SHF RESONATORS ON THE BASIS OF UNIAXIAL HEXAFERRITES WITH DOMAIN STRUCTURE

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We have confirmed experimentally the possibility to use the plates of uniaxial hexaferrites with domain structure (DS) as a resonant element for functional units of SHF electronics. It is shown that the Q-factor of such structures with active element made of barium hexaferrite does not differ in the domain region from that of a resonant element which operates under saturation. We give two versions of the structures of such resonators.

1. Introduction

Ferrite resonators are quite widely used in the tuned filters and the unreciprocal units of devices operating in the SHF range. The simplicity, reliability, possibility to tune the frequency in significant limits, and possibility to use plane structures promote the searches for and the development of new structures [1–3] and the technologies of production of new ferrite materials with improved characteristics [4]. Ferrite materials on the basis of single crystals of iron-yttrium garnet (IYG) in both the bulk [1] and film realizations [5, 6] become integral parts of many radiotechnical devices in the centimeter wavelength range.

The significant expansion of technical means in the millimeter and submillimeter wavelength ranges stimulated the development and the application of resonators on single crystals of hexaferrites [7] which can operate at frequencies up to 120 GHz due to the presence of intense fields of anisotropy [7, 8].

However, all the mentioned structures require to use cumbersome magnetic systems of magnetizing [2], because their resonance systems work in the region of saturation. This fact is a serious obstacle on the way of solving the technological and technical problems [7] and restricts significantly the possibility to miniturize such devices.

The essential step forward, which would allow one to remove these drawbacks, consists in the use of magnetostatic resonances in single crystals of hexaferrites with DS. This creates the perspective for both a significant miniaturization of SHF devices and the application of ferrite resonators in the integrated circuits of functional electronics in the millimeter range [9–11].

2. Magnetostatic Oscillations in Uniaxial Hexaferrites with DS

It is known [12] that, in the state of residual magnetization in uniaxial crystals of hexaferrites in the absence of a magnetizing field, a DS of the certain type can be realized: a plane-parallel domain structure (PPDS) or a lattice of cylindrical magnetic domains (CMD) [13–16]. Each of the mentioned types of DS is characterized by several clearly pronounced resonances in the corresponding frequency region [15–17]. For a given thickness of a ferrite layer t in the case of PPDS, the formula for the low-frequency branch of the frequency-field dependence of FMR on the normal magnetizing takes the form [17]

$$\omega_1^2 = \frac{\gamma^2}{2}\left(A^2 + B^2 + BD + AC - \left[(A^2 + B^2 + BD + AC)^2 - 4\left(A^2 - B^2\right)(AC - BD)\right]^{\frac{1}{2}}\right), \quad (1)$$

where γ is the gyromagnetic ratio; A, B, C, D are coefficients depending on the field of a crystallographic anisotropy H_a, magnetization M, the external magnetizing field H_0, and t.

In the case of a saturated specimen, the resonant frequency

$$\omega_0 = \gamma(H_a + H_0 - 4\pi M). \quad (2)$$

For the CMD structure, the calculation of the frequency-field spectrum of FMR was carried out like that in [15]:

$$\omega_1 = \omega_a, \quad (3)$$

$$\omega_2 = \frac{\omega_m}{2}\left\{\left[\left(1 - \frac{S_m}{Q_m}\eta^m\right)^2 + \right.\right.$$

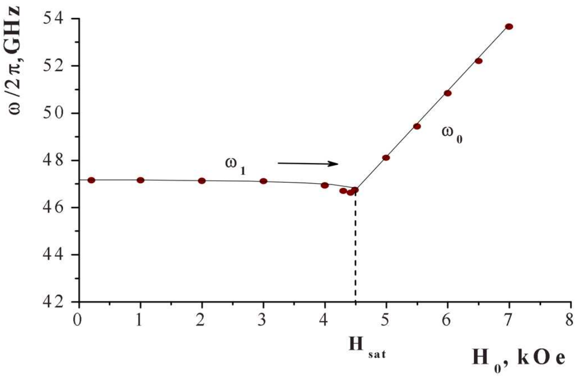


Fig. 1. Frequency-field dependence of FMR for a monocrystalline plate of barium hexaferrite $BaFe_{12}O_{19}$ with PPDS. $t = 48$ μm, $a \times b = 2.5 \times 1.9$ mm^2, $H_a = 16.91$ kOe, $M = 0.375$ kGs, and $H_{\rm sat}$ – the saturating field. Solid lines – the result of calculations by formulas (1) and (2), filled circles are the experimental data

$$+\frac{4\omega_a^2}{\omega_m^2}+\frac{4\omega_a}{\omega_m}\Bigg]^{1/2}-1+\frac{S_m}{Q_m}\eta^m\Bigg\}, \tag{4}$$

where $\omega_a = \gamma H_a$, $\omega_m = \gamma 4\pi M$, and S_m, Q_m, and η_m are the quantities depending on the mode number m.

The field dependences of resonant frequencies calculated by formulas (3) and (4) for a CMD structure are shown in Fig. 2 for the basic mode ($m = 1$).

3. Absorption Spectra

The executed experimental studies showed that the shape, intensity, and width of the FMR line of absorption peaks at $H_o = 0$ and on saturation practically coincide [18]. But this result is only related to regularized domain structures. We note that a lot of works are devoted to the creation of domain structures of certain types by means of the preliminary action of the external saturating magnetic field on a plate or a film of an uniaxial crystal [1–21]. However, the visualization of a DS [21] demonstrated that the domain lattice is irregular in the initial state and is characterized by a number of defects. On the creation of regularized domain structures in the bulk single crystals of hexaferrites, most optimum are the angles $\varphi = 2°30'$ for a CMD lattice and $\varphi = 17°$ for PPDS [12]. We showed experimentally in [22] that, for epitaxial films in the interval of angles between the external saturating field and the plane of a film, where CMD or PPDS is generated, the angles $\varphi = 2°20'$ or $\varphi = 15°$ are, respectively, optimum. At these angles, these structures are most regular, and the absorption peaks are most intense and narrow.

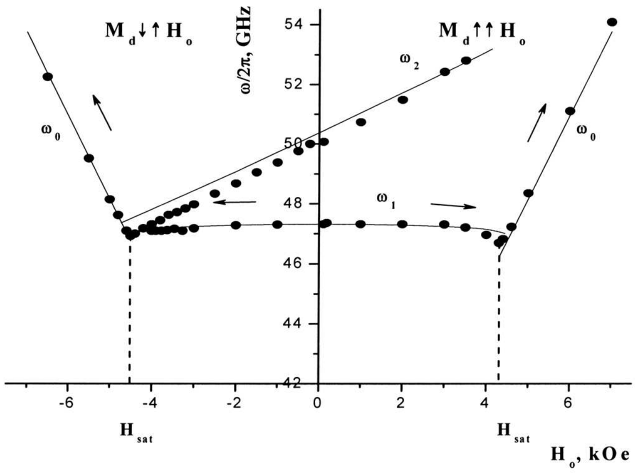


Fig. 2. Frequency-field dependence of FMR in a monocrystalline plate of barium hexaferrite with the CMD structure. M_d – magnetization in a domain, $t = 51$ μm, $a \times b = 2.4 \times 1.8$ mm^2, $H_a = 16.91$ kOe. Solid lines – the result of calculations by formulas (3) and (4), filled circles are the experimental data

We calculated the magnetic permeability for an uniaxial plate of hexaferrite in the case of normal magnetization by the formulas [18]

$$\chi''_{lf} = \frac{2\gamma^2\omega\omega_r\left(H_a+\pi M\right)MH_a}{\left[\left(\omega^2-\gamma^2H_a^2\right)^2+4\omega^2\omega_r^2\right]\left(2H_a+\pi M\right)},$$

$$\chi''_{hf} = \frac{2\gamma^2\omega\omega_r M\left(H_a+\pi M\right)^2}{\left[\left(\omega^2-\gamma^2\left(H_a+\pi M\right)^2\right)^2+4\omega^2\omega_r^2\right]\left(2H_a+\pi M\right)}, \tag{5}$$

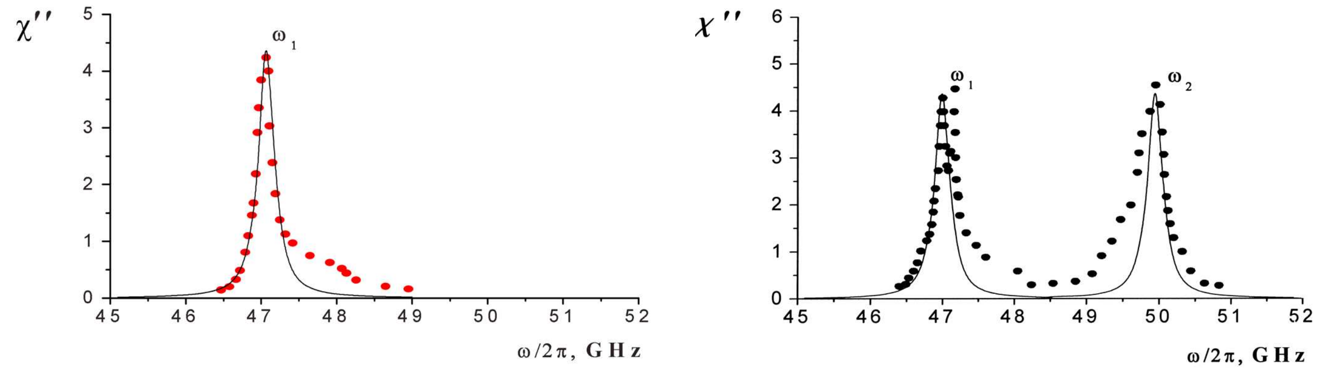
where ω_r is the half-width of the absorption line of FMR of a specimen of barium hexaferrite.

In experiments [18, 22], one measured the "scalar" susceptibility defined as

$$\chi'' = \frac{\lambda_g K S_w}{8\pi^2 t S_f}, \tag{6}$$

where λ_g is the wavelength in the waveguide, S_w is the cross-section area of the waveguide, S_f is the area of ferrite, and K is the traveling wave factor.

The resonance curves were measured for various types of a DS (labyrinthine, cylindrical, and plane-parallel ones) on a monocrystalline volumetric plate of the rectangular form with $t = 48$ μm. In Fig. 3, we present the dependences of the absorption intensities on the resonant frequency $\omega/2\pi$ at $H_0 = 0$ for specimens with an induced PPDS (a) and a CMD structure (b), respectively. In Fig. 4, we show the absorption spectra in the case of a labyrinthine DS and under the saturation.



a **b**

Fig. 3. Absorption lines of FMR for a PPDS ($\varphi = 17°$) (a) and a CMD structure $\varphi = 2°30'$ (b), $H_0 = 0$. Solid lines – result of calculations by (5), filled circles are the experimental data

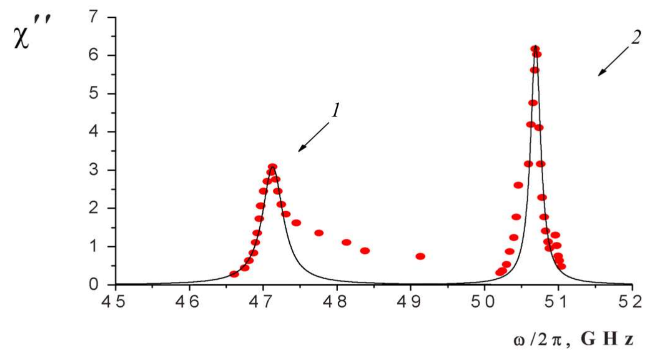


Fig. 4. Absorption lines of FMR with a labyrinthine DS ($H_0 = 0$) (*1*) and under the saturation, $H_0 = 6$ kOe (*2*). Solid lines – result of calculations by (5), filled circles are the experimental data

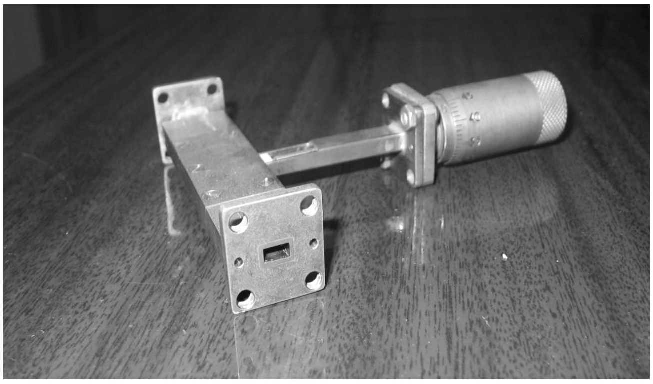


Fig. 5. Model of an SHF resonator with PPDS or a CMD lattice

As is seen from the given plots, the form of resonance curves and the absorption spectra in the domain region do not differ practically from the spectra in the region of saturation. This allows one to construct SHF devices with resonating elements operating in the field-free mode or in fields $H_0 < H_{\mathrm{sat}}$.

4. Models of Devices

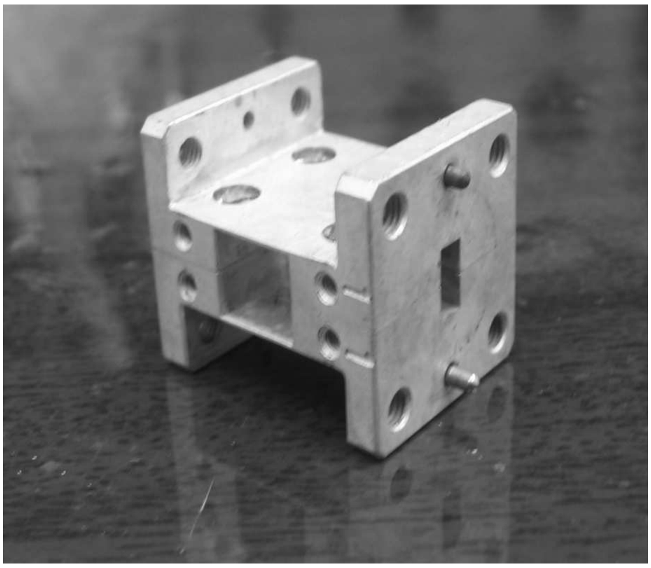
4.1. SHF resonator on the base of a waveguide

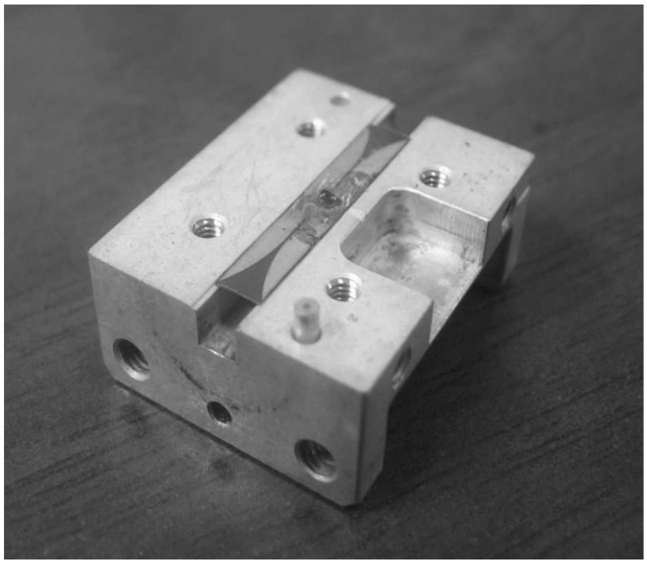
In a monocrystalline plate or an epitaxial film of barium hexaferrite with a regular PPDS or a CMD lattice created there, one can register the clearly manifested resonances at frequencies ω_1 and ω_2 with the line width comparable with that of a similar line in the region of saturation. If one uses an epitaxial film, the absorption increases sharply (almost by one order) because the support plays the role of a concentrator of the SHF field ($\varepsilon \geq 10$). For this reason, the intensity of the resonance interaction of the SHF field in an epitaxial film of hexaferrite of 5–7 μm in thickness is the same as that in a monocrystalline plate of hexaferrite of 30–40 μm [23] in thickness. The enhancement of the resonance interaction in epitaxial films that was established by us allowed us to use ferrite films of 5–10 μm in thickness with the created DS of a certain type close to the ideal one and, thus, to avoid a wedge-like surface DS. As a result, the Q-factor of a resonator was essentially increased. The operating model of such a device is given in Fig. 5.

The characteristic Q-factor of such resonators is mainly defined by magnetic losses in ferrite and was calculated by the formula [5]

$$Q = \frac{f_0}{\Delta f} = \frac{H_0}{\Delta H}. \tag{7}$$

Under specific conditions of the operation of a device, one needs a certain coupling of the SHF resonator with





a b

Fig. 6. Resonator on SSL: *a* – general view, *b* – slit line with a specimen

the field, which is ensured by a choice of the optimum position of a film in the waveguide. The maximum coupling and, respectively, the maximum resonance interaction are observed in the case where an epitaxial film of hexaferrite is positioned near the narrow wall of the waveguide. The minimum coupling corresponds to the position of a film at the middle of the wide wall.

Testing the device [11] was performed on a measuring stand with a network analyzer SWF. Preliminarily, we created a regularized PPDS in the film. The attenuation was 1 dB outside of the resonance and, at the resonance frequency, 6 dB near the narrow wall and 2 dB at the middle of the wide wall. The displacement of the epitaxial film was carried out with the help of a micrometric unit. The resonance frequency was 47.2 GHz, the bandwidth on the level of 3 dB was 200 MHz, and the loaded Q-factor ~300. In this case, the Q-factor of the resonator on the epitaxial film did not exceed the Q-factor of a resonator on a plate of hexaferrite of 30–40 μm in thickness, because of the imperfect technology of the growing of epitaxial films of hexaferrites, as distinct from that for monocrystalline volumetric specimens. We expect that the Q-factor of such resonators will be significantly increased with novel technologies of the growing of films.

As was mentioned above, the structure with a CMD lattice is characterized by two intense peaks, which allowed one to fabricate a two-frequency SHF resonator. The structure of this device is analogous to that of a PPDS-based resonator. It is essential that the frequencies of the branch ω_2 in the domain region depend on H_0, i.e. such a resonator is tunable [10]. With this purpose, the device was supplemented by a magnetic system in order to regulate the magnetic field. The bandwidth of such a resonator on the level of 3 dB was 200 MHz, and the loaded Q-factor ~300. Thus, the proposed device ensures the two-frequency mode of operation, a change of working frequencies, and the possibility to vary the coupling with the SHF field.

4.2. SHF resonator on the base of a symmetric slit line

The working section of a symmetric slit line (SSL) [24] is composed from a dielectric support ($\varepsilon \gg 1$), on one side of which a metallic film with a narrow slit is sprayed (Fig. 6). The section of SSL is positioned in the waveguide normally to the wide wall at its center (symmetrically). The structure of a field in such a construction, i.e. the basic type of a wave of SSL, is analogous to that of the wave H_{10} of a rectangular waveguide.

The resonating element was positioned on the narrow slit (Fig. 6*b*), where the concentration of a SHF field is significantly greater than that in a rectangular waveguide, which results in a sharp enhancement of the coupling between the SHF field and a specimen. This allows one to use specimens, whose area is at most 1 mm^2. In addition, the use of SSL for the development of SHF devices allows one to significantly decrease their size.

We note that, on the use of a resonator in the transmission slit line in order to realize the critical coupling, it is sufficient that the specimen size was about $1.00\times1.00\times0.06$ mm^3. In Fig. 6*b*, we display the resonating element in a transmission slit line. The ferrite resonator under study with small sizes has a quite high value of the Q-factor in the millimeter range. By the parameter characterizing the clearance [25] $K_G = V_R/\lambda^3 \approx 10^{-3}$, this resonator has a significant advantage as compared with dielectric resonators (here, V_R is the resonator volume, and λ is the working wavelength).

5. Conclusions

We have experimentally shown that, as resonators in the millimeter range, one can use monocrystalline plates and epitaxial films of barium hexaferrite with a created regular DS that are operating in the field-free mode.

We have constructed SHF resonators, where the resonating element is a plate or an epitaxial film of barium hexaferrite in the state with PPDS or a cylindrical domain structure.

The parameters of such resonators are experimentally studied, and the possibility to use them in facilities of the millimeter range is established.

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НВЧ-РЕЗОНАТОРИ НА ОСНОВІ ОДНОВІСНИХ ГЕКСАФЕРИТІВ З ДОМЕННОЮ СТРУКТУРОЮ

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Р е з ю м е

Експериментально підтверджена можливість використання пластинок одновісних гексаферитів з доменною структурою (ДС) у ролі резонуючого елемента для функціональних пристроїв НВЧ-електроніки. Показано, що добротність таких структур з активним елементом із барієвого гексафериту в доменній області не відрізняється від добротності резонансного елемента, який працює при насиченні. Наведено два варіанти конструкцій таких резонаторів.