mu_1}, \\
k_{yb} &= \frac{\varepsilon_2 k_y + k_{3x}}, \\
N_1 &= Q_1 + Q_2 - Q_1 \frac{\mu_2 k_{ya}}{\mu_2 k_{ya}} + Q_2 \frac{\mu_2 k_{ya}}{\mu_2 k_{ya}}, \\
N_2 &= Q_1 + Q_2 - Q_1 \frac{\mu_2 k_{ya}}{\mu_2 k_{ya}} + Q_2 \frac{\mu_2 k_{ya}}{\mu_2 k_{ya}}, \\
Q_1 &= (\coth(k_{1x}d_1) - \frac{\mu_2 k_{ya}}{\mu_2 k_{ya}}) \exp(k_{2x}d_2), \\
Q_2 &= (\coth(k_{1x}d_1) + \frac{\mu_2 k_{ya}}{\mu_2 k_{ya}}) \exp(-k_{2x}d_2).
\end{align*}
\]

The next step was the introduction into (12) of the behavior of the investigated layered structure in a changing stationary electric field: 1) for a ferroelectric layer – the dependence of the dielectric constant on the electric field \(\varepsilon_j(E), j = 1, 2\); 2) for a ferromagnetic layer – the dependence of the effective internal magnetic field on the electric field \(\omega_H = \gamma H_{eff}(E)\). The procedure for taking into account the above dependencies in modeling is presented in [9]. Hence, it follows that for the bound lead zirconate titanate (PZT) – yttrium iron garnet (YIG):

\[
\begin{align*}
k_{1x}^2 &= k_{2x}^2 - \varepsilon_j(E) \mu_j k_0^2, \\
\omega_H &= \gamma H_{eff}(E) = \gamma \left( H_{e0} - 4\pi M_0 + \frac{2K_1}{M_0} + 0.125 E \right).
\end{align*}
\] (13) (14)

Here, \(E\) has the dimension \([kV/cm]\).

Thus, on the basis of the unified wave solution (12) obtained through Maxwell’s equations for a four-layer structure, and the introduced dependences of the properties of the ferroelectric and ferromagnetic layers on the magnitude of the applied electric field through the accompanying effects (13) and (14), the mathematical model of the behavior of a layered multiferroic structure in inhomogeneous electric and magnetic fields was built. Further calculation were carried out on this basis of the constructed model.

3. Dispersion characteristics of magnetoelectric gradient structures

Dispersion characteristics were calculated for two structures: 1) classical ME multiferroic structure – metal-ferroelectric-ferromagnetic-dielectric-metal; 2) ME gradient structure – metal-artificial dielectric-ferroelectric-ferromagnetic-dielectric-metal (MADFFDM). As indicated in the previous section, the transition from one, classical, structure to another, with an integrated AD, can be carried out quite simply within the boundaries of the constructed mathematical model.

The calculation of the full spectrum of eigenwaves based on the following consideration.

From the analysis of expressions (11) relating the projections of the wave vector in the layers of the structure, it follows that at certain value \(f\) and \(k\) imaginary \(k_i\) values may appear. The region of imaginary values will be different for each layer. Consequently, if the real part \(\Re \{\}\) of the expression (12) is
equated to zero in the calculation of the full spectrum of eigenwaves, then it becomes possible to describe mathematically not only situation with the simultaneous existence of waves in all layers, but also situation in which waves can exist separately in the layers of the structure under study.

The following parameters were used to calculate the dispersion characteristics of the presented structures.

For the structure of the MFFDM: 1-layer – ferroelectric PZT with thickness of \( d_1 = 100 \) um, the relative permittivity is \( \varepsilon_1(0) = 1870 \); 4-dielectric layer – gadolinium gallium garnet (GGG) with thickness of \( w = 500 \) um, the relative permittivity is \( \varepsilon_4 = 11 \); 3-ferromagnetic layer YIG with thickness of \( s = 5 \) um, saturation magnetization is \( M_0 = 1750 \) G, external constant magnetic bias field of ferromagnetic is \( H_{\theta 0} = 4126 \) Oe. The thickness of the second layer is taken to be zero, and \( \varepsilon_2 = 1 \).

For the structure of the MADFFDM: 1-layer is AD with thickness of \( d_1 = 1 \) mm; 2-layer is PZT with thickness of \( d_2 = 100 \) um; 3-layer is YIG with thickness of \( s = 20 \) um; 4-layer is GGG with thickness of \( \varepsilon_4 = 500 \) um; \( H_{\theta 0} = 4126 \) Oe.

The spectrum of eigenwaves for the structure of the MFFDM is shown in figure 3. It also presents the results of calculating the spectrum of eigenwaves at various values of external stationary electric and magnetic fields.

**Figure 3.** The spectrum of eigenwaves: a) initial; b) behavior in an inhomogeneous magnetic field \( H_{\theta 0} \) 1 – 2022 Oe, 2 – 4126 Oe, 3 – 5000 Oe; c) behavior in an inhomogeneous electric field \( E \) 1 – 0 kV/cm, 2 – 40 kV/cm.
As can be seen from figure 3, the spectrum of eigenwaves of a layered ME multiferroic structure is composite, which include the dispersion branches of magnetostatic waves in the ferromagnetic layer (in figure 3a are highlighted in bold) that depends on the magnitude of the magnetic field \( H_e \) (figure 3b), and dispersion branches of electromagnetic waves in dielectric layers, which depend on the magnitude of the dielectric constant. The latter, in turn, due to the ferroelectric properties of the PZT directly depends on the value of the applied field (figure 3c). The change in the electromagnetic dispersion component of the spectrum (characteristic 1 and 2 in figure 3c) was around 2.6 GHz with a change in the electric field strength \( E \) by 40 kV/cm. However, the applied electric field also led to a change in the magnetostatic dispersion component of the spectrum due to the magnetoelectric effect. This change is smaller and amounted to around 14 MHz.

The dispersion characteristic of eigenwaves of the MADFFDM structure is shown in figure 4. The calculation was carried out for the following values of the relative permittivity of the AD: 1000, 5000, 10000.

![Wave dispersion characteristic of the layered MADFFDM structure](image)

**Figure 4.** The wave dispersion characteristic of the layered MADFFDM structure, at different values of the relative permittivity of the AD: 1 \( \varepsilon_1 = 1000 \); 2 \( \varepsilon_1 = 5000 \); 3 \( \varepsilon_1 = 10000 \).

Let us analyze the wave dispersion characteristic of a layered multiferroic structure with an integrated artificial dielectric layer obtained based on the constructed model. The introduction of an integrated AD layer with different values of the relative permittivity does not affect the dispersion branches of magnetostatic (spin) waves present in the ferromagnetic layer (highlighted by bold lines). The dispersion branches related to the electromagnetic waves undergo changes due to a change in the total dielectric constant, since the thickness of the integrated AD layer prevails. Consequently, for \( \varepsilon_1 = 1000 \), the total dielectric constant of the two upper layers becomes smaller, which leads to a frequency rise of this dispersion branch. The dispersion branches of the EMW of the composite spectrum for the values \( \varepsilon_1 = 5000 \) and \( \varepsilon_1 = 10000 \) can be characterized by slightly different behavior. Following the trend traced throughout the calculation, an increase in the value of the total dielectric constant of the dielectric layers leads to a frequency decrease in the dispersion branches of electromagnetic waves. At the value of the relative permittivity of the AD \( \varepsilon_1 = 10000 \), in the observed frequency range, in its upper boundary, another thickness mode appears.
The distinguishing feature for the cases 2 and 3 (figure 4) will be the following revealed behavior: when the dispersion branches of the magnetostatic (spin) and electromagnetic waves intersect (areas of point A, B, C and D on figure 4), the latter change their character (further in the direction of increasing the wave numbers) to character of magnetostatic waves. This revealed feature, obtained as a result of a numerical experiment on the MADFFDM structure based on constructed mathematical model, is more than confirmed by previously conducted experimental studies to study the phenomenon of conversion of surface magnetostatic waves into electromagnetic waves, conducted be scientist A.V. Vashkovskij and E.H. Lock [15-17]. Their general meaning was as follows: when studying the propagation of wave beams of a surface magnetostatic wave in inhomogeneously magnetized YIG films, it was found that if the wavelength increases with the propagation of the beam, then in the region of the film surface, where the wavenumber of the SMSW become close to the wavenumber of the EMW of the adjacent space, the surface magnetostatic wave is converted into an electromagnetic wave.

4. Discussion on the obtained results
As can be seen from the dispersion characteristics obtained in the course of the numerical experiment of the structures presented for the study (figures 3 and 4), the spectrum of eigenwaves of a multilayer ME multiferroic structure can be influenced through changes in the magnetic and electric fields through a number of effects. However, this influence will have the scale of the entire layered structure, due to the complexity of the implementation of the point effect of the fields. In turn, the spectrum of eigenwaves depends on the dielectric constant of the layer with AD, the distribution of which can be artificially set at the stage of designing a microwave device. From this, we can conclude that the magnetoelectric gradient structure (MADFFDM structure) is characterized by a system of three control mechanisms: magnetic field – electric field – artificial distribution of dielectric constant.

The areas of intersection of the dispersion branches of magnetostatic and electromagnetic waves are of sufficient interest (areas of point A, B, C, and D on figure 4). These areas refer us to research carried out in parallel by two independent group of scientists: hybrid electromagnetic-spin waves [4-8] and the effect of transformation of surface magnetostatic wave into an electromagnetic [15-17]. In fact, the same effect is considered, with the only difference that in the second case a small region of interaction of these types of waves is experimentally investigated. In the first case, the interaction region is “stretched” over the entire structure under study, in which conditions are created for the simultaneous existence of SMSW and EMW, and the definition is introduced – hybrid electromagnetic-spin waves. And, as can be seen from the theoretical study presented above, through three mechanisms there is a possibility of influencing the interaction areas of these waves.

5. Conclusion
ME multiferroic structures are promising for the design of electronically controlled microwave devices. They fully combine the properties of both ferroelectrics and ferromagnetics, as well as the possibility of double control, both magnetic and electric fields. From the point of view of efficiency, the electric field is more preferable due to the inertia inherent in ferromagnetics. In turn, the role of choice of the operating point is assigned to the magnetic field.

The integration of the AD into the ME multiferroic structure will make it possible to carry out a qualitative transition, to go from volumetric electronic control of microwave devices to point control. This will allow starting designing a new class of controlled microwave devices with a given controlled distribution of wave characteristics on the scale of not only the entire structure, but also a given gradient. Magnetoelectric gradient structures are most preferable to use in the development of solid-state microwave electronically controlled devices for directional energy transfer: directional couplers, cavity, valve and patch antennas.

References
[1] Bichurin M I 1990 Microwave resonant magnetoelectric effect Ferro-magnetic Substances (collections of scientific papers) (Moscow: Science) pp 53–66
[2] Bichurin M and Petrov V 2014 *Modeling of Magnetoelectric Effects in Composites* 201 ed R Hull *et al.* (Netherlands: Springer) p 108

[3] Bichurin M I and Petrov V M 2012 Modeling of magnetoelectric interaction in magnetostrictive-piezoelectric composites *Adv in Condens Matter Phys* 798310 1–12

[4] Demidov V E and Kalinikos B A 2001 Spectra of exchange dipole electromagnetic-spin waves in asymmetric metal-insulator-ferromagnetic-insulator-metal systems *Tech. Phys.* 46 219–22

[5] Demidov V E and Kalinikos B A 2000 The spectrum of dipole-exchange spin waves in tangentially-magnetized metal-ferroelectric-ferromagnet-ferroelectric-metal sandwich structures *Tech. Phys. Let.* 26 273–75

[6] Nikitin A A, Ustinov A B, Semenov A A and Kalinikos B A 2014 A microwave phase shifter based on a planar ferrite-ferroelectric thin-film structure *Tech. Phys. Let.* 40 277–79

[7] Ustinov A B, Tiberkevich V S, Srinivasan G, Slavin A N, Semenov A A, Karmanenko S F, Kalinikos B A, Mantese J V and Ramer R 2006 Electric field tunable ferrite-ferroelectric hybrid wave microwave resonators: Experiment and theory *J. Appl. Phys.* 100 093905 1–6

[8] Nikitin A A, Nikitin A O, Ustinov A B, Läheranta E and Kalinikos B A 2018 Theory of spin-electromagnetic waves in planar thin-film multiferroic heterostructures based on a coplanar transmission line and its application for electromagnonic crystals *IEEE Transactions on Magnetics* 54 2501805 1–5

[9] Petrov R V, Nikitin A O, Bichurin M I and Srinivasan G 2020 Magnetoelectric antenna array *IRECAP* 10 (6) 371–75

[10] Zhang Y, Aratani Y and Nakazima H 2017 A microwave free-space method using artificial lens with anti-reflection layer *Sens. Imaging* 18 (17) 1–12

[11] Awai I 2008 Artificial dielectric resonators for miniaturized filters *IEEE Microwave Magazine* 9 (5) 55–64

[12] Zhang Y, Imahori T and Fujita Y 2019 Artificial material for patch antenna gain enhancement and its application in microwave free-space method *Int. Conf. on Electromagnetic in Advanced Applications (ICEAA)* 0203–0203

[13] Biber S, Richter J, Martius S and Schmidt 2003 Design of artificial dielectrics for ant-reflectioncoatings *33th Eur. Microwave Conf. Proceeding* 7 Oct. 2003 Munich, Germany pp 1115–18

[14] Nikitin A O, Petrov R V and Havanova M A 2019 Control of magnetoelectric antenna by electric field *ITM Web of Conferences* 30 05028 1–9

[15] Vashkovskij A V and Lock E H 1995 Radiation patterns resulting owing to transformation of surface magnetostatic waves to electromagnetic waves *J. of Communication Technology and Electronics* 40 (7) 1030–37

[16] Vashkovskij A V and Lock E H 2004 On the parameters of patterns of radiation arising in the process of transformation of a magnetostatic surface wave into an electromagnetic wave *J of Communication Technology and Electronics* 49 (8) 904–09

[17] Vashkovskij A V and Lock E H 2009 The mechanism of transformation of a magnetostatic surface wave into an electromagnetic wave *J of Communication Technology and Electronics* 54 (4) 456–67