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Modulation of Millimeter Waves by Acoustically Controlled Hexagonal Ferrite Resonator

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To develop millimeter-wave modulators, high-anisotropy uniaxial monocrystalline hexagonal ferrite resonators (HFRs) can be used. One of the ways to modulate the hexagonal ferrite resonator's resonance frequency is to periodically vary the angle between the equilibrium magnetic moment and the external magnetization field. This angular control can be exercised by the mechanical (acoustic) oscillations excited in a piezoelectric slab having a good acoustic contact with the HFR. We consider a quasi-static mathematical model of the uniaxial HFR with the angular control of its resonance frequency. We analyze the amplitudes of harmonics of the modulated millimeter-wave signal, and we derive the optimal orientation of the ferrite crystallographic axis. We suggest some ideas regarding the design of a modulator on the basis of an HFR and a piezoelectric slab, and we present experimental results.

***Index Terms*—Angular control of the resonance frequency, crystallographic anisotropy, modulation of millimeter waves, piezoelectric slab, uniaxial monocrystalline hexagonal ferrite resonator.**

I. Introduction

A frequency-selective microwave modulator is a part of a device for microwave frequency and power conversion, such as a ferrite cross-multiplier [1] or a modulator-demodulator system (MDS) [2]. A modulator can consist of a section of a transmission line with a ferrite resonator (FR) placed on a dielectric substrate. The ferromagnetic resonance (FMR) frequency of the FR periodically varies within the limits of the resonance line under the influence of the local modulating radio-frequency (RF) signal. This is called the modulation of the FR resonance frequency. The FR resonance frequency is typically modulated by means of varying the local field of its magnetization (this is the *field control*). A plane spiral microcoil around the FR in its equatorial plane has been used for this purpose [2], [3]. The amplitude of this signal is such that the resonance frequency of the FR changes within the limits of its resonance line. As a result of stable nonlinear resonance effects (SNLRE) in ferrites [3], the envelope of the modulated microwave signal contains harmonics of the modulation frequency. Since the amplitude of each harmonic carries information about the input microwave signal, frequency-selective power conversion can be fulfilled [4].

High-Q resonators made of monocrystalline ferrogarnets, such as YIG or Ca–Bi–V-ferrites, are used for frequency and power conversion over the frequency range from 300 MHz to 30 GHz [1]. The typical width of the ferromagnetic resonance (FMR) line of ferrogarnet monocrystals is 0.5–10 MHz.

However, for millimeter-wave applications (at frequencies above 30 GHz), ferrogarnets typically are not used. To exhibit FMR in the millimeter waveband, high values of magnetization field are required. These values might be unpractical because of the large size and weight of magnetic systems. Application of prospective high-Q monocrystalline hexagonal ferrite resonators (HFR) can extend the frequency range of the devices, using the SNLRE, to the millimeter-waveband without using cumbersome magnets [4]. Hexagonal ferrites $MeO{\cdot}6(Fe_2O_3)$ ($Me = Ba$, Sr, or Pb) have the crystallographic structure of magnetoplumbites. They may contain additional doping ions, such as Mn, Zn, Ti, Sc, Co, Ni, etc., that shift the resonance frequency [5]–[7]. Because of their high internal field of magnetic crystallographic anisotropy, they do not need high fields for magnetization up to saturation, and are tunable over wide frequency ranges by a comparatively low-amplitude electric current. High-Q monocrystalline uniaxial hexagonal ferrites of M-type with fields of anisotropy of about 10–20 kOe seem well suited for applications at frequencies of 30–70 GHz.

The uniaxial monocrystalline HFR can be used for the design of millimeter-wave frequency-selective devices, such as ferrite cross-multipliers and gyromagnetic converters [4]. However, field control of the modulation frequency of the HFR might be not effective. This is because their resonance line is comparatively wide—presently 50–200 MHz [5]. The required amplitude of the modulation signal might be so big that it would cause the damage of the microcoil.

An alternative *angular control* of the HFR resonance frequency was proposed in [8], [9]. The HFR has a high internal crystallographic anisotropy field $\vec{H}_A$ and an equilibrium magnetic moment $\vec{M}_0$, not necessarily oriented along the bias magnetic field $\vec{H}_0$. If it is possible to provide the periodical deviation of the HFR anisotropy axis orientation relative to the bias magnetic field, then the resonance frequency of the HFR will be modulated.

Herein, one of the ways of producing modulation of the HFR resonance frequency by angular control using acoustic oscillations is considered. Section II contains a mathematical model of the uniaxial monocrystalline HFR with angular control of its resonance frequency and predicts the amplitudes of harmonics of this modulated millimeter-wave signal. In Section III, the ideas on the design of a modulator on the basis of HFR and

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a piezoelectric slab having a good acoustic contact are represented. Modulation of the 8-mm-wave signals by means of an M-type doped barium hexagonal ferrite controlled by the piezoelectric $BaTiO_3$ slab is shown experimentally.

II. Mathematical Model

Analysis of the FR magnetization vector behavior is based on the solution of the magnetization vector motion equation [10], which is in the form of a vector nonlinear differential equation with time-dependent coefficients [11], [12]. However, the solution of this equation in an analytical form can be obtained only for the case of modulation at a low frequency and when the crystallographic anisotropy field of the uniaxial HFR is parallel to the external magnetic field $\vec{H}_A || \vec{H}_0$.

A. Quasi-Static Approach Using an HFR Susceptibility Tensor

In practice, the resonance line width of an HFR is much greater than the modulation frequency. Then the quasi-static approach to the problem solution is preferable. This method was used in [13] for ferrogarnets, and is based on representing the magnetic susceptibility tensor components as the Fourier series of the modulation frequency. The nine-component susceptibility tensor for a uniaxial monocrystalline HFR is known [14]. In the initial Cartesian coordinate system (x, y, z), this tensor is related to the direction of the magnetization field $\vec{H}_0$ through

$$\overset{\leftrightarrow}{\chi} = \begin{vmatrix} \chi_{xx} & \chi_{xy} & \chi_{xz} \\ \chi_{yx} & \chi_{yy} & \chi_{yz} \\ \chi_{zx} & \chi_{zy} & \chi_{zz} \end{vmatrix} \tag{1}$$

and its components are

$$\begin{aligned} \chi_{xx} &= \chi_{11} \sin^2 \Phi + \chi_{22} \cos^2(\theta - \theta_0) \cos^2 \Phi; \\ \chi_{yy} &= \chi_{11} \cos^2 \Phi + \chi_{22} \cos^2(\theta - \theta_0) \sin^2 \Phi; \\ \chi_{xy} &= \frac{1}{2} \left(\chi_{22} \cos^2(\theta - \theta_0) - \chi_{11}\right) \sin 2\Phi + j\chi_a \cos(\theta - \theta_0); \\ \chi_{yx} &= \frac{1}{2} \left(\chi_{22} \cos^2(\theta - \theta_0) - \chi_{11}\right) \sin 2\Phi - j\chi_a \cos(\theta - \theta_0) \end{aligned} \tag{2}$$

etc., where

$$\chi_{11} = \frac{\omega_M(\omega_1 + j\omega\alpha)}{\Delta}; \quad \chi_{22} = \frac{\omega_M(\omega_2 + j\omega\alpha)}{\Delta}; \quad \chi_a = \frac{\omega_M \omega}{\Delta} \tag{3}$$

and

$$\Delta = \omega_1 \omega_2 - \omega^2 \left(\alpha_r^2 + 1\right) + j\omega\alpha_r(\omega_1 + \omega_2) \tag{4}$$

with

$$\begin{aligned} \omega_1 &= \omega_0 \cos \theta_M + \omega_A \cos^2 \theta_0; \\ \omega_2 &= \omega_0 \cos \theta_M + \omega_A \cos 2\theta_0. \end{aligned} \tag{5}$$

In (3)–(5), $\omega_0 = \mu_0 \gamma H_0$ is the angular resonance frequency; $\omega_M = \mu_0 \gamma M_0$ is the angular frequency associated with the magnetization of saturation; $\omega_A = \mu_0 \gamma H_A$ is the angular frequency associated with the field of crystallographic anisotropy; $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the permeability of a vacuum; $\gamma = 1.76 \cdot 10^{11}$ C/kg is the gyromagnetic ratio; and $\alpha_r = \omega_r / \omega_{\rm res}$ is the Landau–Lifshitz relaxation parameter, where $\omega_r = \mu_0 \gamma \Delta H / 2$ is the angular relaxation frequency with ΔH as the width of the resonance line of the hexagonal ferrite in terms of the magnetic field (at the level of -3 dB).

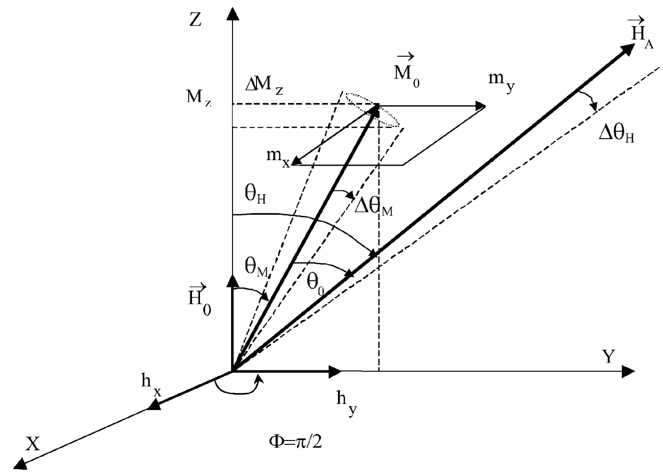

Fig. 1. Orientation of the main vectors.

According to Fig. 1, the angle $\theta = \theta_H$ shows the direction of the crystallographic axis c, or anisotropy field $\vec{H}_A$ with respect to the field $\vec{H}_0$ chosen along the axis z. The angle Φ is counted from the axis x to the direction of the field $\vec{H}_A$. The equilibrium magnetic moment $\vec{M}_0$ belongs to the same plane where the vectors $\vec{H}_0$ and $\vec{H}_A$ lie, but the direction of the vector $\vec{M}_0$ is determined by the angle θ_M, counted from the axis z.

The HFR resonance frequency is found from (4), when $\Delta = 0$ and $\alpha_r = 0$

$$\omega_{\rm res} = \sqrt{\omega_1 \omega_2}. \tag{6}$$

For a hexagonal ferrite, the Landau–Lifshitz relaxation parameter is $\alpha_r \approx \Delta H / (2 H_A \cos \theta_0)$.

For simplicity, it is reasonable to choose the angle $\Phi = \pi/2$, so that the equilibrium magnetic moment $\vec{M}_0$ is in the (yz), as shown in Fig. 1. The susceptibility tensor (1) is then

$$\overset{\leftrightarrow}{\chi} = \begin{vmatrix} \chi_{11} & j\chi_a \cos \theta_M & j\chi_a \sin \theta_M \\ -j\chi_a \cos \theta_M & \chi_{22} \cos^2 \theta_M & \chi_{22} \sin \theta_M \cos \theta_M \\ -j\chi_a \sin \theta_M & -\chi_{22} \cos \theta_M \sin \theta_M & \chi_{22} \sin^2 \theta_M \end{vmatrix}. \tag{7}$$

If the magnetic moment $\vec{M}_0$ is in the (xz) plane, then the angle $\Phi = 0$, and the susceptibility tensor is

$$\overset{\leftrightarrow}{\chi} = \begin{vmatrix} \chi_{11} \cos^2 \theta_M & j\chi_a \cos \theta_M & -\chi_{11} \sin \theta_M \cos \theta_M \\ -j\chi_a \cos \theta_M & \chi_{22} & j\chi_a \sin \theta_M \\ -\chi_{11} \sin \theta_M \cos \theta_M & -j\chi_a \sin \theta_M & \chi_{11} \sin^2 \theta_M \end{vmatrix}. \tag{8}$$

The transverse components of the microwave magnetization after interacting with the FR having a modulated resonance frequency

$$\omega_{\rm res} = \omega_{\rm res0} + \omega_m \cos\Omega t \tag{9}$$

can be represented as oscillations with a slowly varying envelope $G_{x,y}$ and phase $\varphi_{x,y}$

$$m_{x,y} = G_{x,y}\cos(\omega t + \phi_{x,y}) \tag{10}$$

where

$$G_\alpha = \sqrt{|\chi_{\alpha x}|^2 h_{xm}^2 + |\chi_{\alpha y}|^2 h_{ym}^2 + 2h_{xm}h_{ym}(\chi'_{\alpha x}\chi''_{\alpha y} - \chi''_{\alpha x}\chi'_{\alpha y})},\quad (\alpha = x, y) \tag{11}$$

any component of the susceptibility tensor is complex in the general case, $\chi_{\alpha\beta} = \chi'_{\alpha\beta} + j\chi''_{\alpha\beta}(\alpha, \beta = x, y, z)$, and the amplitudes of the microwave (or millimeter-wave) magnetic field are h_{xm} and h_{ym}.

The modulation coefficient of the transmitted wave is found using the *self-matched field method* [15], [16]. The HFR is represented as an elementary magnetic dipole radiating into the waveguide. The radiated field components depend on the HFR magnetization components, and the latter, in turn, depend on the radiated microwave magnetic field. Any component of microwave magnetization in phasor form

$$\tilde{m}_\alpha = \chi^e_{\alpha x}\tilde{h}_x + \chi^e_{\alpha y}\tilde{h}_y, \quad \text{with } \alpha = x, y \tag{12}$$

is represented through an equivalent susceptibility which includes coupling of the HFR with the waveguide according to

$$\chi^e_{\alpha\beta} = \frac{\chi_{\alpha\beta}}{1 + \eta_c} \tag{13}$$

where η_c is the coupling coefficient that depends on the parameters of the HFR, the waveguide geometry, the mode propagating, and the position of the HFR in the waveguide.

Then the envelopes of microwave magnetizations are

$$G_\alpha = \frac{\sqrt{(\chi'_{\alpha x}h_{xm} - \chi''_{\alpha y}h_{ym})^2 + (\chi''_{\alpha x}h_{xm} + \chi'_{\alpha y}h_{ym})^2}}{|1 + \eta_c|} \tag{14}$$

where, for example, for the TE_{10} fundamental mode in a rectangular metal waveguide

$$|1+\eta_c| = \left\{ \begin{array}{c} 1 + \frac{A^2}{4}\left(\chi'_{xx}h_{xm}^2 + \chi'_{yy}h_{ym}^2\right)^2 + \frac{A^2}{4}\left(\chi''_{xx}h_{xm}^2 + \chi''_{yy}h_{ym}^2\right)^2 \\ -A\left(\chi'_{xx}h_{xm}^2 + \chi'_{yy}h_{ym}^2\right)\sin\beta_{10}(x - x_0) \\ -A\left(\chi''_{xx}h_{xm}^2 + \chi''_{yy}h_{ym}^2\right)\cos\beta_{10}(x - x_0) \end{array} \right\}^{1/2} \tag{15}$$

with the coefficient $A = \omega\mu_0 V_f/N$ depending on the ferrite resonator volume V_f and the norm of the wave N. The norm of a waveguide mode is determined through the condition of orthogonality of the full set of modes, and is proportional to the complex power of the mode passing through the waveguide cross section S [17]

$$N = -4P = -2\int_S \tilde{e} \times \tilde{h}^* ds \tag{16}$$

where $\tilde{e}$ and $\tilde{h}$ are the phasors of microwave electric and magnetic fields.

The modulation coefficient of the wave that has passed the HFR is then approximately calculated as in [4]

$$Q \approx \frac{A^2}{2}\left(G_x h_{xm}^2 + G_y h_{ym}^2\right). \tag{17}$$

The spectra of $G_{x,y}$ determine the spectra of the modulation coefficient Q at the chosen harmonic of the modulation frequency. These spectra depend on a number of factors, such as

- the signal power $P(f_0)$;
- the modulation signal parameters, specifically considering that amplitude and frequency of modulation signal have an impact on an HFR resonance frequency deviation and speed of its variation;
- detuning of the HFR resonance frequency from the signal carrier $|\omega - \omega_{\rm res}|$;
- the waveguide or transmission line geometry;
- the external (bias) magnetic field H_0;
- the geometry of the FR through the form demagnetization factors and the volume V_f of the FR;
- the FR magnetization saturation M_s; field of crystallographic anisotropy H_A (or anisotropy constants K_1, K_2); the initial orientation of the crystallographic anisotropy axis relatively to the bias field; geometry of the FR, the FMR line width ΔH in terms of magnetic field (or the corresponding relaxation frequency $\omega_r = \mu_0\gamma\Delta H/2$); and the static susceptibility χ_0.

B. Resonance Frequency and Its Deviation Due to Angular Control

Using the angular control, the angles of orientation vary periodically with time

$$\theta_i = \theta_{i0} + \Delta\theta_i \cos\Omega t, \quad (i = M, H, 0). \tag{18}$$

Since there is a nonlinear relation between the angle of orientation and the resonance frequency, the latter should be represented as the series

$$\omega_{\rm res} = \omega_{\rm res0} + \sum_{k=1}^{\infty}\omega_{mk}\cos k\Omega t. \tag{19}$$

For small deviations $\Delta\theta_{M,0}$, it is possible to consider only the first harmonic, $k = 1$. Then, the central resonance frequency can be written as

$$\omega_{\text{res}0} = \begin{bmatrix} \frac{\omega_0^2}{2}(1+\cos 2\theta_{M0} J_0(2\Delta\theta_M)) \\ +\frac{3\omega_0\omega_A}{4}(\cos(\theta_{M0}+2\theta_{00})J_0(\Delta\theta_M+2\Delta\theta_0) \\ +\cos(\theta_{M0}-2\theta_{00})J_0(\Delta\theta_M-2\Delta\theta_0)) \\ +\frac{\omega_0\omega_A}{2}\cos\theta_{M0}\cdot J_0(\Delta\theta_M)+\frac{\omega_A^2}{2}(1+\cos 4\theta_{00}J_0(4\Delta\theta_0)) \end{bmatrix}^{1/2} \tag{20}$$

and the resonance frequency amplitude of the deviation can be written as

$$\omega_m = -\frac{1}{2\omega_{\text{res}0}} \cdot \begin{bmatrix} \omega_0^2 J_1(2\Delta\theta_M)\sin 2\theta_{M0} \\ +\frac{3}{4}\omega_0\omega_A \begin{pmatrix} \sin(\theta_{M0}+2\theta_{00})J_1(\Delta\theta_M+2\Delta\theta_0) \\ +\sin(\theta_{M0}-2\theta_{00})J_1(\Delta\theta_M-2\Delta\theta_0) \end{pmatrix} \\ +\frac{1}{2}\omega_0\omega_A\sin\theta_{M0}J_1(\Delta\theta_M)+\frac{1}{2}\omega_A^2\sin\theta_{M0}J_1(\Delta\theta_M) \end{bmatrix}. \tag{21}$$

For small arguments of the Bessel functions, the latter can be approximated as $J_0(\Delta\theta) \approx \cos\Delta\theta$ and $J_1(\Delta\theta) \approx 0.5\sin\Delta\theta$, and then (20) and (21) simplify.

C. Determining the Optimal Angle of the HFR Orientation to Reach the Maximum Deviation of Resonance Frequency

Since the amplitudes of the harmonics of the susceptibility tensor depend on the initial orientation angle of the ferrite, i.e., the angle between the HFR crystallographic axis and the external magnetic field, it is important to determine the optimal angle of orientation, when these amplitudes are maximum. For angular control of the resonance frequency, this occurs when the maximum deviation of the resonance frequency $\Delta\omega_{\text{res}}$ is reached for a given angle deviation $\Delta\theta_H$. The limitation is that the deviation of the resonance frequency should be smaller than the HFR resonance line in terms of angular frequencies $\Delta\omega_{\text{res}} \le 2\delta$, where $\delta = \omega_r(1 + (\chi_0)/(3\mu_0))$ for a spherical FR (in the case of an arbitrary spheroid, instead of the coefficient $1/3$, the transverse demagnetization form factor N_t should be used); however, typically the second term is small, so $\delta \approx \omega_r = \mu_0\gamma\Delta H/2$. The resonance frequency is determined by (5) and (6), where only the first constant of anisotropy K_1 is taken into account, so that the crystallographic anisotropy field is $H_A = (2K_1)/(\mu_0 M_S)$ (in SI units), or $H_A(\text{kOe}) = (2K_1(\text{erg/cm}^3))/(4\pi M_S(G))$ (in Gauss system) [5], [15].

Since the frequency of modulation in a quasi-static case is essentially lower than that of the relaxation, the relative orientation of the main vectors can be assumed as in the static case. At any instant of time the angles are related as

$$\sin\theta_M = \frac{H_A}{2H_0}\sin 2\theta_0 \tag{22}$$

and

$$\theta_H = \theta_M + \theta_0. \tag{23}$$

Finding the solution of (22) with respect to θ_0(θ_H is taken as a parameter) and substituting into (5)–(6) allows for calculating the dependences of the HFR resonance frequency on the bias magnetic field at different angles of orientation for the HFR.

To find the optimum angle of the HFR orientation for reaching the maximum deviation of resonance frequency, let us introduce the parameter S, which is the slope of variation of resonance frequency versus angle of orientation θ_H

$$S = \Delta\omega_{\text{res}}/\Delta\theta_H. \tag{24}$$

It can be also expressed as

$$S = \partial\omega_{\text{res}}/\partial\theta_0 \cdot d\theta_0/d\theta_H \tag{25}$$

where the derivative $\partial\omega_{\text{res}}/\partial\theta_0$ can be directly calculated from (6)–(7) as

$$\partial\omega_{\text{res}}/\partial\theta_0 = \frac{\omega_1(\omega_0\sin(\theta_H-\theta_0)-2\omega_A\sin 2\theta_0)}{2\sqrt{\omega_1\omega_2}} + \frac{\omega_2(\omega_0\sin(\theta_H-\theta_0)-\omega_A\sin 2\theta_0)}{2\sqrt{\omega_1\omega_2}} \tag{26}$$

and the derivative $d\theta_0/d\theta_H$ is calculated from (22)–(23)

$$\frac{d\theta_0}{d\theta_H} = \frac{\cos(\theta_H-\theta_0)}{\cos(\theta_H-\theta_0)+H_A/H_0\cos 2\theta_0}. \tag{27}$$

The optimal angle of orientation depends on the HFR anisotropy field and the external field of magnetization. However, the formulas above include only the first anisotropy constant of the magnetouniaxial ferrite. As was shown in [18], the influence of the second constant of anisotropy of a magnetouniaxial HFR on the FMR can be also substantial, especially, at large angles of orientation θ_H. In this case, the formulas above should be corrected, so that the field H_A is replaced everywhere with $H_{A1} = H_A(1 + K_2\sin^2\theta_H)$. Then, taking into account the second anisotropy constant K_2, the angles are related as

$$\sin 2\theta_0 \cdot \left(1 + K_2\sin^2\theta_H\right) = \frac{2H_0}{H_A}\sin(\theta_H-\theta_0). \tag{28}$$

The corresponding substitutions should be done to find the corrected slope S. The maximum slope in the dependence $S(\theta_H)$ gives the optimal orientation, where the deviation of resonance frequency is maximum for a fixed deviation of the angle $\Delta\theta_H$.

The calculated dependence of the slope of the resonance frequency variation $df_{\text{res}}/d\theta_H$ versus θ_H for the HFR with an anisotropy field of $H_A = 11.3$ kOe ($K_1 = 1.9\cdot 10^6$ erg/cm^3); $4\pi M_S = 4.3$ kG, and $K_2 = 0.5\cdot 10^6$ erg/cm^3 at various values of the bias field H_0 is shown in Fig. 2. The optimal angle $\theta_{H\text{opt}}$ is different for ferrites with different H_A and K_2, as seen from Fig. 3. Moreover, the angle $\theta_{H\text{opt}}$ depends on the magnetization field H_0, which determines the resonance frequency. As is shown in [4, Fig. 2], almost 100% modulation depth can be achieved for the optimal angle of orientation and parameters

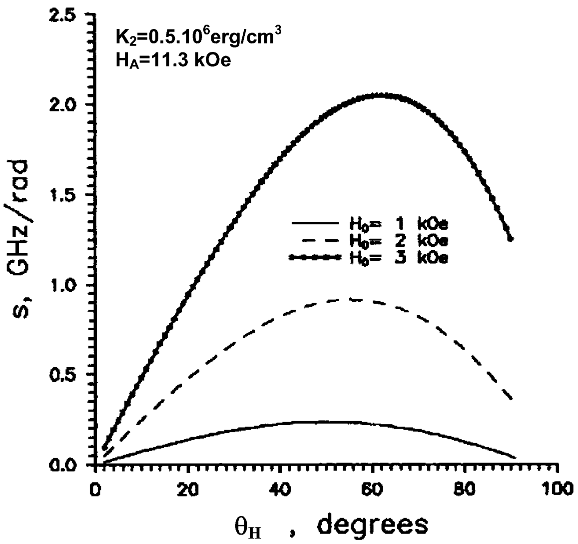

Fig. 2. Dependence of speed of resonance frequency variation upon angle of HFR orientation.

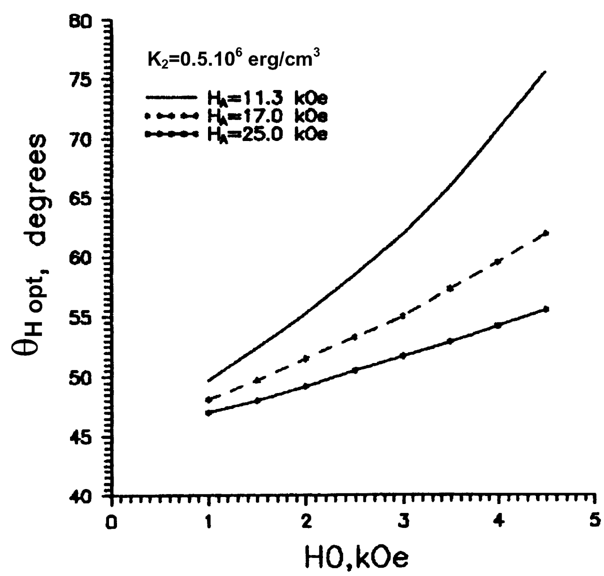

Fig. 3. Optimal angle of the HFR orientation versus field of magnetization.

of the modulating signal. The possibility of modulating millimeter-wave signals using a piezoelectric slab in contact with the HFR for acoustic control of its resonance frequency is considered next.

III. Experiments

Angular control of an HFR resonance frequency can be achieved by mechanically varying the angle between the axis of crystallographic magnetic anisotropy and the direction of the external magnetic field. The possibility of using acoustic oscillations for this purpose is studied herein experimentally. Experiments were conducted in the 8-mm waveband using a spherical HFR, placed in a section of a standard metal rectangular waveguide of 7.2×3.4 mm cross section, with only the main mode TE_{10} propagating. The experimental setup is shown schematically in Fig. 4. The geometry of a waveguide section

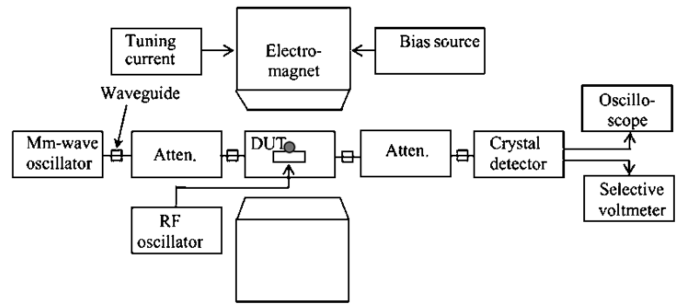

Fig. 4. Experimental setup.

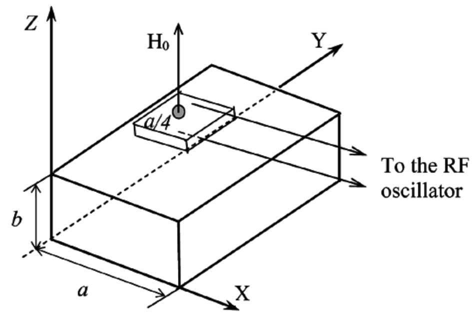

Fig. 5. Waveguide with HFR and piezoceramic slab inside.

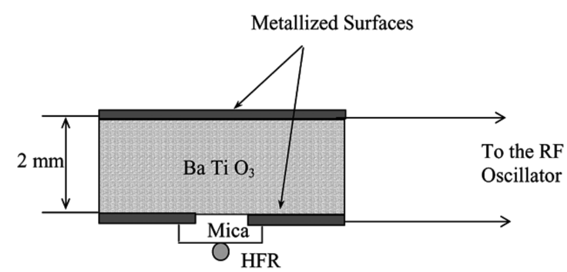

Fig. 6. Piezoceramic-HFR structure.

with an HFR and a piezoelectric element made of $BaTiO_3$ are shown in Figs. 5 and 6.

A rectangular 2-mm-thick piezoelectric slab (PES) with metallization on the two 25 mm^2 surfaces was placed in an aperture in the wide wall of the waveguide. The metallization of the slab closed the aperture in the waveguide. In the metallized surface of the PES looking into the waveguide, there was a small window with a diameter close to that of the HFR. The HFR was glued directly on the piezoceramic or on the mica layer 0.05 mm thick. Acoustic resonances for this PES were observed at 0.26 and 1.46 MHz, as well as at a number of higher frequencies. However, maximum peak was at 1.46 MHz. The width of the acoustic resonance line was 80 kHz.

HFR was a spheroid $0.585 \times$ 0.557 mm of a monocrystal of M-type barium ferrite doped with Ti and Zn ions ($BaFe_{9.8}Ti_{1.1}Zn_{1.1}0_{19}$) [7]. Its parameters were $H_A = 11.3$ kOe, $4\pi M_S = 3.1$ kG, and its FMR line width $\Delta H = 31.1$ Oe. The insertion loss in the waveguide section with the HFR-PES structure in the 8-mm waveband was less than 1 dB, and the voltage standing-wave ratio was $K_{\rm SWR} < 1.2$. The HFR-PES structure absorbed about 5 dB when tuning in the frequency range 35–41 GHz. Experiments have shown the possibility of modulating the millimeter-waveband signal using HFR and a

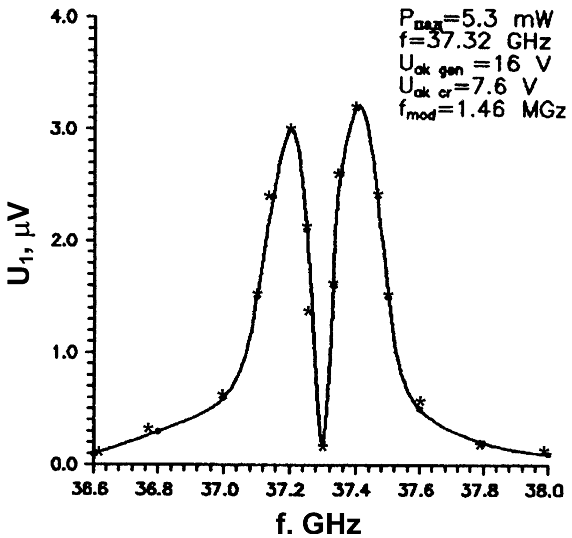

Fig. 7. The first harmonic of modulation.

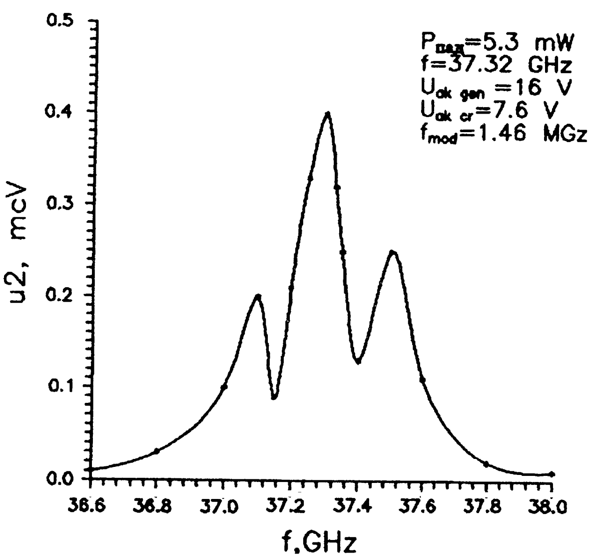

Fig. 8. The second harmonic of modulation.

piezoelectric slab. The maximum modulation was observed at the steepest slope of the PES acoustic resonance curve. The measured amplitudes of the first and the second harmonics of the modulation frequency versus detuning in the vicinity of the FMR frequency are shown in Figs. 7 and 8. The second harmonic was consistently noticeable at the frequency-selective receiver-microvoltmeter (the bandwidth was 0.3 kHz and the sensitivity was 0.01 μV).

The modulation is explained by both dilatation and shear modes of the PES affecting the angle of the HFR orientation due to the local bending of the PES medium. The deviation of the angle of orientation of equilibrium magnetization moment can be expressed through the variation of the magnetic moment as

$$\cos\Delta\theta_M \approx \sqrt{1-\frac{2\Delta M}{M_0}\cos\theta_M}. \qquad (29)$$

If the HFR with the field of anisotropy $H_A = 11.3$ kOe and $4\pi M_S = 4.3$ kG has the angle of orientation $\theta_H = 45°; \theta_0 = 7°; \theta_M = 38°; \theta_M \ll 1, \Delta\theta_M = 10^{-3}$, the estimated magnetization moment variation is $4\pi\Delta M = 2.73$ G. This value agrees with that estimated $4\pi\Delta M = 3$ G according to [4] for the HFR with $\Delta H = 30$ Oe at an input of microwave power of $P = 5.3$ mW; where the modulating signal had a frequency of $f_{\rm mod} = \Omega/2\pi = 1.5$ MHz, the relative frequency of modulation was $p = (\Omega)/(\delta) = 0.035$. The deviation of the resonance frequency was $\Delta f_{\rm res} = S\cdot\Delta\theta_H = 1.15$ MHz, and the normalized amplitude of modulation was $q = (\Delta f_{\rm res})/(f_{\rm mod}) = (\delta)/(\Omega) = (1)/(p) = 0.77$.

The PES made of $BaTiO_3$ has $\varepsilon_r = 2000$ at $f = 1.5$ MHz with the piezoelectric coefficient $d_{33} = 150\cdot 10^{-12}$ m/V to produce the converse piezoelectricity effect. At the amplitude of voltage applied to the crystal $V = 7.6$ V, the amplitude of mechanical oscillations is $\Delta x = V\cdot d_{33} = 1.14$ nm. The greater is the amplitude of mechanical oscillations, the greater the deviation of the angle of orientation $\Delta\theta_M = k\cdot\Delta x$, where k is an empirical bend coefficient on the order of 10^6 radians/m depending on the elasticity of the PES and its tie with the HRF. This is consistent with the deviation of the angle θ_M on the order of $\Delta\theta_M = 10^{-3}$ radians, and variations in the magnetic moment $4\pi\Delta M$ are of the order of units of gauss. To increase $\Delta\theta_M$ at least 10–30 times, the material with the greater piezoelectric coefficient is needed, e.g., lead zirconate titanate (PZT). If possible, higher voltage should be applied to the crystal, and the better acoustic contact should be provided. It should be mentioned that the inverse magnetoelastic effect in the HFR at the amplitudes of mechanical oscillations of units of nanometers is negligible.

The calculated dependence of the first harmonic amplitude versus the magnetization field H_0 for different angles θ_H is shown in Fig. 9, and the first and second harmonics versus relative detuning $a = (\omega - \omega_{\rm res})/\delta$ at different angles of orientation θ_H are given in Figs. 10 and 11. The calculated amplitudes of the first and second harmonics of the modulation frequency are somewhat greater than those obtained in the experiment. The discrepancy might come from neglecting the effect of the mica layer between the PES and the HFR; overestimating the acoustic contact in the HFR-PES system; neglecting loss in the waveguide; and a lack of accuracy in adjusting the HFR initial angle of orientation, measurements and data used in the model. Also, the resonance frequency in experiment (37.32 GHz) was shifted from that in the computations (37.9 GHz).

Another structure for modulating millimeter-wave signals is shown in Fig. 12. A pure quartz glass capsule serving as a conductor of acoustic waves was glued to the PES. The HFR was placed inside the capsule.

There were two options. First, the HFR was oriented in the external magnetic field and fixed firmly. Second, the HFR could freely orient itself inside the capsule. The capsule was placed in the middle of the wide wall of the rectangular waveguide, where the loss was minimum (about 1 dB), and $K_{\rm SWR} < 1.2$. The HFR was placed at a point of linear polarization of the magnetic field of the TE_{10} waveguide mode. Measurements were conducted at the frequency of 37.9 GHz.

The influence of the glass capsule and the effect of fixing the HFR on the characteristics of FMR were studied. Experiments show that the quartz capsule concentrates the electromagnetic

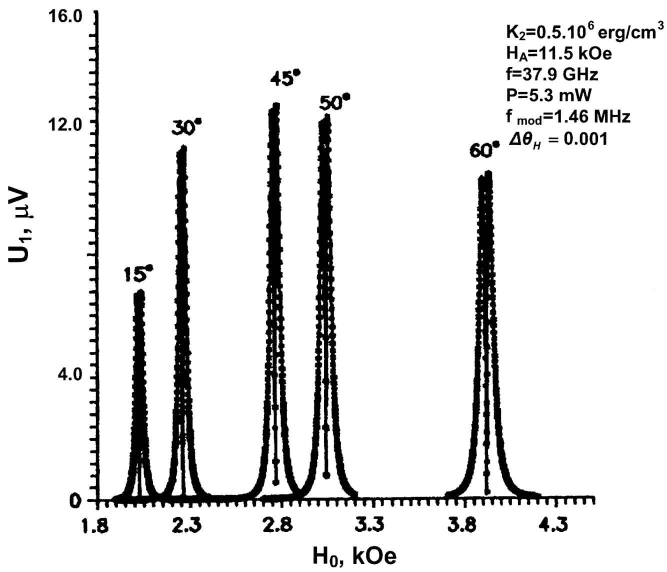

Fig. 9. The calculated first harmonic of modulation frequency at different angles of orientation of ferrite θ_H.

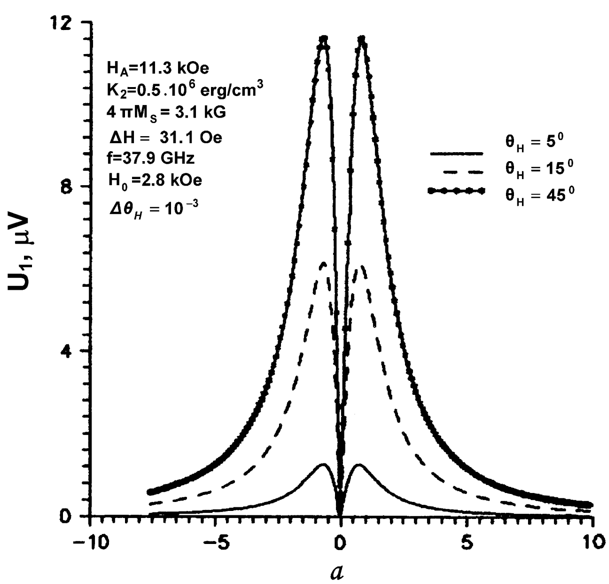

Fig. 10. The first harmonic of modulation versus the relative detuning from resonance at different angles of orientation.

field, changes eccentricity, and shifts its magnetic field polarization because of its high dielectric constant $\varepsilon_r = 10$. This causes an increase of the coupling between the HFR and the waveguide, and the absorption at the FMR increases. Nonreciprocal electromagnetic wave absorption is observed, though the HFR is placed in the center of the wide waveguide wall, where the microwave magnetic field would have been linearly polarized. The loaded width of the resonance line of a free HFR is smaller than that of the glued HFR, and this is explained by the influence of the glue. This leads to a better absorption of electromagnetic energy by a free HFR than by an HFR fixed with glue. The resonance frequency and absorption of the fixed HFR depend on the orientation much greater, when the HFR is placed into the capsule than without it.

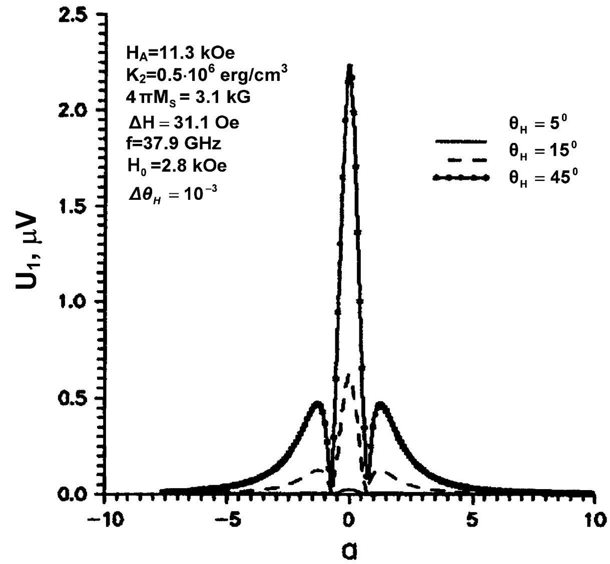

Fig. 11. The second harmonic of modulation versus the relative detuning from resonance at different angles of orientation.

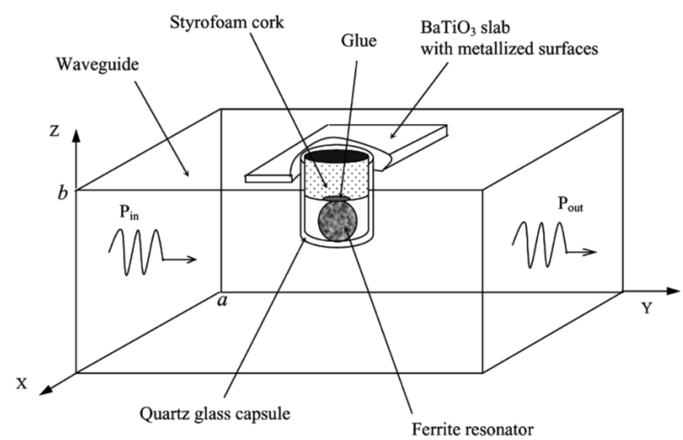

Fig. 12. Structure HFR-PES with a quartz capsule in the waveguide.

The calculated optimum angles of the HFR orientation for obtaining the maximum modulation depth are close to 45° (at the corresponding bias field for FMR), and the experimental value is also close to 45° for the similar HFR. Measurements were conducted using a frequency-selective receiver. Fig. 13 shows the dependence of the amplitude of the first harmonic of the modulation versus detuning from the resonance magnetic field at a frequency of 37.9 GHz of the millimeter-wave signal. The HFR is in acoustic contact with the piezoceramic slab either through the quartz capsule, or without. At the HFR 15° angle of orientation, the amplitude of the harmonic is approximately two times smaller than the amplitude of the harmonic for an angle of 45°.

The maximum modulation depth is essentially greater, when a quartz capsule is present. This is explained by the fact that the coupling of the HFR with the waveguide when the capsule is present becomes more critical to the small shift of the HFR position caused by the acoustic oscillations.

Modulation by a free HFR placed into a capsule is not observed. This is because the acoustic signal frequency is much lower than the relaxation frequency of the HFR. The equilibrium magnetization has enough time to become oriented along

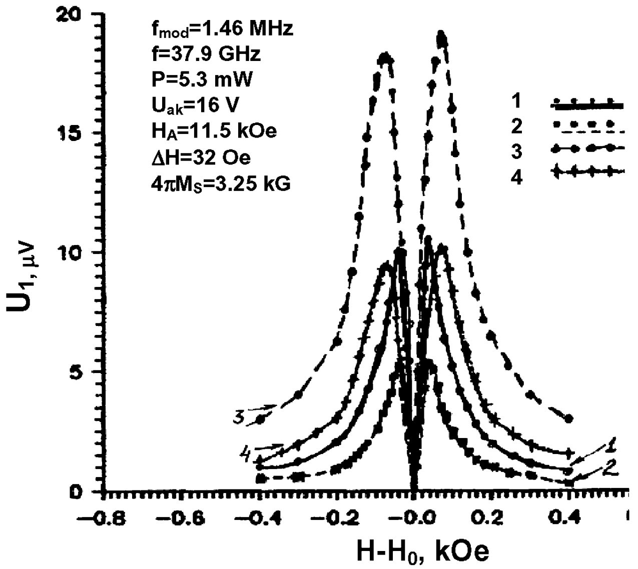

Fig. 13. The first harmonic of modulation frequency at different angles of orientation of ferrite. 1: $\theta_H = 45^\circ$ without capsule; 2: $\theta_H = 15^\circ$ without capsule; 3: $\theta_H = 45^\circ$ with capsule; 4: $\theta_H = 15^\circ$ with capsule.

the external magnetization field, so that the angle between this field and the crystallographic anisotropy axis in a free HFR is always zero. Some slight modulation can be observed only because the HFR position shifts, and coupling with the waveguide changes with the acoustic oscillations. Placing viscous media (petroleum or lube) in the capsule increases the acoustic loss and decreases the effect of modulation. Putting water or alcohol inside the capsule leads to the increase of electromagnetic loss, because molecules of alcohol and water absorb millimeter waves.

Thus, for designing of this kind of a modulator, optimum coupling between the HFR and PES, as well as between the HFR and the waveguide is desirable. The latter coupling can be increased by placing the HFR with fixed optimum orientation into a quartz glass capsule without admitting any moisture, liquid, or viscous media inside the capsule. The HFR's easy crystallographic axis should be oriented at such an angle with respect to the bias field that at the given deviation of the angle, the maximum modulation depth is achieved. This can be done by firmly fixing the HFR in the sound-conducting capsule.

IV. Conclusion

The possibility of an angular acoustic control of the resonance frequency of a hexagonal ferrite resonator and a corresponding modulation of millimeter-wave signals is demonstrated.

The quasi-static model of the uniaxial HFR with angular control of its resonance frequency is considered. It allows for analyzing the magnetization vector components in the vicinity of FMR at comparatively low frequencies of modulation.

Harmonics of modulation frequency in the magnetization vector components and in modulated millimeter-wave signals are shown to be proportional to the intensity of the input signal, and they also depend on physical parameters of the ferrite, its angle of orientation, the waveguide geometry, as well as on the parameters of the modulating signal. The formulas for finding an optimal angle of orientation and the parameters of the modulation yielding the maximum modulation depth of the millimeter-wave signal have been obtained, and the results of calculations are represented. The calculated optimal angles of the HFR orientation agree with the experimentally obtained results.

Practical realization of a modulator on the basis of an HFR and a piezoelectric slab (PES) has been proposed.

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References

[1] V. F. Balakov, V. A. Kartsev, A. A. Kitaitsev, and N. I. Savchenko, "Application of gyromagnetic effects in ferrite monocrystals for electromagnetic signals parameters measurement" (in Russian), in *Proc. 5th Int. Conf. Microwave Ferrites*, vol. 3, Moscow, Russia, 1980, pp. 86–99.

[2] M. Y. Koledintseva and A. A. Kitaytsev, "Millimeter wave hexagonal ferrite power converter with automodulation for frequency-selective tolerance control and measurement," in *Proc. 13th Int. Wroclaw Symp. Electromagnetic Compatibility*, Poland, Jun. 25–28, 1996, pp. 372–374.

[3] A. A. Kitaytsev and M. Y. Koledintseva, "Physical and technical bases of using ferromagnetic resonance in hexagonal ferrites for electromagnetic compatibility problems," *IEEE Trans. Electromagn. Compat.*, vol. 41, no. 1, pp. 15–21, Feb. 1999.

[4] M. Koledintseva, A. Kitaitsev, V. Konkin, and V. Radchenko, "Spectrum visualization and measurement of power parameters of microwave wide-band noise," *IEEE Trans. Instrum. Meas.*, vol. 53, no. 4, pp. 1119–1124, Aug. 2004.

[5] R. C. O'Handley, *Modern Magnetic Materials. Principles and Applications*. New York: Wiley, 2000, pp. 485–491.

[6] L. L. Eremtsova, V. P. Cheparin, S. V. Serebryannikov, A. A. Kitaitsev, and A. A. Shinkov, "Doped hexagonal ferrites of M- and W-types" (in Russian), in *Proc. 12 Int. Conf. Spin Electronics and Gyrovector Electrodynamics*. Moscow, Russia, Dec. 19–21, 2003, pp. 424–430.

[7] S. A. Medvedev, B. P. Pollak, V. P. Cheparin, Y. A. Sveshnikov, and A. E. Hanamirov, "Development, investigation, and application of monocrystals of hexaferrites—novel microwave materials" (in Russian), in *Reports of Scientific Conf. Radio Engineering, Microwave Ferrite Radio Physics*. Moscow, Russia, 1969, pp. 80–89.

[8] M. Y. Koledintseva, "Modulation of microwave field by means of the acoustically controlled hexagonal ferrite resonator," in *Proc. 15th Int. Symp. Electromagnetic Theory EMT'95*, St. Petersburg, Russia, May 23–25, 1995, pp. 735–740.

[9] A. A. Kitaytsev and M. Y. Koledintseva, "Quasistatic approach to the analysis of magnetization vector behavior of monocrystal hexagonal ferrite with controlled resonance frequency," in *Proc. 13th Int. Conf. Microwave Ferrites ICMF'96*, Busteni, Romania, Sep. 23–27, 1996, pp. 33–41.

[10] L. D. Landau, E. M. Lifshitz, and L. P. Pitaevskii, *Electrodynamics of Continuous Media*, 2nd ed. Oxford, U.K.: Pergamon, 1984.

[11] A. A. Kitaistev and N. I. Savchenko, "Influence of the external magnetic field variation velocity on the oscillation of the longitudinal component of the ferrite magnetization at the FMR" (in Russian), in *Proc. Conf. Electronic Engineering*. Moscow, Russia, Apr. 1970, pp. 77–79.

[12] A. A. Kitaitsev, "Oscillation of magnetization when microwave signal and noise act on the magnetic detector" (in Russian), in *Rep. Scientific Conf. Radio Engineering, Microwave Ferrite Radio Physics*. Moscow, Russia, 1969, pp. 36–39.

[13] V. F. Balakov, "Oscillations of the ferrite magnetization at the bias magnetic field variation" (in Russian), *Voprosy Radioelektroniki (Problems of Radio Electronics, Radio Measurements)*, vol. 4, 1966.

[14] B. P. Pollak and A. E. Hanamirov, "Characteristic features of ferromagnetic resonance in monocrystalline hexagonal ferrites" (in Russian), in *Reports of Scientific Conf. Radio Engineering, Microwave Ferrite Radio Physics)*. Moscow, Russia, 1969, pp. 90–100.

[15] A. G. Gurevich and G. A. Melkov, *Magnetic Oscillations and Waves* (in Russian). Moscow, Russia: Fizmatlit, 1994.

[16] A. G. Gurevich, "Ferrite ellipsoid in a waveguide" (in Russian), *Radiotehnika i elektronika (Radio Engineering and Electronics)*, vol. 8, no. 5, pp. 780–790, 1963.
[17] L. A. Vainshtein, *Electromagnetic Waves* (in Russian). Moscow, Russia: Radio i Svyaz, 1988.
[18] L. K. Mikhailovsky, B. P. Pollak, and O. A. Sokolov, "On the question about ferromagnetic resonance in a uniaxial single-domain particle" (in Russian), *Fizika metallov i metallovedenie (Physics of Metals and Metallography)*, vol. 21, no. 4, pp. 524–528, 1966.

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