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Dispersion Characteristics of Spin-Electromagnetic Waves in Planar Multiferroic Structures with Coplanar Transmission Line

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Abstract

Introduction. The distinctive feature of a coplanar transmission line with thin ferrite and ferroelectric films is the absence of undesirable irregularities in dispersion for relatively low frequencies when the wavelength approaches the thickness of ferroelectric layer, in contrast to the open ferrite-ferroelectric wave-guiding structure without metallization.

Aim. The purpose of this paper is twofold: (i) to develop a theory of the wave spectra in the multiferroic structures based on the coplanar lines; (ii) using this theory to find ways to enhance the electric tuning range.

Materials and methods. The dispersion relation for spin-electromagnetic waves was derived through analytical solution of the full set of the Maxwell's equations utilizing a method of approximate boundary conditions.

Results. A theory of spin-electromagnetic wave spectrum has been developed for the thin-film ferrite-ferroelectric structure based on a coplanar transmission line. According to this theory, dispersion characteristics of the spin-electromagnetic waves were described and analyzed for different parameters of the structure. The obtained results show that the investigated structure demonstrates a dual electric and magnetic field tunability of wave spectra. Its efficiency increases with an increase in the thicknesses of the ferrite and ferroelectric films and with a decrease in the width of the central metal strip.

Conclusion. The distinctive features of the proposed coplanar waveguides are the thin-film planar topology and dual tunability of the wave spectra. All these advantages make the proposed structures perspective for development of new microwave devices.

Keywords: coplanar waveguide, ferrites, ferroelectrics, microwaves, spin-electromagnetic waves

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Introduction. Recent advances made in the area of thin film deposition techniques have resulted in the application of the multilayered multiferroic structures that combine advantages of ferrite and ferroelectric materials. Ferroelectrics are widely used in the modern microwave devices due to their dependence of dielectric permittivity on the bias electric field. This phenomenon allows to controle the operation characteristic of such a device by means of changing the electric field [1]. At the same time, distinguished features of the ferrite material devices are the low insertion losses and magnetic field tunability in a wide frequency range [2].

An interaction between the ferromagnetic and ferroelectric phases is realized through the electrodynamic coupling of the microwave spin waves (SW) and electromagnetic waves (EMW). This interaction leads to formation of the hybrid spin-electromagnetic wave (SEW) [3]. Owning to the dual tunability, the multiferroic materials have been used to develop various microwave devices. The first experimentally investigated devices based on the ferrite-ferroelectric structures were resonators [4]. After that, a great number of theoretical and experimental work in this area was carried out (see, e. g., [5–8] and references therein). As is seen from the literature, the multiferroic structures had a great success in development of the microwave devices. Among them are the delay lines [9, 10], the tunable microwave resonators [11, 12], the ferromagnetic resonance phase shifters [13–15], and the multiband filters [16, 17]. Besides, an increased interest to investigate a new class of microwave devices utilizing the periodic multiferroic structures is evident [18–24].

A further development of the microwave multiferroic devices is connected with the planar thin-film structures. Such structures allow one not only to decrease the sizes of the devices, but also to reduce drastically the control voltage, which is necessary for an effective electrical tuning of the SEW spectra. In order to provide an effective hybridization among the SWs and the EMWs the different multiferroic structures were suggested. These structures may be divided into the two major families. The first one is the ferrite-ferroelectric-ferrite multilayers [25]. The main advantage of these structures is an existence of the magneto-dipole interaction between the ferrite films separated by a thin ferroelectric film. The second family is the layered structures consisting of thin magnetic and ferroelectric films combined with a slot or a coplanar microwave transmission line (TL) [14, 26, 27]. In the latter case, the SEWs are originated from the electrodynamic coupling of the EMW propagating in a slot or a coplanar TL, with the SW existing in the ferrite film.

As follows from analysis of the published articles, a large part of the studies was devoted to the multiferroic structures with transmission lines in a slot-line geometry, while to the coplanar TL were given a little attention. In our opinion, this was due to the lack of a theory describing the dispersion characteristics of spin-electromagnetic waves in such a structure. Therefore, the purpose of the present work is to develop a theory of the wave spectra in the multiferroic structures based on the coplanar lines.

Analytical theory. The studied structure is shown in Fig. 1. Here, a central metal strip of width h and two metal ground electrodes are placed in the $z=0$ plane between dielectric (or ferroelectric) and ferrite layers (Fig. 1). The metal electrodes are transparent to the microwave electromagnetic field and so

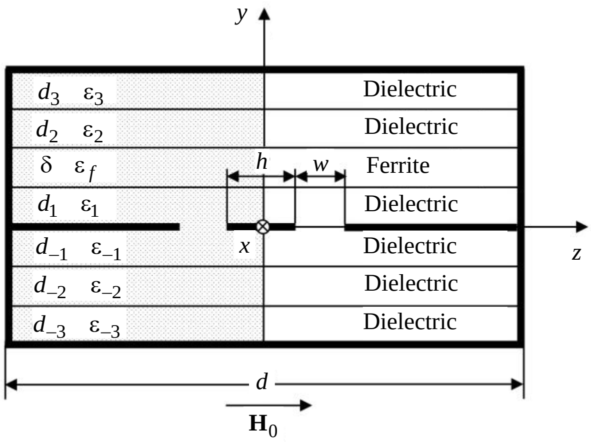

Fig. 1. Coplanar line cross section

can be neglected in the numerical simulations. This assumption is valid because the thickness of the electrodes is much smaller compared to the skin depth at the operating frequencies. Below and upper of the electrodes, there are six homogeneous dielectric layers with the dielectric permittivities ε_j and thicknesses d_j. Here j is a layer number according to Fig. 1. The thickness of the ferrite layer is δ and its permittivity is ε_f. We assume that the SEW propagates along the coplanar TL. The ferrite layer is tangentially magnetized along z-axis.

As it was shown in [28], the electromagnetic wave in the rectangular waveguide loaded with the multiferroic structure and transmission line is a superposition of the longitudinal-section magnetic (LSM) and the longitudinal-section electric (LSE) modes. Using this, we express the electric and magnetic field components in the dielectric layers of the considered structure as the sums of the LSM and LSE modes $\mathbf{E}_j = \mathbf{E}_j^{\text{LSM}} + \mathbf{E}_j^{\text{LSE}}$, $\mathbf{H}_j = \mathbf{H}_j^{\text{LSM}} + \mathbf{H}_j^{\text{LSE}}$. These fields are expressed through the Hertzian potentials as $\mathbf{E}_j^{\text{LSE}} = -\nabla \times \mathbf{\Pi}_j^h / \varepsilon_j$; $\mathbf{H}_j^{LSM} = \nabla \times \mathbf{\Pi}_j^e$, where $\mathbf{\Pi}^e$ and $\mathbf{\Pi}^h$ are the magnetic and electric Hertzian potential functions, respectively.

To treat the multiferroic structure with the coplanar TL as a waveguide boundary-value problem, some general comments regarding the electrodynamic model should be mentioned:

– the solution of the boundary-value problem will be reduced to the derivation of the dispersion equation for a symmetrical rectangular waveguide loaded with a coplanar TL surrounded by perfectly conducting metal walls (Fig. 1). This approach is physically applicable because the electric and magnetic fields of a coplanar waveguide with narrow gaps w are symmetrical and are localized in the gaps of the TL. Therefore, if the distance between the metal walls is significant, then their influence on wave processes is negligible;

– in the dispersion equation derivation, it will be considered that the coplanar TL is surrounded by the metal walls where the tangential components of the magnetic field are equal to zero. This boundary condition is called as "magnetic wall" and has the following form:

$$\mathbf{\Pi}_j^e = \frac{\partial}{\partial z}\mathbf{\Pi}_j^h = 0; \qquad (1)$$

– in order to simplify the theoretical derivation, an approximate dispersion relation will be found by using the method of approximate boundary conditions for the ferrite film. An applicability of this method is determined by a relatively weak exponential dependence of the electric and magnetic field distributions on the transverse coordinate for the long-wave dipolar surface SW in the thin ferrite film having the unpinned surface spins [2]. A high accuracy of this method was shown in our recent work for a planar all thin-film multiferroic structure with a slot TL [29].

Considering the above listed comments and the symmetry of the fundamental coplanar TL mode, the rectangular waveguide boundary-value problem is reduced to the equivalent approach for a slot TL with the "magnetic wall" boundary conditions. In other words, we derive the approximate dispersion relation for the SEW in thin-film multiferroic coplanar TL following the same algorithm like in our previous work for a slot TL [29]. As a result, we obtained the dispersion relation from the vanishing of the following matrix determinant composed by G elements:

$$G_{m,s} = \sum_{n=0}^{N}\begin{bmatrix} X_{11}z'_{11,n,m,s} & X_{12}z'_{12,n,m,s} \\ \varphi_n X_{21}z'_{21,n,m,s} & X_{22}z'_{22,n,m,s}\end{bmatrix}, \qquad (2)$$

where X_{11}, X_{12}, X_{21}, X_{22} are the same elements of matrix $\boldsymbol{X}$ as for the structure with slot transmission line (see [28]), $z'_{11,n,m,s} = (-1)^{1+m+s} J_{2s}(q_n) \times \times \frac{(2m+2)J_{2m+2}(q_n)}{q_n} S$; $z'_{12,n,m,s} = (-1)^{m+s}\varphi_n J_{2m}(q_n) \times \times J_{2s}(q_n) S$; $z'_{21,n,m,s} = (-1)^{1+m+s}\frac{4(m+1)J_{2m+2}(q_n)}{q_n} \times \times \frac{(s+1)J_{2s+2}(q_n)}{q_n} S$; $z'_{22,n,m,s} = (-1)^{m+s}\varphi_n \times \times J_{2m}(q_n)\frac{(2s+2)J_{2s+2}(q_n)}{q_n} S$. The following notations are used in (2): $\varphi_n = \begin{cases} 1/2 \text{ at } n = 0, \\ 1 \text{ at } n \neq 0; \end{cases}$ $J_{2m}(q_n)$ and $J_{2m+2}(q_n)$ are Bessel functions of the first kind; $S = \sin^2\left[a_n(h+w)/2\right]$; m, s = 0,1 ... M; n = 0, 1 … N; values of M and N are determined by the width of the slot gap w; $q_n = \frac{n\pi w}{2d}$; $a_n = \pi n/d$.

Note that the "magnetic wall" boundary condition affects only the elements of matrix z' in (2).

Let us consider in more detail a derivation of these elements. As was mentioned above, the tangential components of the magnetic field equal zero outside the slot-line gap. In this case, the potentials $\mathbf{\Pi}^e$ and $\mathbf{\Pi}^h$ satisfy the condition (1) and have the following form:

$$\mathbf{\Pi}_j^e = \sum_{n=0}^{\infty}\left[A_{jn}^e(y)\cos(a_n z)e^{i(\omega t - kx)}\mathrm{e}_y\right];$$

$$\mathbf{\Pi}_j^h = \sum_{n=0}^{\infty}\left[A_{jn}^h(y)\sin(a_n z)e^{i(\omega t - kx)}\mathrm{e}_y\right],$$

where A_{jn}^h and A_{jn}^e are the arbitrary coefficients for the j layer; k is the wavenumber of spin-electromagnetic wave. In order to find these coefficients, a conventional electrodynamics boundary condition was used. According to it, the tangential components of vectors $\mathbf{E}$ and $\mathbf{H}$ are equal on the layer boundaries. It allows to establish a relationship among the arbitrary coefficients in the form:

$$\begin{aligned}
&\sum_{n=0}^{\infty} x_{11}\cos(a_n z)\frac{2}{d}\varphi_n\int_{-w/2}^{w/2} g(z)\cos(a_n z)dz + \\
&+\sum_{n=0}^{\infty} x_{12}\cos(a_n z)\frac{2}{d}\varphi_n\int_{-w/2}^{w/2} f(z)\sin(a_n z)dz = 0; \\
&\sum_{n=0}^{\infty} x_{21}\sin(a_n z)\frac{2}{d}\int_{-w/2}^{w/2} g(z)\cos(a_n z)dz + \\
&+\sum_{n=0}^{\infty} x_{22}\sin(a_n z)\frac{2}{d}\varphi_n\int_{-w/2}^{w/2} f(z)\sin(a_n z)dz = 0,
\end{aligned} \qquad (3)$$

where $g(z)$ and $f(z)$ are unknown distributions of the electric field normal components. Since these unknown distributions enter in (3) under integrals, their solution can be written using the Galerkin method.

For convenience of integration, the unknown distributions of the electric field normal components inside the TL gap $g(z)$ and $f(z)$ are represented as a function of the normalized coordinate ξ having zero at the center of this gap. Therefore, the origin of the z-axis can be transformed to the center of this gap, which corresponds to $z_0 = (h+w)/2$ in Fig. 1. According to the new location of the coordinate system, a new coordinate $\xi' = z-(h+w)/2$ can be introduced and normalized to $w/2$:

$$\xi = 2\xi'/w. \quad (4)$$

Note that the variable ξ varies on the width of the gap in the interval $[-1,+1]$.

Following the Galerkin method, the Chebyshev polynomials of the first (T_{2m}) and second (U_{2m+1}) kind were chosen as an orthogonal basis for expanding $f(z)$ and $g(z)$, respectively. As functions of the normalized variable ξ these polynomials have the following form:

$$f(\xi) = \sum_{m=0}^{M} t_m \frac{T_{2m}(\xi)}{\sqrt{1-\xi^2}};$$
$$g(\xi) = \sum_{m=0}^{M} u_m \sqrt{1-\xi^2}\,U_{2m+1}(\xi), \quad (5)$$

where t_m and u_m are the unknown coefficients.

It is worth mentioning that the Chebyshev series are used to take into account a finiteness of electromagnetic energy near an infinitely thin layer of perfect metal [30]. By substituting (5) into (4), we obtain:

$$\sum_{n=0}^{\infty} x_{11}\cos(a_n z)\sum_{m=0}^{M} u_m \int_{-w/2}^{w/2} \sqrt{1-\xi^2}\,U_{2m+1}(\xi)\cos(a_n z)\,dz +$$
$$+\sum_{n=0}^{\infty} x_{12}\cos(a_n z)\varphi_n \sum_{m=0}^{M} t_m \int_{-w/2}^{w/2} \frac{T_{2m}(\xi)}{\sqrt{1-\xi^2}}\sin(a_n z)\,dz = 0;$$
$$\sum_{n=0}^{\infty} x_{21}\sin(a_n z)\sum_{m=0}^{M} u_m \int_{-w/2}^{w/2} \sqrt{1-\xi^2}\,U_{2m+1}(\xi)\cos(a_n z)\,dz + \quad (6)$$
$$+\sum_{n=0}^{\infty} x_{22}\sin(a_n z)\varphi_n \sum_{m=0}^{M} t_m \int_{-w/2}^{w/2} \frac{T_{2m}(\xi)}{\sqrt{1-\xi^2}}\sin(a_n z)\,dz = 0.$$

According to the fact that $z = \xi' + (h+w)/2$ and $\xi = 2\xi'/w$, it is found that:

$$\cos(a_n z) = \cos(q_n\xi)\cos[a_n(h+w)/2] -$$
$$-\sin(q_n\xi)\sin[a_n(h+w)/2];$$
$$\sin(a_n z) = \sin(q_n\xi)\cos[a_n(h+w)/2] + \quad (7)$$
$$+\cos(q_n\xi)\sin[a_n(h+w)/2].$$

Taking into account the even character of the Chebyshev polynomials in $f(z)$ and the odd character of these polynomials in $g(z)$, we define:

$$\int_{-w/2}^{w/2} \sqrt{1-\xi^2}\,U_{2m+1}(\xi)\cos(a_n z)\,dz =$$
$$= -\sin[a_n(h+w)/2]\int_{-1}^{1}\sqrt{1-\xi^2}\,U_{2m+1}(\xi)\sin(q_n\xi)\,d\xi;$$
$$\int_{-w/2}^{w/2} \frac{T_{2m}(\xi)}{\sqrt{1-\xi^2}}\sin(a_n z)\,dz = \quad (8)$$
$$= \sin[a_n(h+w)/2]\int_{-1}^{1}\frac{T_{2m}(\xi)}{\sqrt{1-\xi^2}}\cos(q_n\xi)\,d\xi.$$

In accordance with [31], the integrals in the last relations are calculated analytically:

$$\int_{-1}^{1} T_{2m}(q_n)\cos(q_n\xi)\frac{d\xi}{\sqrt{1-\xi^2}} = (-1)^m \pi J_{2m}(q_n);$$
$$\int_{-1}^{1}\sqrt{1-\xi^2}\,U_{2m+1}(q_n)\sin(q_n\xi)\,d\xi = \quad (9)$$
$$= (-1)^m \pi \frac{J_{2m+2}(q_n)}{q_n},$$

where $J_{2m}(q_n)$ and $J_{2m+2}(q_n)$ are the Bessel functions of the first kind.

Taking in account (4)–(9), (3) can be written as:

$$-\sum_{n=0}^{\infty} x_{11}\cos(a_n z)\times$$
$$\times\sum_{m=0}^{M} u_m(-1)^m \frac{J_{2m+2}(q_n)}{q_n}\sin[a_n(h+w)/2] +$$
$$+\sum_{n=0}^{\infty} x_{12}\cos(a_n z)\varphi_n \times$$
$$\times\sum_{m=0}^{M} t_m(-1)^m J_{2m}(q_n)\sin[a_n(h+w)/2] = 0, \quad (10)$$

$$-\sum_{n=0}^{\infty} x_{21}\sin(a_n z)\times$$
$$\times\sum_{m=0}^{M} u_m(-1)^m \frac{J_{2m+2}(q_n)}{q_n}\sin[a_n(h+w)/2]+$$
$$+\sum_{n=0}^{\infty} x_{22}\sin(a_n z)\varphi_n\times$$
$$\times\sum_{m=0}^{M} t_m(-1)^m J_{2m}(q_n)\sin[a_n(h+w)/2]=0. \quad (11)$$

Using the Galerkin method, we multiply (10) and (11) by $T_{2m}(q_n)\big/\sqrt{1-\xi^2}$ and $\sqrt{1-\xi^2}\,U_{2m+1}(q_n)$, respectively. After changing the order of summation and integration, we obtain:

$$-\sum_{n=0}^{N} x_{11}\sum_{m=0}^{M} u_m(-1)^m\frac{J_{2m+2}(q_n)}{q_n}\sin[a_n(h+w)/2]\times$$
$$\times\int_{-1}^{1}\frac{T_{2s}(\xi)}{\sqrt{1-\xi^2}}\cos(a_n z)\,dz+$$
$$+\sum_{n=0}^{N} x_{12}\varphi_n\sum_{m=0}^{M} t_m(-1)^m J_{2m}(q_n)\sin[a_n(h+w)/2]\times$$
$$\times\int_{-1}^{1}\frac{T_{2s}(\xi)}{\sqrt{1-\xi^2}}\cos(a_n z)\,dz=0, \qquad (12)$$
$$-\sum_{n=0}^{N} x_{21}\sum_{m=0}^{M} u_m(-1)^m\frac{J_{2m+2}(q_n)}{q_n}\sin[a_n(h+w)/2]\times$$
$$\times\int_{-1}^{1}\sqrt{1-\xi^2}\,U_{2m+1}(q_n)\sin(a_n z)\,dz+$$
$$+\sum_{n=0}^{N} x_{22}\varphi_n\sum_{m=0}^{M} t_m(-1)^m J_{2m}(q_n)\sin[a_n(h+w)/2]\times$$
$$\times\int_{-1}^{1}\sqrt{1-\xi^2}\,U_{2m+1}(q_n)\sin(a_n z)\,dz=0. \qquad (13)$$

Similar mathematical manipulations, as for (4)–(9), are performed for integration of (12) and (13). After that we obtain:

$$\begin{aligned}-\sum_{n=0}^{N} x_{11}z'_{11,n,m,s}+\sum_{n=0}^{N} x_{12}z'_{12,n,m,s}&=0,\\ -\sum_{n=0}^{N} x_{21}z'_{21,n,m,s}+\sum_{n=0}^{N} x_{22}z'_{22,n,m,s}&=0,\end{aligned} \qquad (14)$$

where

$$z'_{11,n,m,s}=(-1)^{1+m+s}J_{2s}(q_n)\times$$
$$\times\frac{(2m+2)J_{2m+2}(q_n)}{q_n}\sin^2[a_n(h+w)/2];$$
$$z'_{12,n,m,s}=(-1)^{m+s}\varphi_n J_{2m}(q_n)\times$$
$$\times J_{2s}(q_n)\sin^2[a_n(h+w)/2];$$
$$z'_{21,n,m,s}=(-1)^{1+m+s}\frac{(2m+2)J_{2m+2}(q_n)}{q_n}\times$$
$$\times\frac{(2s+2)J_{2s+2}(q_n)}{q_n}\sin^2[a_n(h+w)/2];$$
$$z'_{22,n,m,s}=(-1)^{m+s}\varphi_n J_{2m}(q_n)\times$$
$$\times\frac{(2s+2)J_{2s+2}(q_n)}{q_n}\sin^2[a_n(h+w)/2].$$

The (14) represents a homogeneous system of linear algebraic equations. The vanishing of its determinant results in the dispersion relation:

$$\sum_{n=0}^{N}\det\begin{bmatrix} X_{11}z'_{11,n,m,s} & X_{12}z'_{12,n,m,s}\\ \varphi_n X_{21}z'_{21,n,m,s} & \varphi_n X_{22}z'_{22,n,m,s}\end{bmatrix}=0. \quad (15)$$

The dispersion relation (15) describes the spectrum of the spin-electromagnetic waves in planar all-thin-film multiferroic structures containing a coplanar transmission line. The following notations are used in (12), (13): $m,\ s=\ 0, 1 \ldots M$, where M is the index of the Chebyshev polynomial order, which is determined by the width of the gap w; $n=0,1,\ \ldots,\ N$, where N is the value at which the Bessel functions converge.

Numerical modeling. Below we apply the developed analytical theory for calculation and analysis of the dispersion characteristics of spin-electromagnetic waves propagating in the all-thin-film multiferroic structures. The numerical calculations are carried out for the typical experimental parameters. Thus, in accordance with Fig. 1, the dielec-

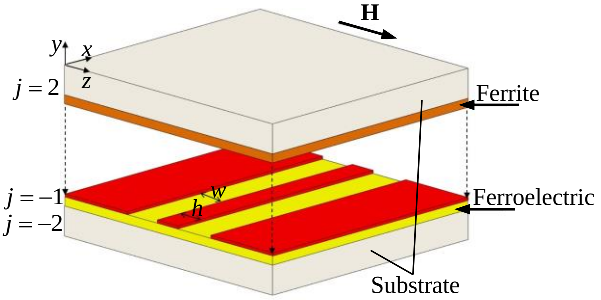

Fig. 2. Coplanar transmission line based on ferrite-ferroelectric structure

tric layer $j = -2$ corresponds to the sapphire substrate with thickness and permittivity d_{-2} and ε_{-2}, respectively. The layer with number $j = -1$ corresponds to the barium-strontium titanate (BST) film with parameters d_{-1} and ε_{-1} that has the exceptionally high tunability, high breakdown field and relatively low loss tangent at microwave frequencies [32].

In order to investigate a typical experimental case, for which the ferrite film is in contact with metal electrodes of the transmission line, we assumed zero thickness of the dielectric layer with number $j = 1$ (see Fig. 2). In consistent with denotations introduced in the previous Section, the parameters of the yttrium-iron garnet (YIG) film are $\delta, \varepsilon_f, H,$ and M_0. The dielectric layer with number $j = 2$ corresponds to the gadolinium gallium garnet substrate with parameters d_2 and ε_2. The layers with $j = -3$ and $j = 3$ are assumed to be a free space.

During simulations, the five parameters, namely the YIG film thickness δ, the BST film thickness d_{-1}, the BST permittivity ε_{-1}, the external magnetic field *H*, the gap width *w*, and the width *h* of the central metal strip were varied. Other parameters were constant. The values of the parameters $d_3 = d_{-3} = 0.1$ m and the distance between metal walls $d = 0.04$ m were chosen to implement the conditions of the multiferroic coplanar waveguide placed in a free space. The other parameters were as follows: $\varepsilon_3 = \varepsilon_{-3} = 1$; $\varepsilon_f = 14$; $M_0 = 1750$ Oe; $d_2 = d_{-2} = 500$ μm; $\varepsilon_2 = 14$; $\varepsilon_{-2} = 10$.

Fig. 3 shows by solid curves the typical dispersion characteristics of the hybrid SEWs in the all-thin-film multiferroic structure with the coplanar TL calculated for $\delta = 10$ μm; $H = 107.4$ kA·m^{-1}; $d_{-1} = 2$ μm; $\varepsilon_{-1} = 1500$; $w = 50$ μm; and $h = 50$ μm. To demonstrate the formation of the spectrum, we also show in Fig. 3 the dispersion branches represented the dispersion characteristics of the surface spin waves in a ferrite film (dash line) and of the main mode of the electromagnetic waves (dash dot line) in a coplanar transmission line with a ferroelectric film on a dielectric substrate.

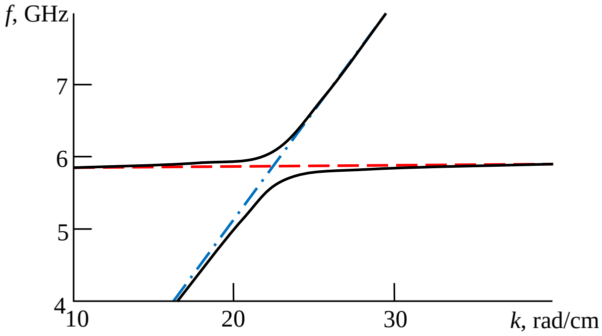

Fig. 3. The spectrum of the hybrid SEWs in the all-thin-film multiferroic structure with a coplanar TL

It is seen from Fig. 3 that away from the ferromagnetic resonance frequency, the dispersion characteristics of the EMW and the SEW coincide. Near this frequency, the SEW phase velocity decreases due to the hybridization of the SW and the EMW. A distinctive feature of the all-thin-film multiferroic structure with a coplanar TL is an absence of undesirable irregularities in dispersion for relatively low frequencies when the wavelength approaches the thickness of ferroelectric layer, which is in contrast to the open ferrite-ferroelectric wave-guiding structure without metallization [3].

Turn now to investigation of the influence of different parameters of the thin-film structure on the dispersion characteristics of SEWs. Fig. 4–7 show the calculated dependences of the wave spectra versus the gap width *w*, the thickness of ferroelectric (d_{-1}) and of ferrite (δ) films, and the width of the central strip *h*. Note that in this figure the solid black lines correspond to the dispersion characteristic shown in Fig. 3.

As is seen from this figure, a decrease of the gap width *w* and the width *h* of the central metal strip, as well as an increase in the thickness of the ferroelectric film d_{-1}, shifts the area of the maximum hybridization to the higher wavenumbers (Fig. 4–6). In this case, the electrodynamic interaction of the SW in the ferrite film and the EMW in the coplanar TL is enhanced. Further, the ferrite film thickness δ explicitly influences on the slope of the SW dispersion branches leading to a drastic change in the SEW group velocity (Fig. 7).

Turn now to investigation of the electric and magnetic tuning of the hybrid spin-electromagnetic waves in the all-thin-film multiferroic structure with a coplanar TL. Fig. 8 and 9 show the results of numerical simulation of the wave spectra for the different values of an external magnetic field *H* and a control voltage *U*. We note that in these figures the solid lines correspond to the dispersion characteristic shown in Fig. 3.

An increase in the external magnetic field *H* leads to a shift of the spin wave spectrum towards the higher frequencies. Therefore, the area of the effec-

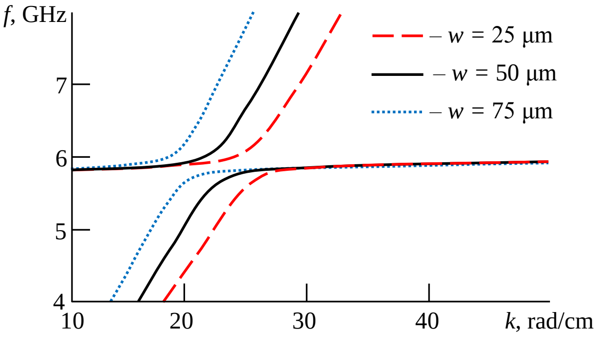

Fig. 4. Influence of the gap width *w* on the dispersion of the SEWs

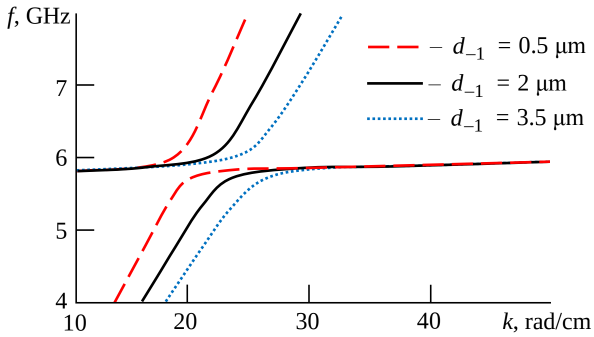

Fig. 6. Influence of the thickness d_{-1} of the ferroelectric film on the dispersion of the SEWs

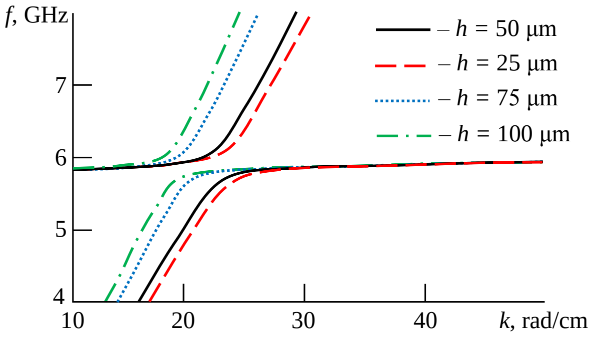

Fig. 5. Influence of the width h of the central metal strip on the dispersion of the SEWs

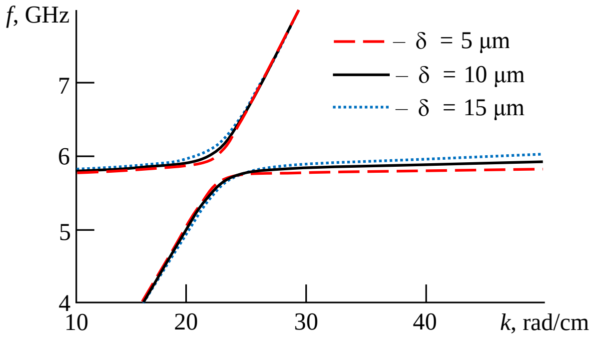

Fig. 7. Influence of the thickness δ of the ferrite film on the dispersion of the SEWs

tive hybridization of electromagnetic and spin waves demonstrates an up-frequency shift too (Fig. 8). An application of a control voltage *U* to the coplanar TL electrodes leads to a reduction of the ferroelectric film permittivity ε_2 and provides an electric tunability. The expression approximating the dependence of the ferroelectric permittivity versus the electric field *E* has the form:

$$\varepsilon_2\left(E_{1,2}\right)=\varepsilon_2(0)-aE_{1,2}^2,$$

where the following typical parameters for the BST film are used: $\varepsilon_2(0)=1500$ and $a=0.194\ \text{cm}^2/\text{kV}^2$ [12].

As can be seen from Fig. 9, an increase in a control voltage provides an increase in the group velocity of the electromagnetic wave in the coplanar TL. Therefore, the area of the maximum hybridization is shifted to the lower wavenumbers.

Conclusions. The dispersion relation for the hybrid spin-electromagnetic waves propagating in the thin-film ferrite-ferroelectric structures based on a coplanar transmission line has been derived with the method of the approximate boundary conditions. Using the developed theory, the dispersion characteristics of SEWs were calculated and analyzed. The electric and magnetic tunability of the wave spectra were investigated. It was found that the range of the electric tuning can be increased due to an EMW retardation that is realized by decreasing the gap and the central metal electrode widths, as well as increasing of the ferroelectric thickness. In summary, the distinctive features of the proposed coplanar waveguides are the thin-film planar topology and dual tunability of the wave spectra. All these advantages make the investigated structures perspective for development of new microwave devices.

Authors' contribution

Aleksei A. Nikitin, development of the theory; numerical modeling; analysis of the theoretical data; preparation of the paper text.

Alexey B. Ustinov, analysis of the theoretical data; discussion of the results; management of the work.

Andrey A. Nikitin, development of the theory and computer programs for numerical simulation analysis; discussion of the results.

Erkki Lähderanta, discussion of the results; management of the work.

Boris A. Kalinikos, management of the work; preparation of the paper text.

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