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Advances in Engineering and Applications of Hexagonal Ferrites in Russia

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1. Introduction

Richard Feynman (Feynman, 2005) once stated that ferrites were one of the most difficult areas for theoretical description, but the most interesting for studies and practical applications. These words are especially true when dealing with a special type of ferrites, which have a hexagonal crystallographic structure – hexagonal ferrites, or hexaferrites.
The world's first permanent magnets based on ferroxdure - hexagonal barium ferrite $BaFe_{12}O_{19}$ (equivalent to $BaO{\cdot}6(Fe_2O_3)$, also called BaM) appeared in 1951 (Rathenau et al., 1952). The main engineering problem that was solved at that time was the replacement of cumbersome metallic (Ni- and Co-alloy) magnets by comparatively compact and light-weight permanent magnetic systems. The systematic study and applications of gyromagnetic properties of hexaferrites started in 1955 (Weiss & Anderson, 1995; Weiss, 1955; Sixtus et al., 1956). Currently, in the world, enormous progress in fundamental theoretical and experimental laboratory studies of various properties of hexaferrites, their synthesis, and engineering of a wide range of microwave and mm-wave coatings and devices on their basis has been achieved – see, for example, papers (Harris et al., 2006, 2009) and references therein.
Hexaferrites as the materials for extermely high-frequency (EHF) range, *Ka* (27-40 GHz), *U* (40-60 GHz), *V* (60-80 GHz), *W* (80-100 GHz) bands, and higher, have been also studied and applied in Russia since middle 1950s. Authors of this paper, being apprentices and followers of the outstanding Russian scientists, V.A. Kotelnikov, L.K. Mikhailovsky, and K.M. Polivanov. V.A. Kotelnikov named the millimeter waveband "a nut in a hard shell", deeply believe that the practical development of this waveband is possible only when using hexaferrites. Herein, the summary of achievements in engineering hexagonal ferrites and various devices of on their basis in Russia for the past over 50 years is presented.
In 1955-1956, a then young scientist from Radio Engineering Department of Moscow Power Engineering Institute, L.K. Mikhailovsky, studied microwave ferrites and developed devices operating at the ferrimagnetic resonance (FMR) with new functional possibilities, such as a magnetic detector and a gyromagnetic cross-multiplier. For mm-wave applications, Mikhailovsky proposed to use instead of huge bias magnets just the internal field of

crystallographic magnetic anisotropy inside a ferrite. According to Kittel's formula (Kittel, 1948, 1949), the frequency of the FMR in a ferrite resonator magnetized to the saturation along the $\hat{Z}$ direction is

$$f_{res} = \gamma/\sqrt{H_x \cdot H_y} \text{ with}$$

$$H_x = H_0 + H_A - (N_z - N_x) \cdot 4\pi M_S \text{ and } H_y = H_0 + H_A - (N_z - N_y) \cdot 4\pi M_S, \quad (1)$$

where $\gamma = 2.8 \frac{\text{MHz}}{\text{Oe}}$ is the gyromagnetic ratio; H_A is the crystallographic anisotropy field; H_0 is the external bias magnetic field; $4\pi M_S$ is the saturation magnetization (G); N_x, N_y, N_z are the demagnetization shape (form) factors of the ferrite sample. The sample may be of an ellipsoidal shape (spheroid, sphere, elongated cylinder, disk), or it may be a flat slab. In (1), the vectors $H_0, H_A, \hat{Z}$ are collinear.

However, in 1950s, no ferrites with significant internal magnetic fields were available in the USSR. In 1958-1962, Mikhailovsky initiated the pioneering work on the study of electromagnetic energy absorption by magneto-uniaxial ferrites. The very first magneto-uniaxial ferrite Ba-Zn (Zn_2W) was synthesized by S.A. Medvedev, who had previously worked in France and got some experience in making ferrites with high crystallographic anisotropy (but not magneto-uniaxial). The results of this first research were published in 1960 (Polivanov et al, 1960), and it was concluded that the absorbed energy at the natural ferrimagnetic resonance (NFMR), i.e., without any bias magnetic field, is significantly higher than the resistive or pure dielectric polarization loss. Thus the NFMR differs from the FMR only by the significantly lower magnetic field needed for the resonance operation of microwave (mm-wave) devices.

In 1962, the Industrial Ferrite Laboratory („OPLF") with Moscow Power Engineering Institute (MPEI) was founded. The OPLF from the very beginning united three working groups from three different Departments of the MPEI: Radio Engineering (with Mikhailovsky as the Head), Electrical Engineering (lead by Polivanov), and Electro-Mechanical Technology (lead by Medvedev). Also, in late 1950-ies, the State Research and Development Institute of Magneto-Dielectrics („NIIMD") was founded in Leningrad in order to engineer and manufacture new types of ferrites. The main goal of the OPLF as a research laboratory within a university was to intensively collaborate with and conduct R&D projects determined by this leading enterprise of the USSR electronics industry. Thus since early 1960s, the OPLF has been one of the world leaders on synthesis, theoretical and experimental research of ferrites, including hexagonal ferrites, and development of new unique microwave and mm-wave designs on their basis.

As a result of the research activity of the OPLF during nearly 50 years of existence, the new school of thought in gyromagnetism was founded. This school continues the best traditions of such Russian physicists as Lebedev, Arkadiev, Polivanov, and Kotelnikov. In 1980s, Mikhailovsky founded, and till now has been leading, the scientific field of „currentless" spin electronics and gyrovector electrodynamics. „Gŷros" in Greek means „revolution". Gyromagnetism in classical phenomenological representation arises from the relation between the angular momentum and the magnetization vector of a magnetic medium. The motion of the magnetization vector in magnetic (ferrite, ferri-, ferro-and antiferromagnetic) media at the magnetic resonance is associated with spin moment rotation of magnetic atoms, and is represented as the precession around the static bias magnetic field direction (Landau & Lifshitz, 1935, 1960). Mikhailovsky has developed a novel theory, which he called „the gyrovector formalism", or „the gyrovector algebra". This theory explains the mechanism of absorption of electromagnetic energy at ferrimagnetic resonance by microwave ferrites, including hexaferrites (Mikhailovsky, 2002). The background of this theory is Maxwell's hydrodynamic model (Maxwell, 1856) and Dirac's quantum spinor electrodynamics (Dirac, 1975). Thus the gyrovector formalism mathematically unites classical and quantum physics approaches, and explains a local quantum (energy) interaction of electromagnetic field with centers of absorption and radiation of a gyromagnetic medium.

This theory lays the basis for many engineering applications, including the hexaferrite radioabsorbing materials with electrical conductivity close to zero; omnidirectionally matched with free space protecting coatings; and devices for spectral analysis and frequency-selective measurements of microwave and mm-wave power. Also, as soon as a new class of ferrite materials, magneto-uniaxial hexagonal ferrites with high internal fields of crystallographic anisotropy, were synthesized, it has become possible to develop gyromagnetic resonance devices operating without external bias magnetization, or with low bias magnetization needed for ferrite saturation and tuning of resonance frequency.

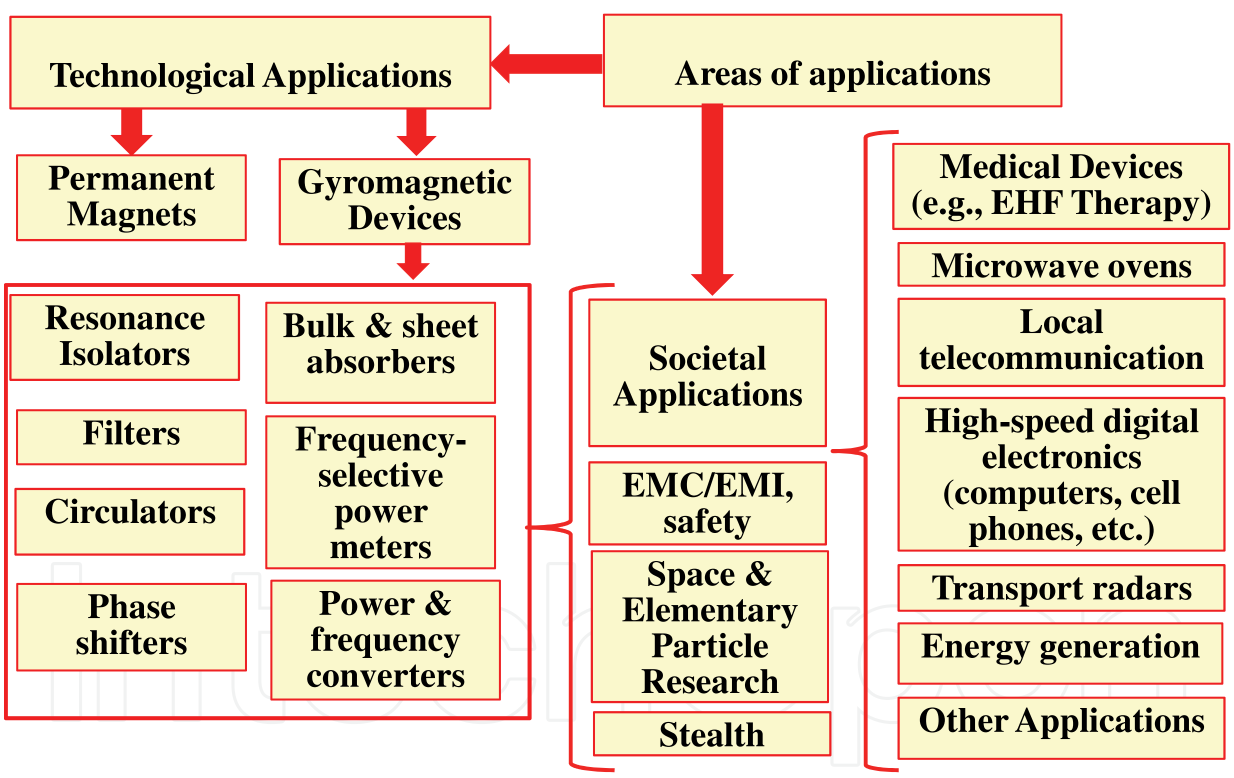


Fig. 1. Fields of application of hexagonal ferrites

Unfortunately, these achievements could not be published in open literature with wide international access for many decades. Very limited number of papers on this topic were published, mainly in Russian. The objective of the present Chapter is to cover this gap, and allow readers to get acquainted with these works not only from retrospective point of view. They contain the present-day novelty, and can be useful for engineers designing electronic equipment operating in a wide frequency range from about 2 GHz to 300 GHz, and potentially even higher. An application of hexagonal ferrites is proven and remains very perspective for solving numerous problems related to microwave engineering, radar engineering, electromagnetic compatibility (EMC), electromagnetic immunity (EMI), and signal integrity (SI). Hexaferrites can be used for detection and suppression of unwanted radiation and coupling paths; for frequency-selective measurements of signal parameters; and for providing proper non-reciprocal isolation in channels of generation, transmission, and reception over the selected frequency bands within the wide range up to a few hundred GHz.

In this Chapter, the review of the engineered modern types of hexagonal ferrites for SHF and EHF frequency bands will given, as well as an overview of research and design experience for various hexagonal ferrite devices gained during multi-year collaboration between MPEI (TU) and Russian industry, in which the co-authors have been directly involved. Different engineering, societal, and other applications of hexagonal ferrites will be also discussed, include agricultural and medical applications, computer engineering, telecommunication, and television. Fig. 1 shows some application fields of hexaferrites.

2. Hexagonal ferrites as advanced ceramic materials for microwave and millimeter wave engineering

Hexaferrites are known to be magneto-dielectric, specifically ferrimagnetic materials with hexagonal magnetoplumbite-type crystallographic structure (Smit & Wijn, 1959). Ferrimagnetic magnetoplumbite has the general chemical formula $MeO{\cdot}6Fe_2O_3$, in which Me may be Ba^{2+}, Sr^{2+}, or Pb^{2+}. The ferric ions can be also partially replaced by Al^{3+}, Ga^{3+}, Cr^{3+}, Sc^{3+}, or combinations of ions, for example, Co^{2+} with Ti^{4+}, Zn^{2+} with Ti^{4+}, etc. Hexagonal ferrites, unlike the other groups of ferrites (spinels and garnets), have a pronounced internal effective magnetic field H_A, associated with the magnetic crystallographic anisotropy. From a crystallographic point of view, a hexaferrite is characterized by the hexagonal basis plane and the axis of symmetry that is orthogonal to the basis plane.

The scanning electron microscopy (SEM) picture in Fig. 2 shows the microstructure of a hexagonal ferrite containing hexagonal shaped flakes. If the direction of easy magnetization is the axis of symmetry of the hexagonal structure, then the ferrite is called a *magnetically uniaxial ferrite*. If the easy magnetization direction belongs to the basis plane, this is a *planar ferrite*. Monocrystalline and polycrystalline magnetically uniaxial hexaferrites are the most widely used in practical applications. Polycrystalline uniaxial hexaferrites are commercially available. As for planar hexaferrites, the possibilities of studying them are limited by the low Curie temperatures.

The concept of a field of magnetic crystallographic anisotropy, or briefly called “anisotropy field”, is widely used for phenomenological description of hexaferrite behavior. It is calculated approximately as (Gurevich & Melkov, 1996)

$$H_A \approx 2\,|K_1|\,/M_s, \tag{2}$$

where M_s is the saturation magnetization, and K_1 is the first constant of anisotropy, such that $K_1 > 0$ for uniaxial ferrites, and $K_1 < 0$ for planar ferrites. The dependence of crystallographic magnetic anisotropy energy of hexagonal ferrites (Gurevich & Melkov, 1996)

$$U_A = K_1 sin^2\theta + K_2 sin^4\theta + \frac{1}{2}\mu_0(N - N_C)(M_S sin\theta)^2. \tag{3}$$

upon the angle θ between the equilibrium magnetization vector $\vec{M}_0$ and crystallographic axis *c* for uniaxial and planar ferrites is shown in Fig. 3. The second constant of anisotropy for hexagonal ferrites is much smaller than the first constant of anisotropy $|K_2| << |K_1|$.

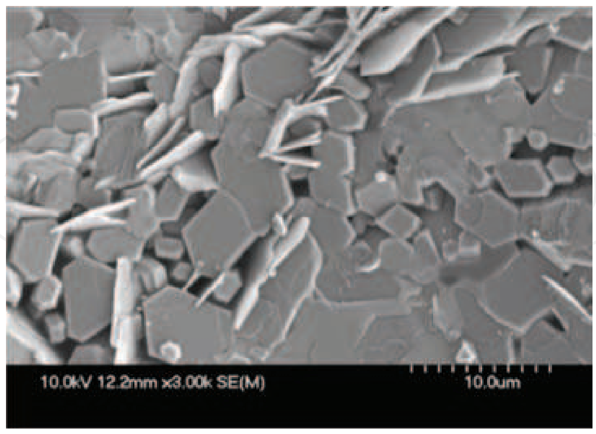


Fig. 2. Microstructure of a Ba-SrM polycrystalline ferrite obtained by SEM

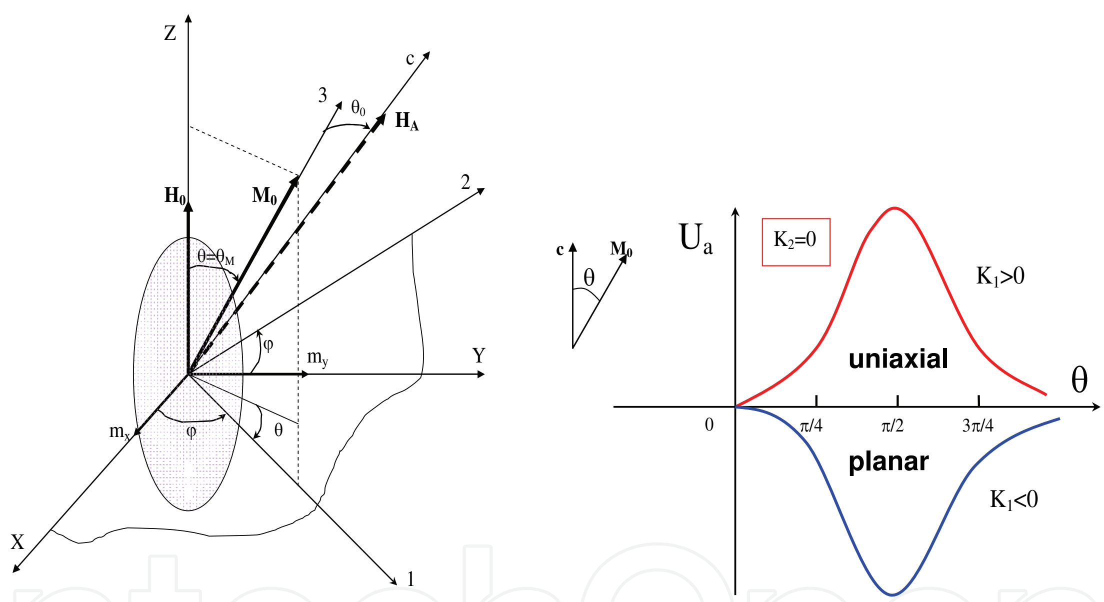


Fig. 3. Dependence of anisotropy energy of hexagonal ferrites U_a upon the angle θ between the equilibrium magnetization vector $\vec{M}_0$ and crystallographic axis c.

The crystallographic magnetic anisotropy field determines the conditions for *ferrimagnetic (gyromagnetic) resonance* (FMR) in hexagonal ferrites. The resonance frequency of a magneto-uniaxial ferrite is related to the magnetization field and orientation of a equilibrium magnetic moment with respect to the constant bias magnetic field. Boris P. Pollak, a scientist from MPEI, in 1964 theoretically and experimentally obtained the curves for H_A field of magneto-uniaxial monocrystalline hexaferrites in negative bias fields, extending Weiss's curves (Weiss, 1955). The dependences shown in Fig. 4 are known as „Weiss-Pollak curves" (Polivanov & Pollak, 1964; Mikhailovsky et al., 1965). The analogous curves were also obtained for the polycrystalline hexaferrites (Mikhailovsky et al., 1966; Pollak et al., 1969). The magnetic field H_0 required to achieve the FMR in the case of a hexagonal ferrite magnetized in the easy direction, appears to be dozens times lower than when using ordinary, low-anisotropy ferrites. Thus, for the uniaxial ferrites, the applied bias field to achieve the resonance frequency ω_{res} is (Kittel, 1948)

$$H_0 = \omega_{res}/(\mu_0 \cdot \gamma) - H_A. \quad (4)$$

For high-coercivity magneto-uniaxial ferrites, the applied field H_0 may be zero or even negative (anti-parallel to the magnetization vector), and this broadens the frequency range of applications of ferrites. The anisotropy field is the main parameter for classifying hexagonal ferrites for applied engineering problems.

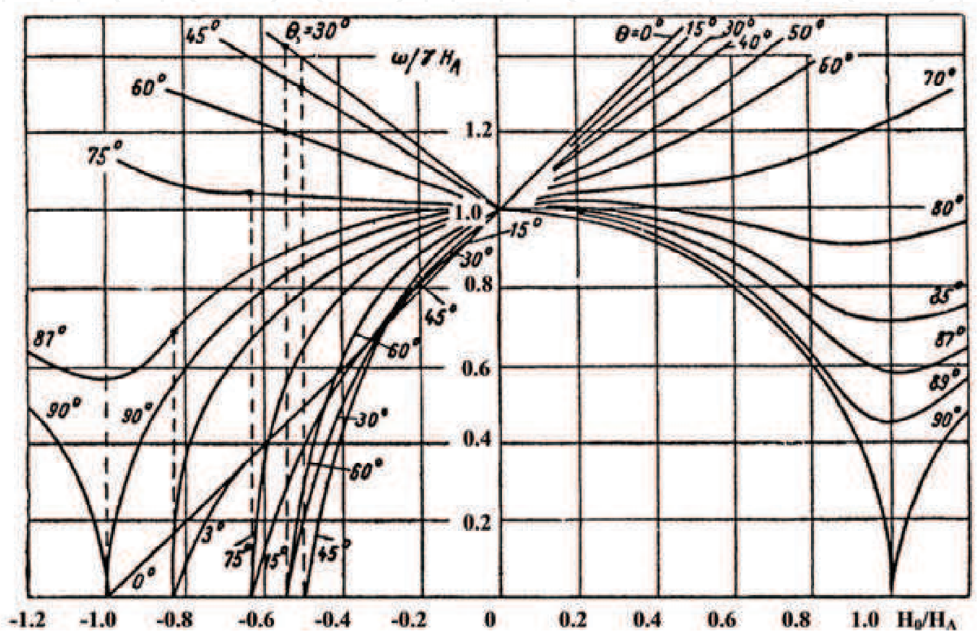


Fig. 4. Weiss-Pollak curves as conditions of gyromagnetic resonance in a single-domain particle of a magneto-uniaxial hexagonal ferrite (Mikhailovsky et al., 1965)

The research on microwave and mm-wave hexagonal ferrites started in the OPLF of the MPEI went through the three stages.

- The first stage included the attempts to synthesize, in the laboratory conditions, different types of ferrites with various fields of crystallographic anisotropy, test their charactristics, and build devices of EHF (30...300 GHz) frequency band on their basis.
- The second stage was focused on the improvement and optimization of the synthesized materials from the point of view of practical applications, as well as engineering of the advanced designs of microwave and mm-waved devices.
- The third stage was developing and producing industrial series of the engineered ferrites of different types and devices on their basis using the facilities of the electronics industry, including those at the leading enterprise NIIMD and the experimental plant of the MPEI.

The work on the synthesis of magneto-uniaxial ferrites was mainly done in two directions: (1) synthesis of ferrites with different anisotropy fields to be able to design devices for different frequency bands, and (2) an optimization of technological processes, structure and stohiometry of ferrites to obtain ferrites with the best possible characteristics.

Practically all the uniaxial hexagonal ferrites synthesized and studied in the OPLF belong to one of two groups: either M-type, or W-type. M-type hexagonal ferrites are based on Barium ($BaFe_{12}O_{19}$) and/or Strontium ($SrFe_{12}O_{19}$) ferrites with partial isomorphic substitution of the Fe^{3+} ions by ions of dia- or paramagnetic metals.

Ferrite series	Type of ferrite	Concentration of dopant ions	$4\pi M_s$, G	H_A, kOe	ΔH, Oe
1 MΦ	*BaMnM*	0.4...0.0	368...380	16.7...17	55...13
2 MΦ	*BaNiZnM*	1.54...0.55	344...364	10.2...13.5	72...18
3 MΦ	*BaTiNiM*	0.5	360	13.0	61
4 MΦ	*BaTiCoM*	1.4...0.25	330...280	10.2...14.4	220...65
5 MΦ	*BaYbM*	0.8...0.5	330	13.5...14.5	32
6 MΦ	*BaLuM*	0.6	330	12.8	21
7 MΦ	*BaScM*	1.4...0.5	225...350	1.2...10.6	200...27
8 MΦ	*SrGaScM*	0.82...0.0	317...380	9.2...18.7	36...12

Table 1. Magnetic parameters for a number of series of synthesized monocrystalline M-type hexaferrites (Mikhailovsky et al., 2002)

Momocrystals of hexagonal ferrites were maily synthesized in OPLF by S.A. Medvedev, A.M. Balbashov, V.P. Cheparin, and A.P. Cherkasov (S.A. Medvedev et al., 1967, 1969; Mikhailovsky et al., 1965, 2002; Pollak et al., 1976). Most of the monocrystals are obtained by the method of spontaneous crystallization of high-temperature melt solution, and in a few cases by the method of non-crucible zone smelting. Results of magnetostaic and microwave measurements conducted on a number of series of synthesized monocrystalline hexaferrites are summarized in Table 1. The data is presented in the Gaussian Magnetic Unit System with 1 Oersted (Oe)=$1000/4\pi \approx 79.6$ A/m, and 1 Gauss (G) =10^{-4} T). The synthesized monocrystalline magneto-uniaxial hexagonal ferrites had the values of crystallograhic anisotropy field H_A = 0.075...7.9 MA/m (corresponding to 0.9...95 kOe). This allows for operating in the frequency range ~2.5...260 GHz both at the NFMR and the FMR. To achieve the latter, significantly reduced bias magnetization fields were applied (less than 3 kOe).

W-type hexagonal ferrites are mainly solid solutions of Me_2W ($Me_2BaFe_{16}O_{27}$), where Me is a bivalent metal, for example, Co_2W, Ni_2W, or Zn_2W. Mainly polycrystalline hexagonal ferrites with different values of anisotropy field have been synthesized with this structure; however, the ferrite Zn_2W was also synthesized as a monocrystal.

The monocrystals with the H_A fields ranging from 1.2 kOe (BaM ferrites doped by Sc, Lu, or Yb) to 120 kOe (BaM and SrM ferrites with Fe ions replaced by ions of Ga and Al) have been synthesized. The minimal FMR linewidth of about 10 Oe was achieved in experimental BaSr ferrites, when Mn ions were doped in the crystal lattice of the hexagonal ferrite, as this is typically done to reduce the linewidth in monocrystal ferrogarnets, e.g., YIG. In the pure BaM ferrite, Mn ions were introduced using the BaO-B_2O_3 solvent, while in Sc-doped ferrites, the solvent $NaFeO_2$ was chosen. As for Ti-containing ferrites, the comparatively narrow lines (~ 10 Oe) were achieved in only Ti-Zn ferrites, when the cooling speed of the crystallizing melt was below 2 ^{0}C/hour (Sveshnikov & Cheparin, 1969). The ion Fe^{2+} is known to be responsible for wider FMR line, so to reduce its contents, the monocrystals were grown by the method of non-crucible zone smelting at the oxygen pressure of 50 atmospheres.

Series	Type of ferrite	Dopant (x)	$4\pi M_s$, G	H_A, kOe	ΔH, kOe
1 ПФ	$BaO \cdot (6-x)Fe_2O_3 \cdot xCr_2O_3$	2.5...0.0	900...4700	43.4...16.3	4.9...1.8
2 ПФ	$SrO \cdot (6-x)Fe_2O_3 \cdot xCr_2O_3$	3.0...0.0	250...3400	52.2...16.2	5.0...0.6
3 ПФ	$BaO \cdot (6-x)Fe_2O_3 \cdot 0.5x(CoO+TiO_2)$	0.65...0.45	3800...4400	9.1...12.1	5.0...1.9
4 ПФ	$BaO \cdot (6-x)Fe_2O_3 \cdot 0.5x(ZnO+TiO_2)$	1.0...0.55	3600...3800	10.0...7.7	3.6...1.3
5 ПФ	$BaO \cdot (5.9-x)Fe_2O_3 \cdot 0.5x(ZnO+TiO_2)$	1.9...0.45	3000...4400	7.2...13.4	4.8...1.4
6 ПФ	$BaO \cdot (5.9-x)Fe_2O_3 \cdot 0.5x(NiO+TiO_2)$	1.0...0.45	3800...3900	11.5...14.1	5.4...4.0
7 ПФ	$BaO \cdot 6Fe_2O_3 \cdot 2[xCoO \cdot (1-x)NiO \cdot 0.9Fe_2O_3]$	0.4...0.36	3540...2900	4.0...4.8	2.95...4.7
8 ПФ	$1.1BaO \cdot 6Fe_2O_3 \cdot 2[xCoO\ (1-x)NiO \cdot 0.9Fe_2O_3]$	0.4...0.26	3520...4300	3.4...6.7	2.5...4.8
9 ПФ	$BaO \cdot 5.4Fe_2O_3 \cdot 2[0.4CoO \cdot 0.6NiO \cdot 1.2Fe_2O_3]$		3900	6.0	3.4
10 ПФ	$SrO \cdot 6Fe_2O_3 \cdot 2[0.4CoO \cdot 0.6NiO \cdot 0.9Fe_2O_3]$		4270	7.7	2.5
11 ПФ	$BaO \cdot 6Fe_2O_3 \cdot 2[xCoO \cdot (1-x)ZnO \cdot 1.2Fe_2O_3]$	0.4…0.0	3000-5020	0.9...11.0	5.3...2.4
12 ПФ	$BaO \cdot (6-x)Fe_2O_3 \cdot xCr_2O_3 \cdot 2(ZnO \cdot 0.9Fe_2O_3)$	1.5…0.0	3900	16.1...10.0	3.3...1.95
13 ПФ	$BaO \cdot (6-x)\ Fe_2O_3 \cdot xCr_2O_3 \cdot 2(NiO \cdot 0.9Fe_2O_3)$	1.2...0.4	3900	18.5...14.6	3.5...2.2
14 ПФ	$SrO \cdot (6-x)Fe_2O_3 \cdot xCr_2O_3 \cdot 2(0.4CoO \cdot 0.6NiO \cdot 0.9Fe_2O_3)$	0.5...0.0	3900	6.8...7.7	3.0...2.5
15 ПФ	$BaO \cdot (6-x)Fe_2O_3 \cdot xAl_2O_3 \cdot 2(NiO \cdot 0.9Fe_2O_3)$	1.1...0.0	3900	18.0...13.3	4.6...2.2

Table 2. Parameters of some laboratory synthesized polyrcystalline hexaferrites (Mikhailovsky et al., 2002)

Polyrcrystalline hexaferrites were synthesized in both the MPEI, and in industry. The final goal was obtaining industrial series of magneto-uniaxial ferrites and devices on their basis. The experimental series of polycrystalline hexaferrites were engineered by S.A. Medvedev, A.M. Balbashov, and V.V. Kolchin (Polivanov et al., 1969).

It is known that partial substitution of Fe_2O_3 by Al_2O_3 in SrM or BaM ferrites due to the presence of Al^{3+} ions of varying concentration allows for comparatively sharp control of crystallographic anisotropy field of hexaferrites (De Bitetto, 1964; Qui et. Al., 2005). This effect is widely used in the world practice to synthesize hexaferrites with different K_1 (or H_A) values. The peculiarity of polycrystalline hexaferrites synthesized in Russia is using Cr_2O_3, since it was found that Cr^{3+} allows for fine tuning of K_1 (or H_A) field to the desirable values. Besides, it has been noticed that the ferrites with Cr^{3+} have better microwave properties than those with Al^{3+} (Nedkov et al., 1988). However, it is more difficult to synthesize ferrites-chromites, since Chrome oxides are gaseous and require ferrite annealing at high pressure in different media. Besides, ferrites-chromites have the higher magnetic saturation and Curie temperature than their aluminate counterparts at the same concentration. The parameters of the polycrystalline hexagonal ferrites of different series synthesized and studied in MPEI are presented in Table 2. The highest achieved anisotropy field in the case of the Sr ferrite-chromite with substitution x=4.5 was H_A = 95 kOe was.

The optimization of the synthesis process was done to acheive the ferrites with the given and controllable anisotropy fields, with the highest-level texture (grain alignment), and the minimal possible NFMR line, determined by the statistical distribution of the anisotropy fields of the grains). As a result of optimization of grinding and burning, it was possible to get polyrcrystalline magneto-uniaxial ferrites with ΔH=0.6...1.0 kOe.

The polycrystalline hexaferrite „parametric series" (series of ferrites with the fixed values of the anisotropy field, differing by 1.0...1.5 Oe) with the increased thermal stability of H_A have been synthesized in industry (Petrova, 1980). These hexaferrites have been intended for the development of EHF devices, in particular, resonance isolators (Pollak et al., 1980). The parameters of such hexaferrites are shown in Table 3. These ferrites exhibit an enhanced thermal stability and low dielectric loss. It is important that all the ferrites of an individual parametric set belong to the same system, i.e., the classification group. An important requirement is using the same ferrite system for as wide anisotropy range as possible. Thus, the system $BaNi_2ScW$ was chosen for the range H_A = 5...12 kOe; the system $BaNi_2Cr_xW$ was used to provide the range H_A = 12...18 kOe; the system $SrNi_2Cr_xW$ allowed for getting H_A = 13...20 kOe. Ferrites-aluminates and ferrites-chromites with H_A = 18...30 kOe have been synthesized on the basis of both BaM and SrM. Aluminates with high density and high Curie temparature are preferable for H_A > 30 kOe. As is seen from Table 3, the present-day polycrystalline ferrites possess substantially better parameters, especially ferrite *04СЧА12*. For this ferrite, the anisotropy field is H_A =24 kOe, and the value of the resonance width has been achieved as small as ΔH < 0.5 kOe, the rectangularity of the hysteresis loop is M_r/M_s = 0.995, coercivity is H_c = 2 kOe, and the dielectric loss is as low as $tan\delta_\varepsilon$ = 6.0x10^{-4}.

Engineering and application of hexagonal ferrite films for the EHF (30-300 GHz) resonance and wideband devices operating without any bias magnetic field is an important advance in improvement and simplification of the manufacturing processes. These films are based on hexaferrite composites, which are the mixtures of hexaferrite powders of the particular contents with a glue-like base (host) material (Pollak, 1980). The powders are obtained by the grinding bulk hexaferrites that have already completely gone through the ferritization process (the metasomatic alteration of initial raw material ingredients into ferrite), and have a well-defined texture. The latter means that the hexaferrites have undergone the ferritization annealing twice, and before the second firing they have been pressed in a magnetic field. The average size of a particle in a powder is close to that of a single domain (~ 1-10 μm). The powder is then mixed with a bonding dielectric, which may be a polystyrene glue, glue *BF* (Russian-make), etc. Then the suspension is deposited on a substrate, and dried at room temperature and normal atmospheric pressure. To assure a high-rate texturing, samples must be dried in a magnetic field. Films have the minimum thickness on the order of 10 μm. They have a relative density of 50%, and their texturing is as good as of the bulk sintered polycrystalline hexaferrite plates.

Type of ferrite	$4\pi M_s$, G	H_A, kOe (f_o, GHz)	ΔH, kOe (f_o, GHz)	ε_r @ f_0=9.4 GHz
06СЧА3	3700	14 (55)	< 2 (55)	16
05СЧА4	4000	16(50)	< 2 (50)	16
05СЧА5	3000	18(65)	< 2 (65)	15
04СЧА11	2500	21(70)	< 2 (70)	15
04СЧА12	2100	24(75)	< 2(75)	15
04СЧА13	1600	27(80)	< 2.5(80)	15
03СЧА2	1500	31(100)	< 2.5(100)	15
03СЧА	1400	35(110)	< 2.5(110)	15

Table 3. Parameters of some industrially manufactured hexagonal ferrites

A mixture of a few types of hexaferrite powders differing by their anisotropy fields can be used to make multiphase composites. They typically have a greater width of the FMR, which is favorable for developing resonance isolators or other devices operating over a wider frequency range. Films based on hexaferrite composites exhibit higher coercivity, which allows for operating without any external bias magnets in the frequency range up to 100 GHz. Another important feature is their comparatively low permittivity, which provides better matching of films with the other dielectric elements in a microwave (mm-wave) transmission line. Besides, it is much easier and cheaper to manufacture such films than the bulk plates. The requirement of having an extremely small thickness is not difficult to satisfy, since the chip technology can be used for their manufacturing, and these films can be used in microwave chips, though there may be problems at the interfaces with other materials. Moreover, when dealing with polycrystalline hexaferrite powders, the control of the ferrite contents at different stages of their manufacturing, is substantially simplified. It is possible to do without making special test samples – plates of thickness less than 0.1 mm, or spheres of at least of 0.4 mm in diameter to apply the standard techniques for measuring intrinsic parameters of ferrites. Also, there is no necessity of texturizing samples for study, and no need in bias field for measurements.

3. Gyromagnetic applications of hexagonal ferrites

Hexagonal ferrites are traditionally applied in microwave and mm-wave engineering. These are different gyromagnetic devices for the EHF range (30...300 GHz). When using hexagonal ferrites, it is possible to reduce the external bias magnetic field by an order of magnitude, or remove it completely. Application of hexaferrites also solves a number of functional problems, which cannot be successfully solved using other types of ferrites. The primary attention in this work is paid to hexaferrite isolators, because isolators are of the greatest demand in general, and hexaferrite isolators, from our point of view, are the most promising as compared to other types of non-reciprocal isolating devices for telecommunication microwave and millimeter-wave systems. An important perspective on hexaferrite isolators is their application for transmission lines and broadcast telecommunication systems, when compact, low-weight, technologically simple, and inexpensive devices are of top priority. Some other examples of applications of hexaferrites in devices developed by the authors are presented below.

3.1 Resonance isolators

Resonance isolators for the 8-mm (*Ka*) waveband are known to be industrially developed and manufactured. They are based on the application of crystallographically isotropic (ordinary) ferrites, as well as on anisotropic (hexagonal) ferrites, inside standard metal rectangular waveguides (cross-section of 7.2 x 3.4 mm). Laboratory samples of *hexagonal ferrite resonance isolators* for operation in the frequency range up to 150 GHz have been designed and studied in the MPEI (Mikhailovsky et al., 1965, 2002; Polivanov et al., 1969; Pollak et al., 1976, 1980). The characteristics of resonance isolators are given in Table 4. They are made on both metal waveguides (MW) and dielectric waveguides (DW). Characteristics of devices are preserved at average power less than 200 mW and over the temperature range -40…+60 ^{0}C.

Frequency range, GHz	Bandwidth at – 3 dB level, %	Return loss, dB	Insertion loss, dB, less than	VSWR	Bias magnetic field, kOe	Transmission line
25 – 150	2…3	20…25	1…2	1.2	0…3	MW, DW
25 – 150	20…40	20…25	1…3	1.3	0…3	MW, DW
40…150	0.5	25…30	0.3…1	1.2	0…3	MW

Table 4. Typical parameters of resonance isolators based on magneto-uniaxial polyrcystalline hexaferrites (Mikhailovsky et al., 2002)

When developing these isolators for the EFH frequency range, many problems have arisen. One of the challenges is the tiny size of isolators. The cross-sectional dimensions b x a of standard metal rectangular waveguides are typically in the range of b = (0.55...3.4) mm and a = (1.1...7.2) mm, the thickness of ferrite slabs is t_f = (0.01... 0.1) mm, the thickness of dielectric plates is t_d = (0.15...1.0 mm), and the mounting dimensions in the waveguide are just d = (0.1...2.0 mm). These miniature isolators typically have high insertion loss which may reach up to 5 dB. Another problem is that to cover the wide frequency range of operation, many types of ferrites with different anisotropy field are needed, for example, the anisotropy field should be in a range of H_A = 0.4...8.0 MA/m (5...100 kOe) with a discrete of $\delta H_A \sim$ 0.1 MA/m (1.0...1.2 kOe). At the same time, the values of M_S, T_C, and density decrease as H_A increases.
The abovementioned difficulties of isolator design and manufacturing have been overcome in an elegant way. The insertion loss in comparatively narrowband isolators was reduced by the following solutions.

- The so-called effect of the "*bound modes*" (Korneyev, 1980) and the *magnetodynamic resonators* (MDR) with different values of anisotropy field (Korneyev & Pollak, 1982) were used. The effect of the "bound modes" is typically observed in bias magnetic fields that are insufficient for achieving resonances, and in comparatively big ferrite samples falls within the bandwidth much less than the FMR line. These isolators operate on a combination of FMR and volume resonance of the hexaferrite slab. These are typically short flange-like isolators with high isolation level in a narrow band, and the resonance frequency can be tunable (± 5...10%) by a low magnetic bias field while keeping good isolation.
- Another solution is an application of *a monocrystalline hexaferrite* resonator, e.g., a spherical resonator, with variable orientation of crystallographic axes with respect to

the external magnetic field (Pollak et al., 1976). Thus, in an isolator with a pure BaM ferrite (H_A=17.5 kOe), when changing its orientation in the limits of 0...60^0, the range of resonance frequency was 62...55 GHz, isolation=40...22 dB, and resonance linewidth was less than 150 MHz.

To broaden the frequency range of isolators (Pollak et al., 1976; Mikhailovsky et al., 2002) the multi-component composite hexaferrite materials with the size of hexaferrite particles not exceeding a few micrometers was proposed. This is a mixture of different polycrystalline ferrites as thin bulk plates or composite films with a spread of different values of anisotropy field H_A . The resultant wideband isolators have a bandwidth of up to an octave (see Fig. 5).

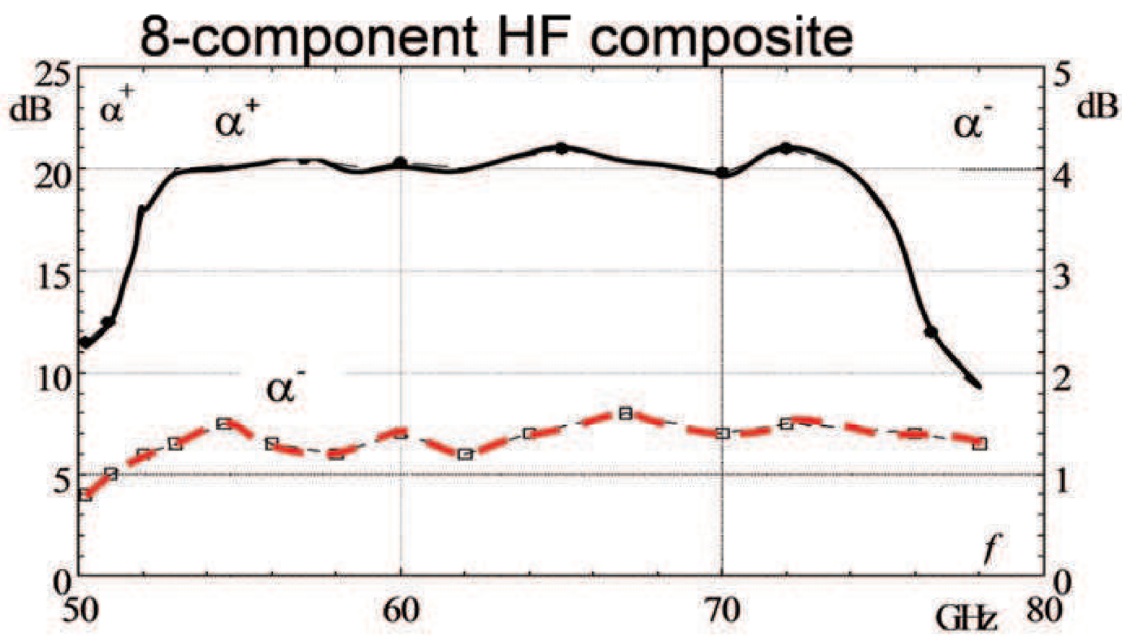


Fig. 5. Frequency characteristics of the eight-component hexagonal ferrite isolator

The return loss (RL) α^+ and the insertion loss (IL) α^- shown in Fig. 5 are calculated as

$$\alpha^{\pm} \approx \sigma V(\mu'' \pm \mu_a''), \tag{5}$$

where σ is the coefficient which depends on the parameters of the transmission line and frequency, V is the resonator volume, and μ'', μ_a'' are the imaginary parts of the tensor components

$$\bar{\bar{\mu}} = \begin{bmatrix} \mu & j\mu_a & 0 \\ -j\mu_a & \mu & 0 \\ 0 & 0 & \mu_{||} \end{bmatrix}, \tag{6}$$

and the hexaferrite slab is in the waveguide points with circular polarization of microwave magnetic field.

Another way to design wideband isolators is an application of a chain of monocrystalline magneto-uniaxial ferrite resonators with various values of H_A and/or different orientations of the internal magnetic field. For example, in an isolator for the fixed band 35.7...36.7 GHz with RL=15...40 dB, six spherical resonators made of Sr-Sc hexaferrite were used (H_A=9 kOe). Their orientation was 0...35^0 with respect to the bias field. Each sphere provided a

resonance absorption of 3...7 dB and an off-resonance loss less than 0.1 dB. Such isolators were implemented in the masers of traveling waves (Mikhailovsly et al., 2002).
Typically, hexaferrite resonators are placed upon a dielectric substrate, e.g. a ceramic slab with relative permittivity $\varepsilon \approx 9$, and this layered structure is fixed in the middle of the wide wall of the waveguide along the propagation direction. To make the isolators shorter, high-coercivity hexagonal ferrite plates or composite films of opposing (subtracting) magnetization are placed on two sides of a dielectric substrate.
Hexaferrite resonance isolators without bias magnets have been designed on various transmission lines (dielectric rod waveguides, dielectric reflecting waveguides, grooved waveguides, planar and cylindrical slot lines, spiral waveguides, and other specific types of the EHF transmission lines – see Fig. 6). The assurance of proper isolation is a crucial issue for practical realization of the required systems. Hexaferrite resonance isolators have been developed for a number of the abovementioned transmission lines.

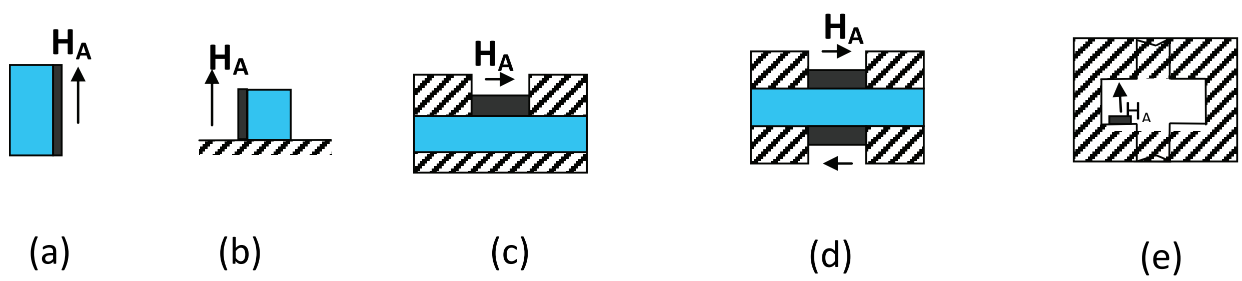


Fig. 6. Examples of hexagonal ferrite isolators on different transmission lines: (a) dielectric rod waveguides; (b) reflective dielectric rod line; (c) single-sided slot line; (d) double-sided slot line; and (e) waveguides with groove.

3.2 Off-resonance non-reciprocal devices

Herein, some examples of using high-coercivity *polycrystalline hexagonal ferrites* for the design of off-resonance non-reciprocal devices operating without any external bias magnetic field are considered. One of them is the Y-circulator. It is well-known that the circulator effect is possible only in gyrotropic media. Due to the presence of the off-diagonal component in the permeability tensor (5) of hexagonal ferrite, this is a gyrotropic, in particular, gyromagnetic medium. This component for magneto-uniaxial ferrites is

$$\mu_a \approx \frac{4\pi M_S H_\omega}{[(H_A + H_\omega)(H_A - H_\omega)]}, \quad (7)$$

where $H_\omega = \omega/\gamma$, even without any bias magnetic field H_0.
The design of such a circulator is analogous to that of traditional waveguide circulators (Tsankov et al., 1992). In the OPLF, the Y-circulator for 8-mm waveband was developed (Musial et al., 1972). It was using a cylinder made of a polycrystalline SrCrM ferrite with H_A=21 kOe, ΔH=1 kOe, H_C=1.5 kOe, $4\pi M_S$ = 3.4 kG, and $4\pi M_r$ =3.1 kG on the basis of the standard metal waveguide with the cross-section 7.2 x 3.4 mm^2 . The ferrite cylindrical was placed in the center completely coveing the cross-section. It was operating at frequencies above FMR.
In the short-wave part of the EHF band (above 100 GHz), the problem of extremely small cross-sections of standard transmission lines arises. Application of metal-dielectric waveguides, e.g., „hollow dielectric channel“ lines (Kazantev & Kharlashkin, 1978) may

solve this problem. Thus, instead of the standard metal waveguides of a cross-section of 1.1 mm x 0.55 mm, the metal-dielectric waveguides of 10 mm x 10 mm cross-section have been used, and three- and four- port circulators based on polycrystalline hexaferrites operating in the regime below the resonance (H_0=0) have been designed (Avakyan et al., 1995). Fig. 7 schematically shows a three-port circulator. If the load at Port 2 is a receiver, this system works as a waveguide switch in a single-antenna radar. In the case of a matched-load termination, this is an off-resonance isolator. In the circulator under study, a hexaferrite sample was magnetized to saturation along the axis of the waveguide, and was completely closing the cross-section of the waveguide. The length of the sample (along the axis of propagation) assured the 45^0 rotation of the polarization plane. In the circuits designed for the frequency ranges of 80-130 GHz and 40-180 GHz, the high-coercivity industrial synthesized hexagonal ferrites 03СЧА (H_A=35.0 kOe; ΔH=3.5 kOe, H_C=4.0 kOe, $4\pi M_s$ = 1400 G) and 04СЧА2 (H_A=23.5 kOe; ΔH=3.5 kOe, H_C=5.0 kOe, $4\pi M_s$ = 1900 G) were used. VSWR was about 1.1 in the 25% frequency bandwidth, and isolation was more than 18 dB.

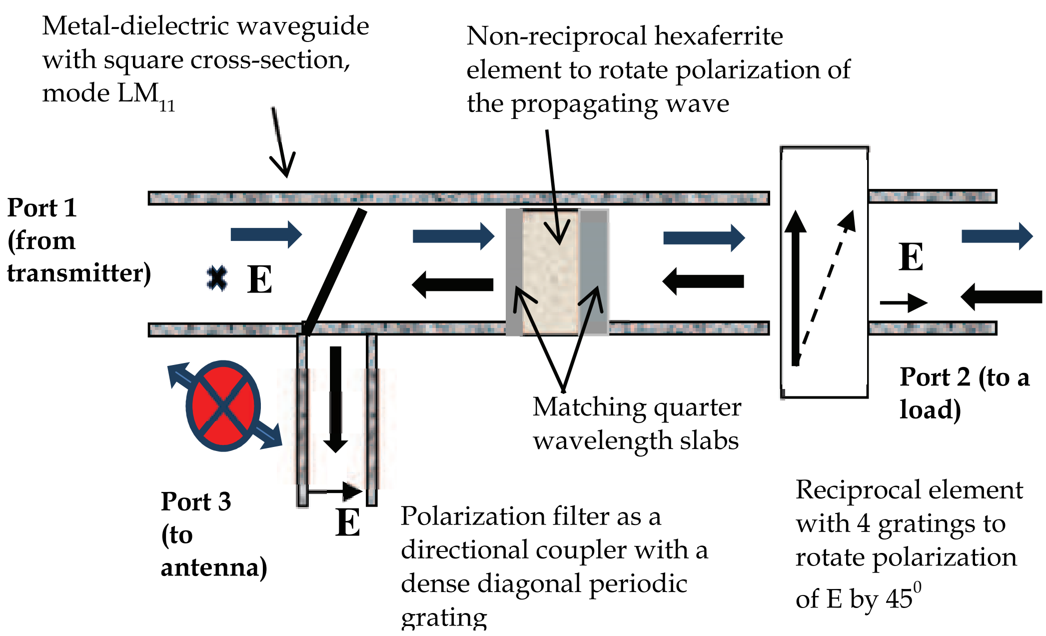


Fig. 7. Three-port circulator based on metal-dielectric waveguide with a hexaferrite slab

3.3 Bandpass and stopband filters

From the very beginning *monocrystalline hexaferrites* were specifically designed for applications in bandpass and stopband filters for the EHF range. Even nowadays, for many practical puropses EHF filters with required parameters can be designed only on the basis of monocrystalline hexaferrites.

An isolator with a monocrystalline hexaferrite is a *stopband filter* indeed. As is mentioned above, it provides signal suppression at the required frequency over a bandwidth of 10…40%. This can be achieved by the proper orientation of a spherical resonator made of a monocrystalline hexaferrite, when the bias magnetic field H_0 is fixed. Such filters were designed in MPEI using standard metal waveguides of cross-sections 7.2 mm × 3.4 mm, 5.2 mm × 2.6 mm, and 3.6 mm × 1.8 mm. They provide the rejection rate (defined as the difference between the power attenuation levels in the stopband and in the passband) of 20…40 dB in the frequency range 60…200 GHz (Mikhailovsky et al., 2002).

In magnetically tunable filters, a magneto-uniaxial hexagonal ferrite resonator is placed in a matched waveguide in such a way that the crystallographic axis would be parallel to the bias magnetic field ($H_A \| H_0$). Three methods have been tested for increasing the rejection rate of filters. First, this is an increase of the microwave field power density near the hexagonal ferrite resonator by placing it on a dielectric substrate in the waveguide. Second, an application of ferrite disk resonators with azimuth modes (Moiseyev & Pollak, 1982). Third method is the abovementioned effect of the "bound modes" due to combination of FMR and volume resonance of the hexaferrite resonator.
Crystals of magneto-uniaxial monocrystalline hexagonal ferrites with parallel orientation of H_A and H_0 have also been used in *bandpass filters* with magnetic tuning. The parameters of such filters are given in Table 5.

Frequency range, GHz	Band width at – 3 dB level, MHz	Insertion loss, dB, less than	Isolation outside the pass band, dB, more than	Transmission line
25 – 38	400	8	30	MW
36 – 52	500	7	30	MW
52 – 78	300	12	30	MW
52 – 78	250	8	30	DW
78 – 119	250	10	23	MW
78 – 105	400	10	30	DW

Table 5. Parameters of designed bandpass filters

An original design based on the orthogonal reflective *dielectric waveguides* has also been used at frequencies up to 150 GHz (Khokhlov et al, 1984). Our studies have shown that filters built on dielectric waveguides are technologically simpler compared to the metal waveguides, and they provide low insertion loss, as well as excellent non-reciprocal and directional properties. Therefore they can serve as elements of the EHF frequency band.

3.4 Ferrite mixers and frequency-selective primary transducers for power meters

A number of novel measuring systems and devices for EHF band have been developed in the OPLF of MPEI. Their design has been based on the application of high-anisotropy hexagonal ferrite resonators that provide a substantially reduced bias magnetic field necessary for operation. First of all, these are the new functional frequency-selective devices for measuring power parameters of signals of medium and high intensity.

Frequency range, GHz	Sensitivity, μW	VSWR	Operating bias field, kOe	Weight with magnet, g
25… 37.5	<150*	< 1.4	2.5 … 6.5	2440
37.5 … 52.5	< 60	< 1.3	2 … 5.3	2440
52.5 … 75	< 30	< 1.9	1 … 10	2440
66 … 74.4	< 60	< 1.7	0	110

* Ferrite contents was not optimized

Table 6. Parameters of designed ferrite mixers for the EHF frequency range

The *ferrite mixers* can be used in the devices for measuring pulse and continuous power in the frequency range of 25 - 75 GHz (Mikhailovsky et al., 1965; 2002). Their parameters are summarized in Table 6. In these mixers, the resonance response proportional to the power level under measurement is induced in a coil surrounding a cylindrical ferrite resonator. These mixers have sensitivity up to 30 μW, and they are characterized by extremely high stability to power overload. They have been developed within a single magnetic system. For the 4-mm waveband, a mixer has been developed without any magnetic system at all.

Another perspective application of monocrystalline hexaferrite resonators is development of magnetically tuned *primary transducers*. These transducers are intended for converting microwave to low-frequency signals. The picture of a stripline device with a magnetic detector – a ferrite resonator surrounded by a spiral microcoil is shown in Fig.8 (a).

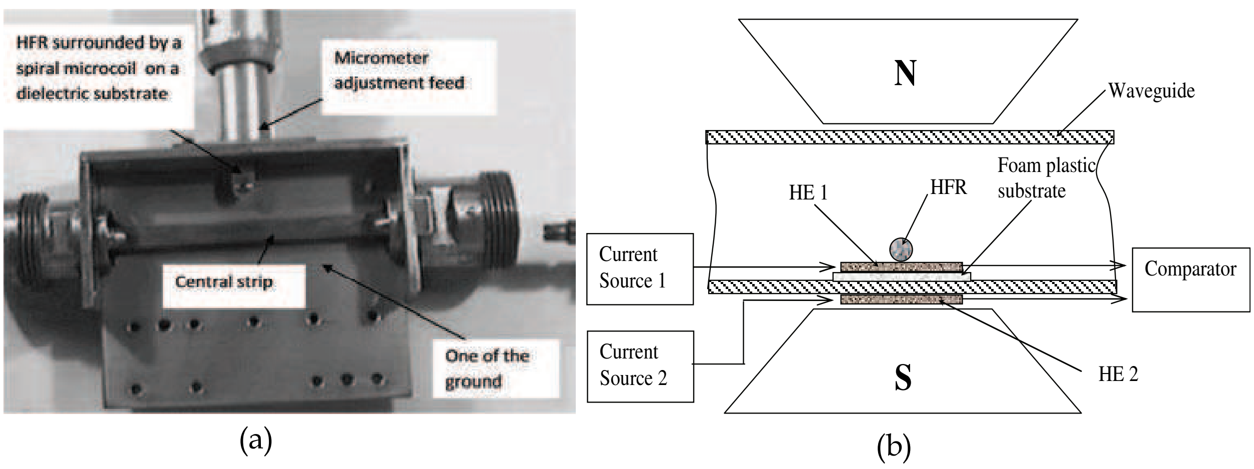
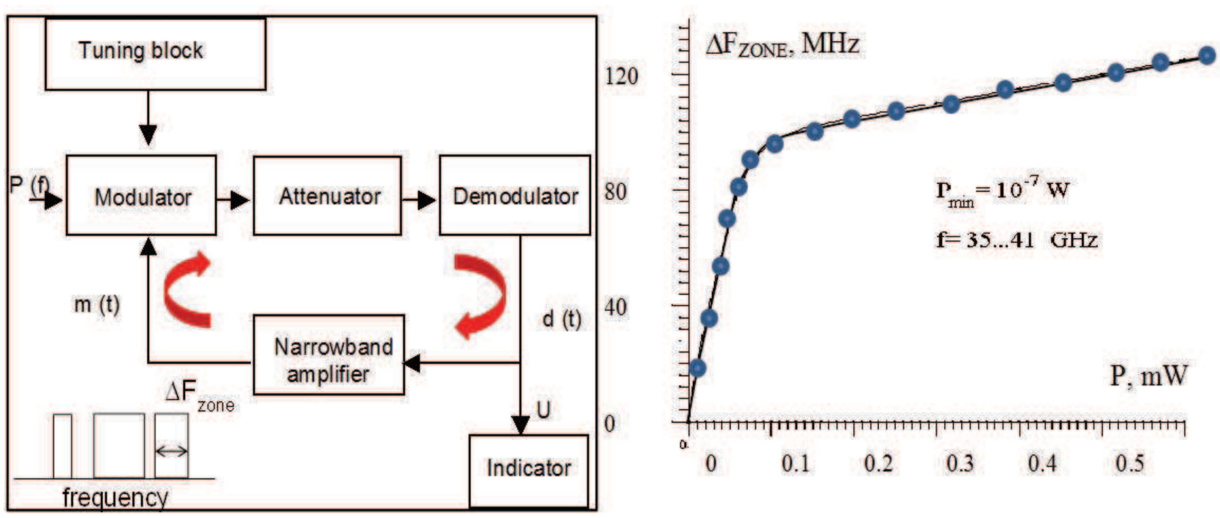


Fig. 8. (a) Stripline gyromagnetic frequency converter (top ground plane cover removed), and (b) primary transducer with two Hall elements

The magnetic detector was invented by L.K. Mikhailovsky (Mikhailovsky, 1964), and it has become the "heart" of a quantum cross-multiplier. This is a cross-non-linear element, which converts a microwave (mm-wave) carrier signal at the FMR (or NFMR) frequency down to harmonics of a pumping RF signal. Based on this element, a tunable single-frequency gyromagnetic converter was designed. It is now used for frequency-selective measuring of microwave power spectral density of short (nanosecond) pulse and noise signals.

However, a primary transducer with a spiral microcoil as shown in Fig. 8 (a) is effective only if it contains an extremely high-Q ferrogarnet monocrystalline resonators ($\Delta H<0.5$ Oe) and operates at comparatively low microwave frequencies (~300 MHz…18 GHz), requiring significant bias magnetic fields for keeping the ferrite resonator in magnetic saturation. For applications in the EHF band, the different design principles are needed. Thus, in early 1990s the authors of this Chapter proposed to use a monocrystalline magneto-uniaxial hexaferrite resonator (HFR) with comparatively narrow for hexagonal ferrites FMR line (ΔH~10 Oe) in direct contact with a semiconductor element. The latter is able to detect variation of the temperature of ferrite resonators at the absorption of electromagnetic power passing through them inside a transmission line. Two types of semiconductor thermo-sensitive elements were used in experimental testing of the hexagonal ferrite primary transducers, designed for the 8-mm band: (1) two Hall-elements (HE) connected in a compensating schematic as Fig. 8 (b), and (2) a chip transistor (without housing), used in a

diode regime, in a direct contact with an HFR. The designed transducers demonstrated a coefficient of power conversion of 10 μV/mW when using the Hall-element, and with chip transistors the coefficient of power conversion was about 1200 μV/mW. In all the cases, the linear dynamic range was in the range of 20-30 dB. Over the 4-mm band, the monocrystalline hexaferrites can have much smaller FMR line widths (since these will be resonators made of pure Ba-ferrites), so the expected parameters of such primary transducers or power converters are expected to be substantially better.
Also, an effect of the RF self-generation in a closed-loop system containing a ferrite resonator was detected and studied. This effect can also be used for frequency-selective microwave and mm-wave power measurements. The schematic is shown in Fig. 9, where a ferrite is affected by two signals - a microwave and a pumping RF (a few MHz), and the output signal of the crystal detector terminating the microwave transmission line is amplified by a narrowband RF amplifier and then is used as a feedback for the RF pumping of ferrite. Such system was built with a modulator which used a high-Q monocrystalline BaScM HFR for the 8-mm waveband.



a) b)

Fig. 9. (a) Autogeneration system with a modulator built with a HFR. (b)The width of a generation zone as a function of the spectral power density within an FMR line.

The system can be used as a threshold detector of power levels at the selected frequencies and also for frequency-selective power measurements. The pumping of the RF (1 MHz) signal is done by a piezoelectric element which modulates the resonance frequency of the hexaferrite resonator by varying its main axis orientation. The lower level of the measured power is determined by the sensitivity of the crystal detector, and the upper level depends on attenuation introduced by a calibrated attenuator in the feedback loop. The resonance frequency of the ferrite resonator is swept by a sawtooth current in the small bias magnetic system (H_0=0…3 kOe).

3.5 Absorbers of electromagnetic waves

Application of monocrystalline, polycrystalline, and dispersed conventional low-anisotropy garnet and spinel ferrites in shields, coatings, and various filtering devices of the EHF band is known to be limited, and in many cases, impossible, because of the necessity of applying intense bias magnetic fields (above ~10^6 A/m). For this reason, hexaferrites that have a high internal magnetic field are very desirable, since they exhibit natural ferromagnetic resonance (NFMR) even if no bias magnetic field is applied. In traditional devices of the SHF (3-30 GHz) and EHF (30-300 GHz) bands, mostly dense hexaferrite samples have been used. This limits the design possibilities for obtaining required frequency characteristics and other microwave or mm-wave parameters.

When monolithic hexaferrite samples are replaced by hexaferrite powders, an additional degree of freedom for engineering composites is created. Application of dispersed hexagonal ferrites allows for designing optimal devices and solving a number of technological problems, e.g., for absorbing the energy of electromagnetic fields and waves. The frequency characteristics of absorption loss in powders of doped hexagonal ferrites, taken from the functional series of the engineered materials, cover the frequency range from 4 to 40 GHz. The possibility of shifting the central frequency of absorption at the NFMR, varying the width of absorption, and modifying the shape of frequency characteristics is possible, for example, due to the variation of Scandium contents in the BaScM ferrites, as is shown in Fig. 10. An example of the absorption frequency dependence for a hexagonal ferrite thick film, which is made of a mixture of two different hexagonal ferrite powders in an epoxy resin base is given in Fig. 11. The frequency dependence is obtained based on the model proposed in (Pollak, 1977) for the effective electromagnetic parameters (permittivity and permeability) for composite materials containing highly anisotropic uniaxial hexagonal ferrite inclusions.

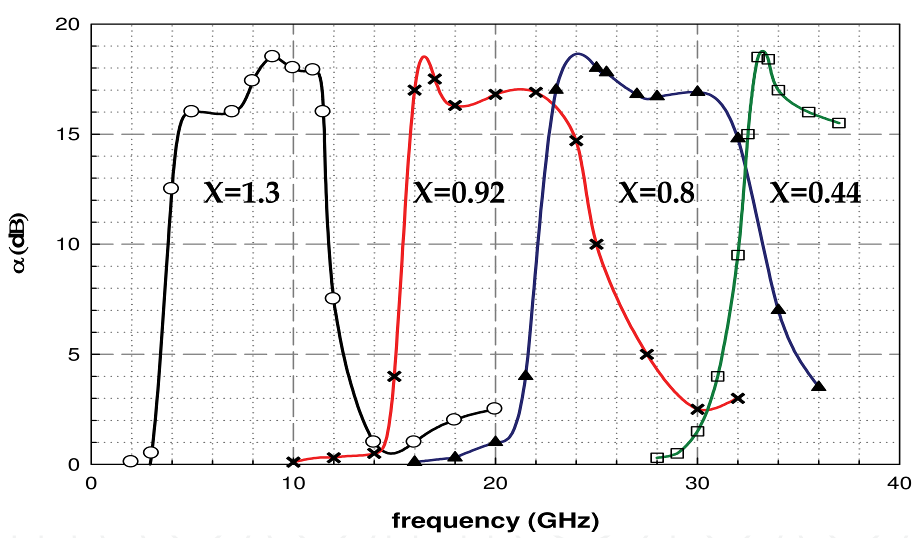


Fig. 10. Frequency characteristics of absorption loss in BaScM ($BaSc_xFe_{12-x}O_{19}$) ferrite

3.6 Phase shifters

Phase shifters are the only group of known gyromagnetic devices, where hexagonal ferrites have not received much attention yet. Application of hexagonal ferrites in phase shifters is substantially less popular compared to isolators and filters. Possibilities of using magneto-uniaxial and planar hexaferrites in laboratory samples of phase shifters in the frequency ranges of 30-35 GHz and 90-94 GHz have been reported in some publications, e.g., (Patton, 1988; Thompson, 1995). However, industrial designs and applications of such devices are still unknown. The reason for this is that to develop phase shifters, more narrowband materials with increased saturation magnetization and low dielectric loss are required.

However, it is clear now that a number of Russian-make hexaferrites (Catalogue, 2006) can be used for this purpose. The above mentioned examples of using hexagonal ferrites in non-resonance isolating devices with a fixed angle of polarization plane rotation (Musial, 1972) can apply to phase shifter design as well.

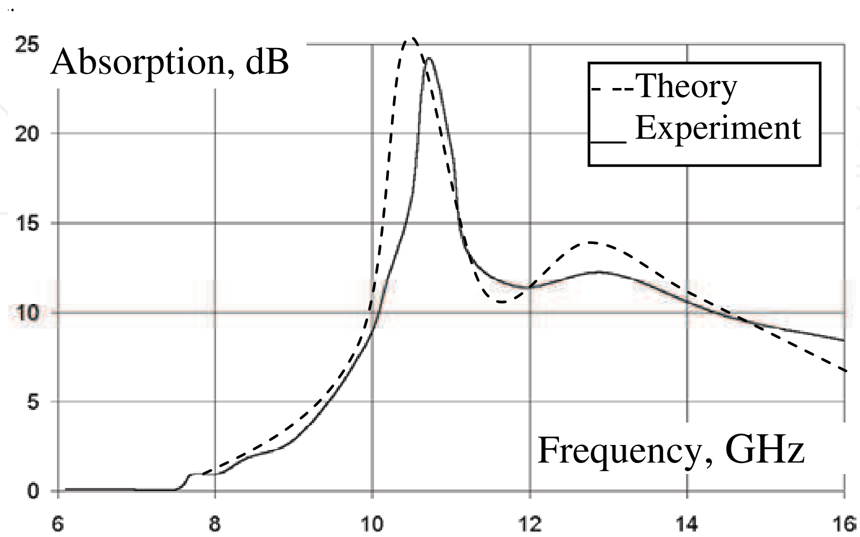


Fig. 11. Frequency characteristic of absorption of a thick film containing powders of hexagonal ferrites with two different compositions

3.7 Traveling-wave generators

The design of the EHF band *traveling-wave masers* (TWMs) requires creating built-in low-size non-reciprocal isolation at a given frequency and a certain magnetic field (the maser‘s operating magnetic field, including a zero magnetic field, is stringenly determined by the specifications). This problem was solved using the polycrystalline hexaferrite isolator. Another model of a TWM on rutile was developed using a chain of hexaferrite spherical resonators. For this purpose, multiple resonators assuring the necessary non-reciprocal per-unit-length isolation both at the fixed frequency and within a given frequency band have been designed. Tuning was achieved by variation of the orientation of the ferrite.

Traveling-wave tubes (TWTs) operating over the the EHF band belong to the class of the devices that definitely need, and we beleive that in future will widely use hexagonal ferrites. The traditional built-in absorbing filters protecting traveling-wave tubes from self-excitation cannot be used in the EHF band. Non-reciprocal isolation in the EHF band can be achieved only using hexaferrites. The experience of developing intra-tube non-reciprocal absorbers based on ferrite garnets in the centimeter waveband (Vambersky et al., 1973) adds optimism about the application of polycrystalline hexaferrites in the EHF band. The analysis of industrially manufactured TWTs shows that the specific delay systems needed for TWTs can be built into hexaferrite isolators. From our point of view, the most appropriate up-to-date design for realization of this idea is the delay system of the so-called *transparent TWT*. This is the output tube in the cascade of two TWT power amplifiers. For example, in the 8-mm waveband tube (which is an analogue of the tubes for 2-cm and 3-cm wavebands), providing an average output power up to 300 W in a frequency bandwidth of 1 GHz, and at the static bias field of 4 kOe, the application of polycrystalline ferrites can readily provide the required non-reciprocal isolation.

4. Societal applications of hexagonal ferrites

Some examples of applications of hexagonal ferrites in non-technical areas are given. These are applications in medical, agriculture, and transport monitoring, as well as in every-day electronic devices.

4.1 Microwave ovens

Microwave ovens are designed in such a way that there are protections against radiation leakage outside their enclosures. However, these measures are provided for the fundamental frequency and its second harmonic, while radiation at higher harmonics is not controlled or tested, although it may be substantial enough to cause EMC/EMI problems for the other electronic devices operating nearby.

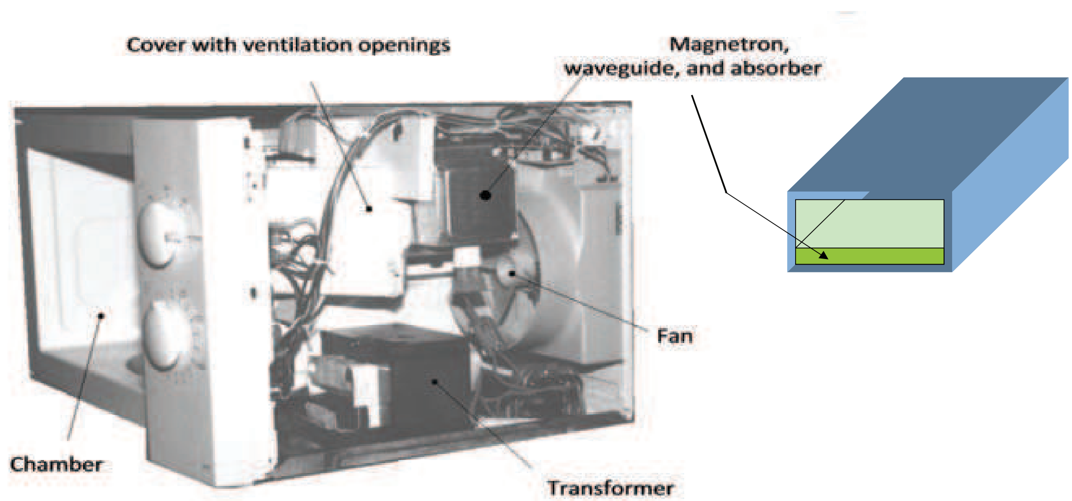


Fig. 12. Microwave oven with hexagonal ferrite absorber

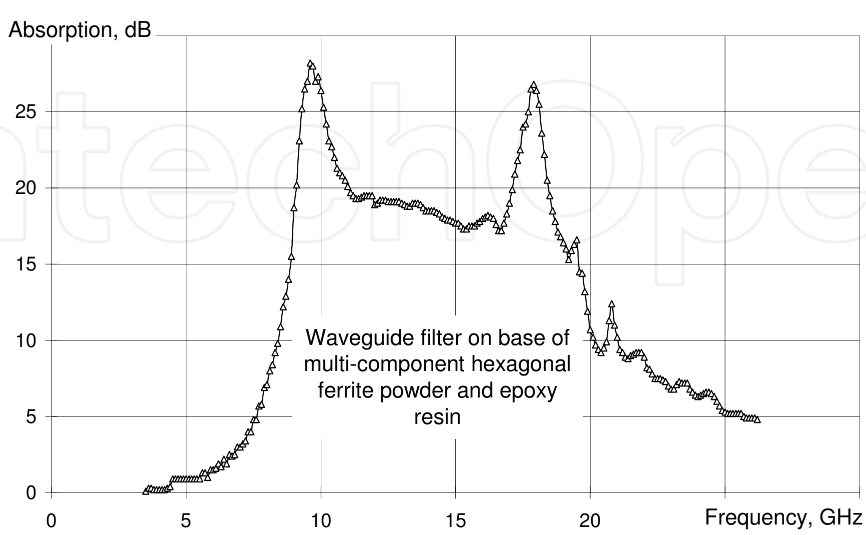


Fig. 13. Frequency characteristic of filter of harmonics for suppressing spurious radiation of microwave ovens

4.2 Protecting shields for high-speed electronic devices

The hexaferrite-based absorbers are recommended for protecting power cords, cables, individual intra-system blocks, enclosures, and antenna caps of modern high-speed electronic devices, including computers and cellular phones, whose operating frequencies fall into the microwave band (> 2 GHz). However, if these are active devices, leakage at the main (clock) frequency and its harmonics should be eliminated, as well as the susceptible circuits should be protected from external noise sources. Also, hexaferrites can be used in stealth-technology for creating non-reflecting surface coatings.

4.3 Medical applications – EHF therapy

Hexaferrite isolators, in addition to their known applications in traditional engineering systems, have been used in narrowband and wideband systems for EHF therapy (Avakian et al., 1995). For introducing the latest achievements and recommendations of EHF therapy, the development of non-reciprocal devices for the frequency bands of 42-95 GHz and 90-160 GHz was needed. Among the obvious requirements for the isolators to be included in medical devices for EHF therapy, are small size and weight, and low cost. From our point of view, only resonance isolators based on hexagonal ferrite composites, operating without any bias magnetic fields, can satisfy these criteria. Wideband isolators of this class have been developed for the frequency range of 37-118 GHz. The insertion (direct) loss in these isolators was 1.3-2.0 dB, while the return loss was 16-19 dB. Maximum return loss and minimum insertion loss have been noticed around 60 GHz. To satisfy the particular technical requirements of customers producing medical equipment, a number of isolators with a maximum of return loss at different frequencies within the above mentioned band have been designed.

4.4 Transport: radar systems for measuring motion parameters

The development of the EHF frequency range is very promising for small-size and highly accurate radars of local operation. Applications of isolated mirror and slot dielectric waveguides provide wide possibilities for integrated technology design of a microwave (mm-wave) system, which is much cheaper than using standard metal rectangular waveguides. The integrated microwave (or mm-wave) blocks unites an antenna, a pattern-forming circuit, and a signal processing device. All these advantages can be realized only when using hexagonal ferrite non-reciprocal isolators without external magnets. The latter can be manufactured using a film-sputtering technology. Thus, based on the mirror dielectric waveguide, the 8-mm wavelength block was tested within an automotive set for measuring parameters of motion and preventing traffic accidents. Based on the double-sided slot waveguide, two blocks were developed. The first was of the 5-mm wavelength Doppler measuring device to operate in the vibrometer (Bankov, 1999), and the second was developed for the 8-mm radar system with linear frequency modulator for the level gauge and other applications (Abdulkin et al., 1991). In addition to the given examples, it is important to also mention the potential advances of applying planar integrated EHF blocks on dielectric slot waveguides with hexaferrite isolation inside cellular network systems.

4.5 Agriculture: processing seeds before sowing

The application of special capsules for green-sprouting of seeds before their sowing is known. Typically, for this purpose, the biologically active porous materials, where seeds are placed together with a nutrient medium, are used. When a hexagonal ferrite particle, which is a miniature magnet (its size is less than 10 μm) is placed together with a seed, it substantially stimulates the process of green-sprouting. Hexagonal ferrite particles orient themselves along the Earth's magnetic lines, and this provides independence of the green-sprouting speed upon the seed's initial spatial orientation. The required magnitudes of the magnetic field intensity and coercive force are 0.5 T and 5 T, respectively.

5. Conclusion

A review of pioneering work conducted in the MPEI since 1950 on the theoretical and experimental study and development of hexaferrites and devices on their basis for different engineering and social applications is presented. As a result of the fundamental theoretical research led by Mikhailovsky, the founder of the OPLF, the magnetic bias field needed for the operation of the devices at higher microwave and mm-wave frequencies was „moved" to the crystal lattice of the gyromagnetic (ferrite) medium.For the first time in Russia, a new class of ferrite materials was synthesized: magneto-uniaxial hexagonal ferrites with high internal fields of crystallographic anisotropy. This allowed for the design of various gyromagnetic resonance devices operating without bias magnetic field or with low bias magnetization needed only for ferrite saturation and tuning of resonance frequency. These are the passive devices, such as resonance isolators, stopband and bandpass filters, circulators, matched loads, electromagnetic wave absorbers, and also cross-non-linear devices for mm-wave power measurements. Hexaferrites can be used for non-reciprocal isolators in masers and traveling-wave generators, and also for the design of frequency-selective microwave absorbing coats and filters that can solve numerous problems of electromagnetic compatibility and immunity. Over a hundred different types of polycrystalline and monocrystalline hexagonal ferrites having different composition have been synthesized in the OPLF, mainly for applications at 3-100 GHz. Based on those ferrites, over 20 different types of various composite electromagnetic wave „currentless" absorbers have been developed for the frequency range of 1.5 – 100 GHz.

Microwave and mm-wave devices of the future generation, whose development has been driven by modern wireless and radar technologies, should be mainly planar and low-loss, operating without huge external bias magnetic fields, and have more functional possibilities compared to conventional present-day devices. The authors are convinced that it would be impossible to solve these problems without using a natural physical advantageous feature of hexagonal ferrites – their high internal field of crystallographic anisotropy.

6. Acknowledgment

Koledintseva and Hanamirov dedicate this work to the memory of the colleague, Dr. Alexander A. Kitaitsev who passed away in November 2010, when the work on this Chapter has already begun. The authors of this review would like to express the deepest gratitude to the „fathers-founders" – Professors Leonard K. Mikhailovsky, Boris P. Pollak, and Vladirim P. Cheparin who for many decades lead the hexagonal ferrite research and synthesis in Russia. The authors are grateful to colleagues Dr. Tatyana S. Kasatkina, Dr. Irina E. Kabina, Dr. Sergey S. Egorov, Andrey A. Shinkov, and Andrey S. Fedotov, for useful discussions and participation in theoretical and experimental research.

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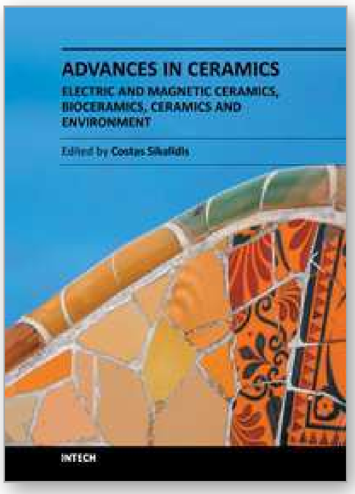

Advances in Ceramics - Electric and Magnetic Ceramics, Bioceramics, Ceramics and Environment
Edited by Prof. Costas Sikalidis

ISBN 978-953-307-350-7
Hard cover, 550 pages
Publisher InTech
Published online 06, September, 2011
Published in print edition September, 2011

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