MOEM

Modern Electronic Materials 5(1): 33–39
DOI 10.3897/j.moem.5.1.51295

Research Article

Measurement of effective magnetic anisotropy field and ferromagnetic resonance bandwidth at ferromagnetic resonance frequency in magnetically uniaxial hexagonal ferrites

Alexey S. Semenov[1], Aleksey G. Nalogin[1], Sergey V. Shcherbakov[1], Alexander V. Myasnikov[1], Igor M. Isaev[2], Vladimir G. Kostishin[2], Natalya E. Adiadulina[1], Albert A. Alekseev[1,2], Evgeny A. Belokon[1,2], Marina P. Mezentseva[2]

1 *JSC «RPC "Istok" named after Shokin», 2A Vokzalnaya Str., Fryazino, Moscow Region 141190, Russia*

2 *National University of Science and Technology MISiS, 4 Leninsky Prospekt, Moscow 119049, Russia*

Corresponding author: *Vladimir G. Kostishin* (drvgkostishyn@mail.ru)

Received 29 January 2019 ♦ **Accepted** 4 March 2019 ♦ **Published** 15 March 2019

Citation: Semenov AS, Nalogin AG, Shcherbakov SV, Myasnikov AV, Isaev IM, Kostishin VG, Adiadulina NE, Alekseev AA, Belokon EA, Mezentseva MP (2019) Measurement of effective magnetic anisotropy field and ferromagnetic resonance bandwidth at ferromagnetic resonance frequency in magnetically uniaxial hexagonal ferrites. Modern Electronic Materials 5(1): 33–39. doi.org/10.3897/j.moem.5.1.51295

Abstract

In this work we have considered metrological problems and measurement of magnetic parameters and presented methods of measuring effective magnetic anisotropy field H_{Aeff} and ferromagnetic resonance bandwidth ΔH in magnetically uniaxial hexagonal ferrites in the electromagnetic microwave working frequency range. The methods allow measuring H_{Aeff} in the 10–23 and 28–40 kE ranges and ΔH in the 0.5–5.0 range. One method (suitable for wavelength measurements in free space in the 3-mm wavelength range) has been implemented for the 78.33–118.1 GHz range. The other method (based on the use of microstrip transmission lines) has been implemented for the 25–67 GHz range.

The methods have been tested for polycrystalline specimens of hexagonal barium and strontium ferrites with nominal composition or complex substituted and having high magnetic texture. The measurement results have been compared with those obtained using conventional measurement methods and spherical specimens. Our methods prove to be highly accurate and reliable.

Keywords

magnetic crystallographic anisotropy, ferromagnetic resonance, magnetically uniaxial hexagonal ferrites, method of measurement in free space, measurement method based on the use of microstrip transmission lines

1. Introduction

Microwave electronics are currently the main development trend of the entire electronics industry [1–3], from material technologies [4, 5], device structures and electronic components to electronic and radioelectronic devices and systems on their basis [6].

The most promising microwave electronics materials are hexagonal ferrites in the form of single crystals or textured polycrystals [7–9]. These materials are the so-called magnetically uniaxial hexagonal ferrites and have high magnetic anisotropy fields [7–9]. Their use in ferrite microwave resonance devices allows reducing the required external field magnitude and hence the dimensions and weight of magnetic systems [9].

The demand for high-quality magnetically uniaxial hexagonal ferrites for microwave applications in electronics stimulates the improvement of existing and the development of new hexagonal ferrite technologies and studies of their properties [10–16].

The main parameters of ferromagnetic resonance **(FMR)** in polycrystalline magnetically uniaxial hexagonal ferrites **(MUHF)** are the effective anisotropy field H_{Aeff} and the ferromagnetic resonance bandwidth ΔH [9]. These parameters determine the position of the resonance spectrum in the magnetic field scale and the resonance absorption bandwidth. Characterization of MUHF specimens requires high-quality H_{Aeff} and ΔH measurement methods. Furthermore, H_{Aeff} should not be determined from statistical data but, as well as the ferromagnetic resonance bandwidth, from measurements directly in the working frequency range of hexagonal ferrites. This frequency range is typically the short-wave part of centimeter-wave range and the millimeter-wave range.

General problems of material properties measurement in microwave electromagnetic range were reported earlier [17–19]. Classical H_{Aeff} and ΔH measurement methods were presented [20]. Today, the electromagnetic properties of ferrites in the centimeter and millimeter wave ranges are mainly determined using unique measurement equipment, the measurement methods being quite labor consuming.

Below we consider methods for H_{Aeff} and ΔH measurement in polycrystalline MUHF in the following ranges:

- effective magnetic anisotropy field H_{Aeff}: 10–23 and 28–40 kE;
- FMR bandwidth ΔH: 0.5–5 kE.

2. Measurement of effective magnetic anisotropy field and FMR bandwidth in free space

2.1 H_{Aeff} and ΔH measurement in free space in 3-mm wavelength range

The method is based on the dependence of the FMR resonance frequency f_r in hexagonal ferrites on their effective magnetic anisotropy field H_{Aeff}. The principles of this method were partially described earlier [21, 22].

H_{Aeff} and ΔH were measured in polycrystalline MUHF with H_{Aeff} = 28–40 kE using demagnetized plane-parallel plates of MUHF materials with the texture axis orthogonal to their planes. Quasi-planar electromagnetic waves were passed through the plates in free space.

The wave impedance of the hexagonal ferrite plates ($\varepsilon_f = 13 \div 18$) was matched with the wave impedance of the free space using plane-parallel quartz plates ($\varepsilon_q = 3.8 \div 3.9$) located at both sides of the hexagonal ferrite plates. The thickness of the quartz plates was $\lambda_q/4$ where λ_q is the wavelength in the quartz plate at the measurement frequency. The specimen and the quartz plates were placed between two horn waveguide transitions one of which generated a quasi-planar electromagnetic wave and the other was excited by the quasi-planar electromagnetic wave after passage through the specimen.

The linear horn aperture size of horn waveguide transitions should be at least $3\lambda_0$ where λ_0 is the wavelength in the free space at the measurement frequency and be matched with the free space and the electromagnetic source. The voltage standing wave ratio of the horn waveguide transition entrance is max. 1.1).

Since the test specimen was demagnetized it could not excite a secondary wave and therefore the wave attenuated while passing through the specimen only due to the electromagnetic absorption at natural FMR. This effect is used for H_{Aeff} determination from resonance frequency f_r of natural FMR which is the minimum transmission coefficient at electromagnetic wave frequency measurement.

The H_{Aeff} determination method semi-empirically takes into account that f_r is affected by alternating demagnetizing fields caused by fluctuations of alternating magnetization at grain layer boundaries (Fig. 1).

Therefore H_{Aeff} is determined using the following formula:

$$H_{A_{\text{eff}}} = \frac{f_r}{\gamma} - \frac{2}{3} 4\pi M_s, \tag{1}$$

where γ is the gyromagnetic ratio and $4\pi M_s$ is the saturation magnetization which is measured using other methods.

The ferromagnetic resonance bandwidth ΔH and f_r are determined from the frequency dependence of the transmission ratio using the following expressions:

$$\Delta H = \frac{f_2 - f_1}{\gamma}, \tag{2}$$

$$f_r = \frac{f_1 - f_2}{2}, \tag{3}$$

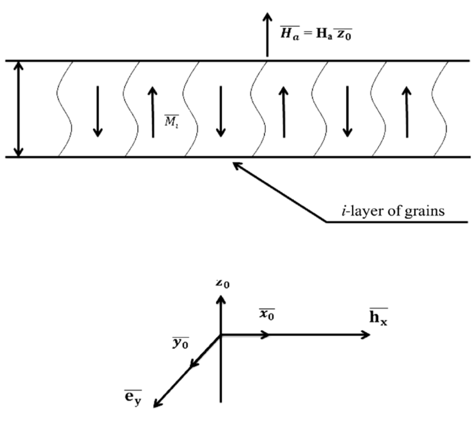


Figure 1. Model of demagnetized hexagonal ferrite plate.

where f_1 and f_2 are the magnetic resonance band frequencies corresponding to the half of the absorbed energy.

The method was tested for the 3-mm wave range using a panoramic device for voltage standing wave ratio and attenuation measurement Rem2.648.020 developed at Shokin NPP Istok JSC. The measurement results for polycrystalline hexagonal ferrite plates with H_{Aeff} = 28÷35 kE in free space were compared with the H_{Aeff} and ΔH measurement results for magnetized spherical specimens placed in the waveguide transmission line of the voltage standing wave ratio and attenuation meter. The spherical specimens were made from the same hexagonal ferrite material as the test plates. The difference of the H_{Aeff} and ΔH measurement results was within instrumental error (max. ±4 %).

2.2 Experimental device for H_{Aeff} and ΔH measurement in free space in 3-mm wave range

The panoramic device for voltage standing wave ratio and attenuation measurement R2-124M for 3-mm wave range (working frequency range 78.33–118.1 GHz) was used as a basis for the experimental unit for H_{Aeff} and ΔH measurement in free space.

The measurement unit included the panoramic device for voltage standing wave ratio and attenuation measurement R2-124M and the measurement module developed by the Authors which is connected into the measurement circuit.

The general appearance of the panoramic device for voltage standing wave ratio and attenuation measurement R2-124M is shown in Fig. 2 and its schematic is presented in Fig. 3.

The measurement module included a platform and two horn waveguide transitions (the waveguide cross-section is 1.2 × 2.4 mm^2 and the horn aperture is 10 × 10 or 14 × 14 mm^2) with the entrance voltage standing wave ratio being max. 1.1 in the working frequency range of the R2-124M meter.

Schematic of the measurement module with the test specimen and the matching quartz plates installed between horn waveguide transitions is shown in Fig. 4.

The experimental unit had the following parameters:

Figure 2. General appearance of R2-124M panoramic voltage standing wave ratio and attenuation meter.

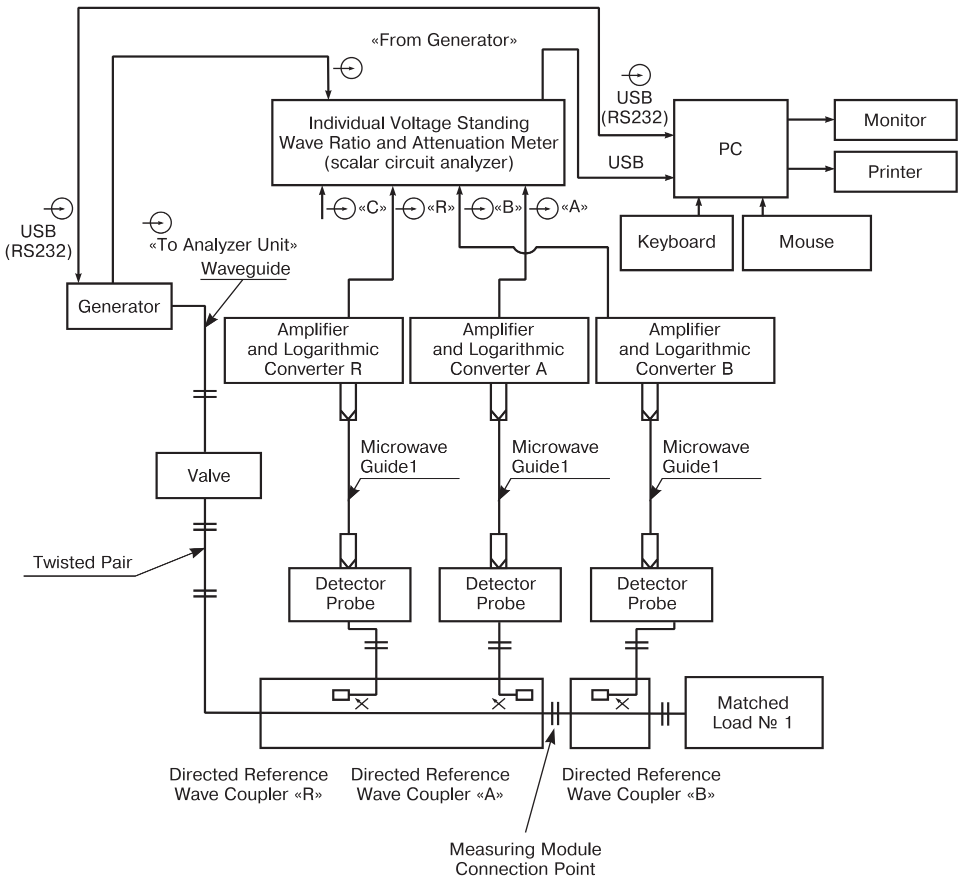


Figure 3. Schematic of R2-124M device.

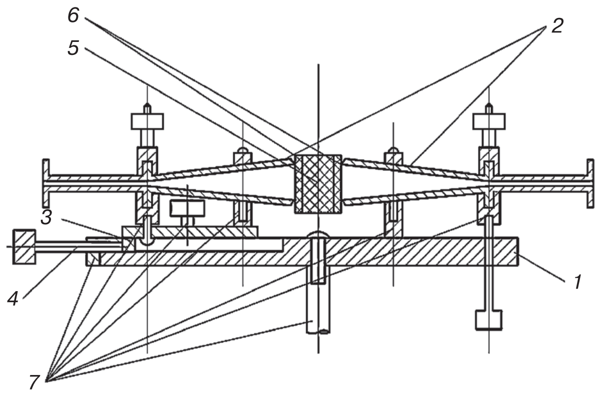


Figure 4. Schematic of measuring module: (*1*) platform, (*2*) measuring horns, (*3*) mobile plate, (*4*) adjustment screw, (*5*) specimen, (*6*) matching quartz plates and (*7*) connection hardware.

- working frequency range 78.33–118.1 GHz;
- measured parameter ranges: effective anisotropy field 28–40 kE, magnetic resonance bandwidth 0.3–5.0 kE;
- test specimen shape: plane-parallel rectangular (or round) plate with transverse sizes of at least 20 × 20 mm^2 (the diameter being at least 20 mm) and a thickness of 0.2–1.0 mm;
- matching quartz plate dimensions: transverse sizes min. 20 × 20 mm^2, thickness $\lambda_q/4$ (λ_q being the wavelength in quartz at the measurement frequency);
- measurement error range at 0.95 confidence: relative error of effective anisotropy field measurement ΔH_{Aeff} is max. ±5%; relative error of FMR bandwidth measurement (ΔH) is max. ±20%;
- operation conditions: ambient temperature (+10 ÷ +35) °C; relative humidity at 25 °C: 80%; atmospheric pressure 86÷106 kPa.

The saturation magnetization is measured using an AMT-4 automatic hysteresis recorder of Mianyang Shuangji Electronic Co. Ltd. (relative error of saturation magnetization measurement ±1%).

3. Measurement of effective anisotropy field and magnetic resonance bandwidth in magnetically uniaxial hexagonal ferrites at 25 to 67 GHz using microstrip transmission lines

We studied the possibility of measuring effective anisotropy field and FMR bandwidth based on analysis of interaction between a small-sized hexagonal ferrite specimen with electromagnetic field in a microstrip transmission line **(MTL)** and the dependence of magnetic resonance bandwidth in hexagonal ferrite specimens on H_{Aeff} using advanced broadband panoramic circuit analyzers.

Broadband measurements were carried out using an Agilent N5227A vector circuit analyzer as an MTL microwave meter with the test hexagonal ferrite specimen. The coaxial entrance cross-section of the circuit analyzer was 1.85/0.8 mm (working frequency range 10 MHz – 67 GHz). The MTL was synthesized on an aluminum substrate ($\varepsilon \approx 9.6$) with a wave impedance of 50 Ohm (substrate thickness 0.25 mm). The MTL substrate dimensions were chosen so to avoid excitation of higher-order modes in the MTL at frequencies of up to 67 GHz. The MTL was connected to the vector circuit analyzer using an Anritsu 3680V coaxial microstrip measurement module. The measurement module was in the form of a platform with two coaxial microstrip transitions (coaxial cross-section 1.85/0.8 mm). The MTL length ($l \approx 30$ mm) was chosen so the points of MTL connection to the coaxial lines be located as far as possible from each other in order to reduce the straight signal (outside the MTL).

The polycrystalline MUHF specimens were in the form of planar regular prisms with square bases and linear dimensions of within 0.5 × 0.5 mm^2, a thickness of 0.15–0.25 mm and the texture axis perpendicular to the prism base. The choice of these specimen dimensions allowed us to avoid the effect of dielectric resonance in the test hexagonal ferrite specimens ($\varepsilon_f \approx 13÷18$) on the shape of the FMR band in the 25–67 GHz range and provide for the excitation of the test specimen with a relatively homogeneous external electric field generated by the MTL.

The measurement unit included an Agilent N5227A vector circuit analyzer (working frequency range 10 MHz – 67 GHz), an Anritsu 3680V coaxial microstrip measurement module and an MTL section installed into the measuring module.

The measurement sequence was as follows.

1. The MTL on an aluminum substrate is installed into the measuring module connected to the circuit analyzer, and its transmission ratio is normalized (equalized).
2. The test specimen in the form of a prism sized max. 0.5 × 0.5 × (0.15–0.25) mm^3 is placed onto the MTL.
3. The frequencies are measured at the magnetic resonance band positions corresponding to the half of absorbed energy (f_1 and f_2).
4. The resonance frequency f_r, the effective anisotropy field H_{Aeff} and the magnetic resonance bandwidth ΔH are calculated using Eqs (3), (1) and (2), respectively. When assessing the effect of demagnetizing factors on the FMR resonance frequency we replaced the prism for an oblate inellipsoid of revolution.

If the specimen is magnetized and the measurements are carried out with an external magnetic field then the ΔH_{Aeff} equation will be as follows:

$$H_{\mathrm{A_{eff}}} = \frac{f_{\mathrm{r}}}{\gamma} + \frac{1}{2}(3N-1)4\pi M_0 - H_0, \qquad (4)$$

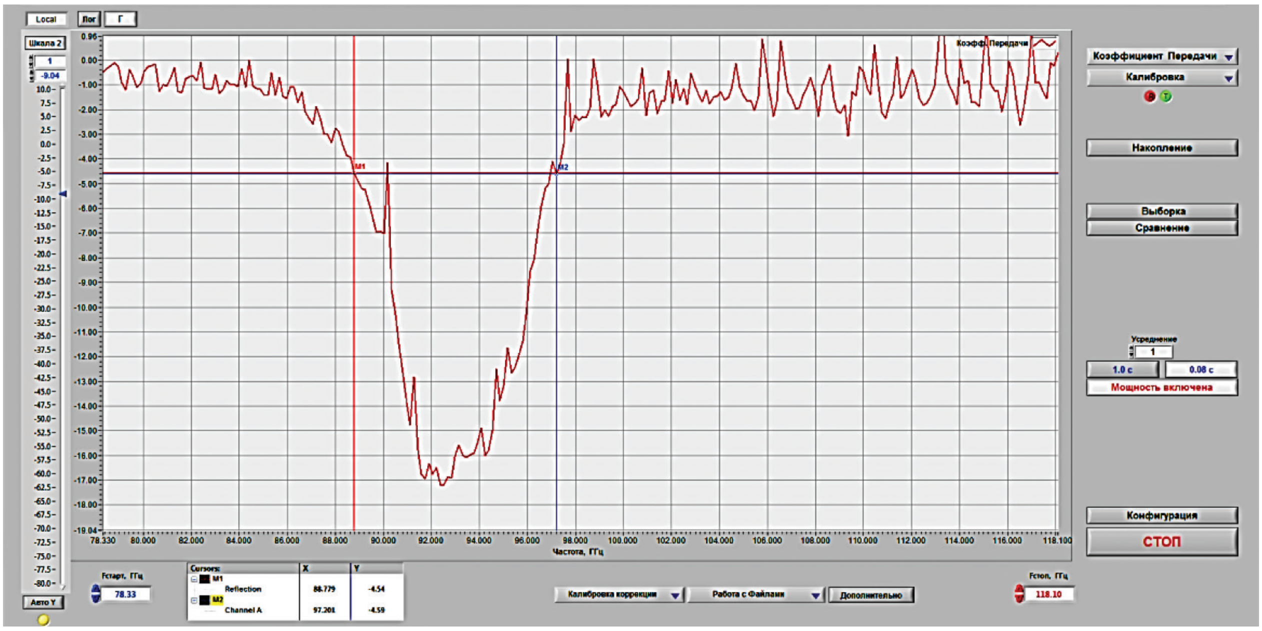


Figure 5. Interface with typical FMR spectrum in a plate of polycrystalline magnetically uniaxial hexagonal $BaFe_{12}O_{19}$ ferrite (measured in free space, specimen HB-13) [in Russian].

where γ is the gyromagnetic ratio, $4\pi M_0$ is the current saturation magnetization of the test specimen, H_0 is the external magnetic field magnitude and N is the demagnetization factor along the axis perpendicular to the prism base (for an oblate inellipsoid of revolution

$$N = \frac{1}{1-\vartheta^2}\left(1 - \frac{\sqrt{\vartheta}}{\sqrt{1-\vartheta^2}}\arccos\vartheta\right)$$

where ϑ is the ellipsoid height to diameter ratio).

If the specimen is magnetized the measurements are carried out without an external magnetic field:

$$H_{\mathrm{A_{eff}}} = \frac{f}{\gamma} + \frac{1}{2}(3N-1)4\pi M_0 \qquad (5)$$

where $4\pi M_s$ is the saturation magnetization of the test specimen and $4\pi M_r$ is the remanence of the test specimen.

If the specimen is demagnetized then:

$$H_{\mathrm{A_{eff}}} = \frac{f_s}{\gamma} + \zeta 4\pi M_s \qquad (6)$$

where ζ is the coefficient determined by the domain structure of the demagnetized test specimen.

When calculating H_{Aeff} using Eqs (4) and (5) one can approximate $M_0 = M_r$. As can be seen from Eqs (4), (5) and (6), more accurate H_{Aeff} calculation requires, depending on measurement mode, $4\pi M_0$, $4\pi M_r$, H_0, N and ζ be known, these parameters being determined from additional calculations. Otherwise the H_{Aeff} calculation error increases by an order of $\pm 4\pi M_s$.

When calculating H_{Aeff} using Eq. (6) for a demagnetized specimen we took ζ = -2/3 based on the results of our studies.

The experimental unit had the following parameters:

– working frequency range 20–67 GHz;
– measured parameter ranges: effective anisotropy field 10–23 kE, magnetic resonance bandwidth 0.1–5 kE;

- test specimen shape: planar rectangular with a square base and linear sizes of max. 0.5 × 0.5 mm^2 and a thickness of 0.15–0.25 mm, the texture axis being perpendicular to the prism base;
- measurement error range at 0.95 confidence: relative error of H_{Aeff} measurement (ΔH_{Aeff}) is max. ±5%; relative error of ΔH measurement $\Delta(\Delta H)$ is max. ±20%;
- operation conditions: ambient temperature 10–35 °C; relative humidity at 25 °C: 80%; atmospheric pressure 86÷106 kPa.

The saturation magnetization was measured using an AMT-4 automatic hysteresis recorder of Mianyang Shuangji Electronic Co. Ltd. (relative error of saturation magnetization measurement ±1%).

4. Testing of measurement methods suggested

4.1 Testing of method for measurement in free space

Figure 5 shows the experimental FMR spectrum in a demagnetized plane-parallel plate of magnetically uniaxial hexagonal barium ferrite in the 78.33–118.1 GHz range obtained by measuring in free space with the above-described experimental unit.

The diameter of the test plane-parallel demagnetized plates of barium MUHF was 30 mm, the thickness being 0.37 mm. The results of frequency measurements (f_1 and f_2) and H_{Aeff} and ΔH calculation using Eqs (1), (2) and (3) are summarized in Table 1.

4.2 Testing of method for measurement in 25 to 67 GHz range using microstrip transmission lines

H_{Aeff} and ΔH measurements using MTL were carried out for magnetized to saturation specimens from polycrystalline barium and strontium MUHF sized 0.5 × 0.5 × 0.25 (N = 0.53) using the above described method. Figure 6 shows the experimental FMR spectra of magnetized barium and strontium substituted MUHF without external magnetic field.

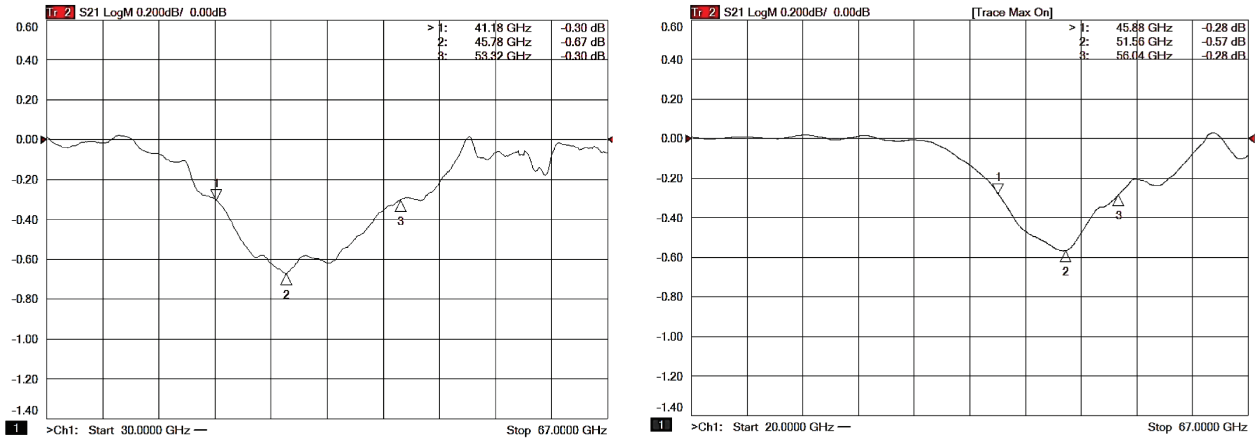
The results of frequency measurements (f_1 and f_2) and H_{Aeff} and ΔH calculation using Eqs (4), (6) and (8) are summarized in Table 2.

Table 1. Results of FMR parameter measurements for demagnetized MUHF plates in free space in millimeter wave range.

Parameter	Specimen	
	HB-13	HB-14
f_1, GHz	88.8	102.8
f_2, GHz	97.2	107.5
f_r, GHz	92.9	105.15
$4\pi M_s$, Gs	1800	1400
H_{Aeff}, kE	32.0	36.5
ΔH, kE	3.0	1.68

Table 2. Results of HAeff and ΔH measurement for MUHF in the 25–67 GHz range using a microstrip transmission line.

Parameter	Specimen (h = 0.25)	
	HB-2-5	HS-8-1
f_1, GHz	41.18	45.88
f_2, GHz	53.32	56.04
Δf, GHz	12.14	10.16
f_r, GHz	47.25	51.00
H_{Aeff}, kE	17.8	19.22
ΔH, kE	4.34	3.63
$4\pi M_r$, Gs	3200	3500



a *b*

Figure 6. Typical FMR spectra in a plate of polycrystalline magnetically uniaxial hexagonal ferrite measured with the MTL method: (*a*) $BaFe_{12}O_{19}$ (specimen HB-2-5) and (*b*) $Sr(Fe,Al,Si,Ca)_{12}O_{19}$ (specimen HS-8-1).

5. Conclusion

Our methods of measuring effective magnetic anisotropy field H_{Aeff} in the 10–23 and 28–40 kE ranges and ferromagnetic resonance bandwidth ΔH in the 0.5–5 kE range in magnetically uniaxial hexagonal ferrites were presented.

Testing of the methods for measuring H_{Aeff} and ΔH in polycrystalline magnetically uniaxial hexagonal barium and strontium ferrites of M type (nominal composition and complex substituted) showed their high accuracy and reliability. As compared with conventional H_{Aeff} and ΔH measuring methods for spherical specimens, our methods increase the measurement accuracy by 10–12 %.

We showed that our methods are effective in the measurement of electromagnetic parameters of magnetically uniaxial hexagonal ferrites used in microwave electronics and they will speed up the implementation of millimeter wave range devices on substrates made from these materials.

Acknowledgements

This work was performed within the Hexagonal Ferrite R&D Project funded by Shokin NPP Istok JSC with financial support from the Ministry of Education and Science of the Russian Federation under Subvention Agreement No. 14.575.21.0030 as of June 27, 2014 (RFMEFI57514X0030).

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