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

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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 $\Delta H$ 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 $\Delta H$ 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 tex-
The wave impedance of the hexagonal ferrite plates \((e_r = 13\pm18)\) was matched with the wave impedance of the free space using plane-parallel quartz plates \((e_r = 3.8\pm3.9)\) located at both sides of the hexagonal ferrite plates. The thickness of the quartz plates was \(\lambda_0/4\) where \(\lambda_0\) 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.

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 \(H_{\text{eff}}\) determination from resonance frequency \(f_r\) of natural FMR which is the minimum transmission coefficient at electromagnetic wave frequency measurement.

The \(H_{\text{eff}}\) 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 \(H_{\text{eff}}\) is determined using the following formula:

\[
H_{\text{eff}} = \frac{f_r - f_0}{\gamma} - \frac{2}{3} \frac{4\pi M_s},
\]

where \(\gamma\) is the gyromagnetic ratio and \(4\pi M_s\) is the saturation magnetization which is measured using other methods.

The ferromagnetic resonance bandwidth \(\Delta H\) and \(f_r\) are determined from the frequency dependence of the transmission ratio using the following expressions:

\[
\Delta H = \frac{f_2 - f_1}{\gamma},
\]

\[
f_r = \frac{f_0 - f_2}{2},
\]

![Figure 1. Model of demagnetized hexagonal ferrite plate.](image)
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 \( H_{\text{eff}} = 28 \pm 35 \text{ kE} \) in free space were compared with the \( H_{\text{eff}} \) and \( \Delta H \) 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 \( H_{\text{eff}} \) and \( \Delta H \) measurement results was within instrumental error (max. \( \pm 4 \% \)).

### 2.2 Experimental device for \( H_{\text{eff}} \) and \( \Delta H \) 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 \( H_{\text{eff}} \) and \( \Delta H \) 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 \( 1.2 \times 2.4 \text{ mm}^2 \) and the horn aperture is \( 10 \times 10 \) or \( 14 \times 14 \text{ mm}^2 \)) 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.](image-url)

![Figure 3. Schematic of R2-124M device.](image-url)
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 $H_{\text{eff}}$ 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 as 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 ($l = 30$ 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 $0.5 \times 0.5$ 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 ($\varepsilon = 13{+}18$) 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. $0.5 \times 0.5 \times (0.15–0.25)$ mm$^3$ is placed onto the MTL.
3. The frequencies are measured at the magnetic resonance band positions corresponding to the half of the energy (f$_r$ and f$_f$).
4. The resonance frequency $f_r$, the effective anisotropy field $H_{\text{eff}}$ and the magnetic resonance bandwidth $\Delta H$ 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 ellipsoid of revolution.

If the specimen is magnetized and the measurements are carried out with an external magnetic field then the $\Delta H_{\text{eff}}$ equation will be as follows:

$$H_{\text{eff}} = \frac{f_r}{f} + \frac{1}{2} (3N - 1) 4\pi M_0 - H_0,$$
where $\gamma$ 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 ellipsoid of revolution)

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

where $\vartheta$ is the ellipsoid height to diameter ratio.

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

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

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:

$$H_{A_{\text{eff}}} = \frac{f}{\gamma} + \zeta 4\pi M_s \quad (6)$$

where $\zeta$ is the coefficient determined by the domain structure of the demagnetized test specimen.

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

When calculating $H_{A_{\text{eff}}}$ using Eq. (6) for a demagnetized specimen we took $\zeta = -2/3$ 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. $0.5 \times 0.5$ 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 $H_{A_{\text{eff}}}$ measurement ($\Delta H_{A_{\text{eff}}}$) is max. $\pm 5$%; relative error of $\Delta H$ measurement ($\Delta (\Delta H)$) is max. $\pm 20$%;
- 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 $\pm 1\%$).

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 $\Delta H$ 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 $\Delta H$ measurements using MTL were carried out for magnetized to saturation specimens from polycrystalline barium and strontium MUHF sized $0.5 \times 0.5 \times 0.25$ ($N = 0.53$) 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 $\Delta H$ 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 |
| $4\Delta M$, Gs | 1800 | 1400 |
| $H_{Aeff}$, kE | 32.0 | 36.5 |
| $\Delta H$, kE | 3.0 | 1.68 |

Table 2. Results of $H_{Aeff}$ and $\Delta H$ 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 |
| $\Delta f$, GHz | 12.14 | 10.16 |
| $f_r$, GHz | 47.25 | 51.00 |
| $H_{Aeff}$, kE | 17.8 | 19.22 |
| $\Delta H$, kE | 4.34 | 3.63 |
| $4\Delta M$, Gs | 3200 | 3500 |

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,St,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 $\Delta H$ in the 0.5–5 kE range in magnetically uniaxial hexagonal ferrites were presented.

Testing of the methods for measuring $H_{Aeff}$ and $\Delta H$ 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 $\Delta H$ 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.

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