Physical and Technical Bases of Using Ferromagnetic Resonance in Hexagonal Ferrites for Electromagnetic Compatibility Problems

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***Abstract*—Frequency-selective measurement of microwave signal parameters based on application of gyromagnetic converters has proven advantageous for the research of microwave radiation over a wide spectrum (several octaves) in multisignal regime in microwave path and for the solution of a number of electromagnetic compatibility (EMC) problems. The measurement frequency band can be enlarged to millimeter-waves with application of monocrystal hexagonal ferrite resonators (HFR) having high internal magnetic fields. Millimeter-wave field interactions with the HFR having alternating resonance frequency are analyzed. This is useful for millimeter-wave signal modulation and demodulation. The analysis is based on the solution of magnetization vector motion equation of the uniaxial spherical HFR with time-varying bias magnetic field or angle of the HFR orientation (for modulation problem) and with amplitude-modulated microwave signal action (for demodulation problem). The novel principle of the HFR frequency-selective measuring system based on automodulation design is discussed.**

***Index Terms*— Automodulation, ferromagnetic resonance, frequency-selective measurements, gyromagnetic converter, hexagonal ferrite resonator, millimeter waves, multisignal regime.**

I. Introduction

SERIOUS problems result from the necessity of performing adequate microwave power measurements with unknown intensity and frequency ranges and in a multisignal regime of active devices operation (more than three signals). Such problems take place, for example, with microwave signal amplification by wide-band microwave output power tubes. Even at the harmonic input signal the output spectrum may be complicated, containing intermodulation, combination, out-of-band, or spurious oscillations. In this situation, the use of traditional measuring devices (integral power measurers, heterodyne spectrum analyzers, and measuring receivers) does not give adequate information on the spectrum character and there are many problems associated with the measurement device power calibration with unmatched active sources and identification of reception channels.

This paper deals with a novel frequency-selective method of power measurement using ferromagnetic resonance (FMR). Its main purpose is to lay the theoretical basis for this method at millimeter frequencies.

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For microwave power spectrum measurements over a wide frequency range (more than two octaves), frequency-selective panorama (with envelope spectrum view) measurements based on gyromagnetic converters (GC) have found application. They are used for investigation of microwave radiation of middle- and high-power level (experimentally, the various constructions of ferrogarnet GC on different types of microwave transmission lines in decimeter and centimeter frequency band permit to operate at the continuous power from 10^{-3} to 10^{3} W with own linear dynamic range of a GC about 25 dB [1]). Due to nonheterodyne principle of frequency and power conversion [2], the GC are free from spurious channels of reception related to combination and intermodulation frequencies. So the devices on the GC are especially useful at multifrequency regime in the microwave waveguide path. They have constant conversion coefficient over a broad frequency band and because of their frequency selectivity can measure rather small signal spectrum density in presence of intensive electromagnetic interference. The demands on the preselector at the input (−60 dB loss outside the passband and minimum possible loss in the passband) may be less stringent when using the GC because the GC has a selectivity curve similar to that of the four-resonator ferrite filter [3].

GC is designed on base of the ferrite resonator (FR) with element (spiral microcoil or Hall-element) for its resonance frequency modulation and the converted signal output. In the frequency range from 300 MHz to 30 GHz, mainly monocrystal ferrogarnet resonators with narrow resonance line are used. The FR is magnetized by the external magnetic system used for the resonator tuning over a wide frequency range. However, ferrogarnets having low field of internal crystallographic anisotropy are not used in the millimeter wave band, because they need field of FR magnetization, increasing with the operating frequency and, thus, the external magnets become too massive. Application of prospective hexagonal monocrystal ferrites having large internal magnetic field of crystallographic anisotropy leads to the possibility of the GC design for millimeter wave band (from 30 to 200 GHz) without massive external magnets [4].

The principle of the GC operation is based on stable nonlinear resonance effects (SNLRE's) at ferromagnetic resonance (FMR) and microwave power lower than the level that would excite spin-wave instability. Interaction of microwave radiation and FR with unmodulated resonance frequency ("resonance detection") or modulated resonance

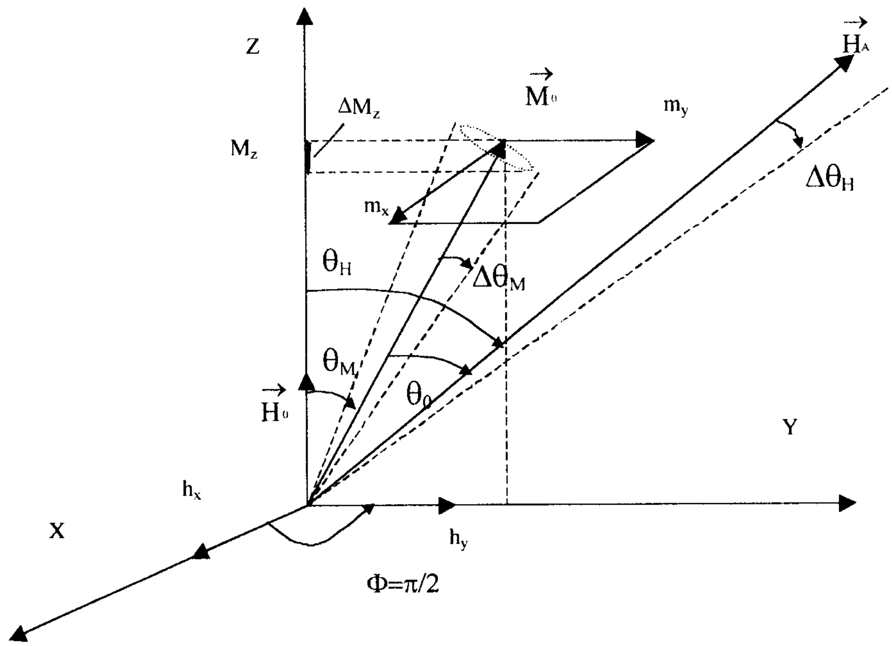

Fig. 1. Orientation of the main HFR vectors.

frequency ("cross-multiplication") result in nonlinear relations between transversal and longitudinal components of the FR magnetization vector [1], [2]. Thus, the longitudinal component and envelope of microwave signal reradiated by the FR contain information of spectrum power density of microwave radiation at the resonance frequency.

At cross multiplication in the vicinity of the FMR the longitudinal component of the FR magnetization vector contains the harmonics of the modulation frequency $\Psi_n(a,p,q)$ [5] and so does the voltage in the output element (microcoil or Hall element) $E_n(a,p,q)$. Each harmonic can be selected by the proper filter of the converted signal at an intermediate frequency. The amplitude of the harmonic depends on the microwave signal power P, relative detuning of the FR resonance frequency from that of the signal $a = (\omega - \omega_0)/\delta$, relative modulation frequency $p = \Omega/\delta$, normalized amplitude of modulation $q = \omega_m/\Omega$, where ω_m is deviation of resonance frequency, Ω is frequency of modulation, and δ is the HFR resonance line width.

SNLRE's have been already studied in crystallographically "isotropic" ferrogarnet FR [5]–[7]. SNLRE's in the HFR are more complicated, because of the large internal field of crystallographic anisotropy H_A. The present paper considers the analysis of these effects taking into account H_A and its arbitrary direction θ_H with respect to the constant field of external magnetization H_0. It is the more general problem, and its solution should coincide with that for the "isotropic" case, where the crystallographic field $H_A \to 0$ and the angle $\theta_H \to 0$.

II. Theoretical Analysis

Theoretical analysis is based on nonlinear vector differential magnetization motion equation [8] with time-varying coefficients. This approach is valid if the FR is a single-domain, magnetically uniaxial saturated particle of spherical form with dimensions essentially less than the wavelength. In the general case of an arbitrarily oriented HFR with arbitrary modulation frequencies, the solution of the problem is intractable. So we make some simplifications, which correspond to real situation in GC design.

- HFR crystallographic anisotropy field is more than bias field $(H_A > H_0)$.
- Modulation frequency is essentially less than relaxation one $(\Omega \ll \omega_r)$.

Then we can use "quasi-static" approach based on application of the known tensor of the magnetic susceptibility of the HFR. We consider small angles of magnetization vector precession and small deviations of the HFR resonance frequency, $\omega_m \ll \omega_{\text{res}}$, so there is no difference on what type of dissipation term to take into account [10]. For simplicity, we assume Landau–Lifshits damping usually used in the hexagonal ferrite susceptibility tensor [8], [11].

A. Interaction of the Harmonic Millimeter-Wave Signal with the HFR Having Alternating Resonance Frequency—Modulation of Millimeter-Wave Signal

The HFR resonance frequency can be controlled in two ways. One way is the same as used in GC with ferrogarnets; that is, "field" control by alternating current in the microcoil surrounding the FR [1]. The second way is specific for the HFR; it is "angular" control via deviation of the angle θ of H_A orientation. We shall consider both mentioned cases.

As it follows from the condition of the uniaxial crystal minimum magnetic energy, the equilibrium magnetic moment $\mathbf{M_0}$, the external (bias) magnetic field $\mathbf{H_0}$ and the crystallographic anisotropy magnetic field $\mathbf{H_A}$ are coplanar vectors [8], [10]. For definiteness, let us consider the magnetic moment $\mathbf{M_0} \in (yz)$, see Fig. 1.

The components of the susceptibility tensor in general case depend on angle Φ [11], but here $\Phi = \pi/2$

$$\overset{\leftrightarrow}{\chi} = \begin{vmatrix} \chi_{11} & j\chi_a \cos\theta_M & j\chi_a \sin\theta_M \\ -j\chi_a \cos\theta_M & \chi_{22}\cos^2\theta_M & \chi_{22}\sin\theta_M\cos\theta_M \\ -j\chi_a \sin\theta_M & -\chi_{22}\cos\theta_M \sin\theta_M & \chi_{22}\sin^2\theta_M \end{vmatrix} \quad (1)$$

where

$$\chi_{11} = \frac{\omega_M(\omega_1 + j\omega\alpha)}{\Delta}; \quad \chi_{22} = \frac{\omega_M(\omega_2 + j\omega\alpha)}{\Delta};$$
$$\Delta = \omega_1\omega_2 - \omega^2(\alpha^2+1) + j\omega\alpha(\omega_1+\omega_2)$$

$$\omega_1 = \omega_0 \cos\theta_M + \omega_A \cos^2\theta_0; \quad (2)$$
$$\omega_2 = \omega_0 \cos\theta_M + \omega_A \cos 2\theta_0 \quad (3)$$

where $\omega_M = \mu_0\gamma M_0$, $\omega_0 = \mu_0\gamma H_0$, $\omega_A = \mu_0\gamma H_A$, α is the dissipation parameter in Landau-Lifshits form [8]. The HFR resonance frequency is determined from the corresponding determinant set equal to zero

$$\omega_{\rm res} = \sqrt{\omega_1\omega_2}. \quad (4)$$

For both "field" and "angular" resonance frequency control we can represent the resonance frequency at small amplitudes of deviation as following:

$$\omega_{\rm res} = \omega_{r0} + \omega_m \cos\Omega t \quad (5)$$

ω_m is proportional to the magnitude of bias magnetic field variation h_z at "field" control and to the deviation of the HFR orientation $\Delta\theta_H$ at "angular" control.

Since the frequency of modulation in the "quasi-static" case is essentially less than that of the relaxation, the relationship between the angles can be assumed as in the static case, which follows from the minimum of the magnetic energy of the crystal [8]

$$\sin 2\theta_0 = 2H_0/H_A \times \sin(\theta_H - \theta_0) \quad (6)$$
$$\theta_H = \theta_M + \theta_0. \quad (7)$$

Each tensor component contains real and imaginary terms

$$\chi_{\alpha\beta} = \chi'_{\alpha\beta} + j\chi''_{\alpha\beta}. \quad (8)$$

We can represent the millimeter wave transverse components of magnetization vector as oscillations with slowly varying amplitude and phase

$$m_\alpha = G_\alpha \cos(\omega t + \varphi_\alpha), \quad \text{at } \alpha = x, y \quad (9)$$

if the millimeter wave field has the components h_x, h_y (for instance, mode H_{10} in rectangular waveguide with axis of propagation x), then [9]

$$G_\alpha = \sqrt{|\chi_{\alpha x}|^2 h_{xm}^2 + |\chi_{\alpha y}|^2 h_{ym}^2 + 2h_{xm}h_{ym}\Delta_\chi} \quad (10)$$

where

$$\Delta_\chi = \chi'_{\alpha x}\chi''_{\alpha y} - \chi''_{\alpha x}\chi'_{\alpha y}$$

and the amplitude G_α can be expanded into Fourier series

$$G_\alpha = g_0^\alpha/2 + \sum_{n=1}^{\infty} \left(g_n^\alpha \cos n\Omega t + f_n^\alpha \sin n\Omega t\right). \quad (11)$$

Because of rather implicit form of this function, the Fourier expansion may be evaluated numerically.

Harmonics of the envelopes of millimeter wave signals, coupled by the HFR into the waveguide (transfer and reflection coefficients), also carry information on the input power at the center frequency. They are determined via the HFR (with dimensions essentially less than the wave length) representation as an elementary magnetic dipole radiating into the waveguide, the radiated field components depending on the magnetization components, and the latter, in their turn, depending on the radiated magnetic field (method of "self-matched field" [8]).

The envelope of millimeter wave magnetization components, taking into account coupling coefficient β of the HFR with waveguide, is expressed as [9]

$$G_\alpha^s = G_\alpha/(1+\beta) \quad (12)$$

where

$$\beta = 1 - \omega\mu_0 V_f/(2N_{10}) \times \cos\gamma_{10}(x - x_0)(|\chi_{xx}|h_{xm}^2 + |\chi_{yy}|h_{ym}^2)$$

V_f is ferrite resonator volume, N_{10} is wave norm [12], γ_{10} is propagation constant of H_{10} wave, $h_{xm,ym}$ are amplitudes of the millimeter wave magnetic field components.

The modulation coefficient of the transferred wave approximately is found from the "self-matched field" problem solution as [9]

$$Q \approx 0.5\left(\frac{\omega\mu_0 V_f}{N}\right)^2 \left(G_x h_{xm}^2 + G_y h_{ym}^2\right). \quad (13)$$

Spectra of $G_{x,y}$ determine the spectra of modulation coefficient Q and, thus, the conversion coefficient at the chosen harmonic. The form of the modulation coefficient harmonic amplitudes versus the relative detuning $a = (\omega - \omega)/\delta$ coincides with the form of corresponding harmonics of the susceptibility tensor components and with the forms of analogous dependencies for the "isotropic" case [5]–[7]. The harmonic amplitudes almost linearly increase with the normalized amplitude of modulation $q = \omega_m/\Omega$ growth at low Ω ("quasi-static" case).

Amplitudes of the harmonics in the envelope of the transferred signal are proportional to the intensity of the input signal and depend on a number of HFR physical parameters: anisotropy field, relaxation frequency, orientation, value of the external field of magnetization, waveguide path parameters, and the point of the HFR placement in the waveguide. Maximum amplitude of any harmonic can be achieved at certain combination of H_0 and angle of orientation θ_H for the ferrite with given H_A. Computations show that at the "field" control maximum amplitude of modulation Q_1 on the first harmonic of frequency Ω corresponds to the "zero" orientation, $\theta_H = 0$. At the "angular" control with fixed angular deviation $\Delta\theta$ maximum amplitude of modulation Q_1 is reached at the optimum angle of orientation θ_H lying in the interval 30°–70° (see Fig. 2) [13].

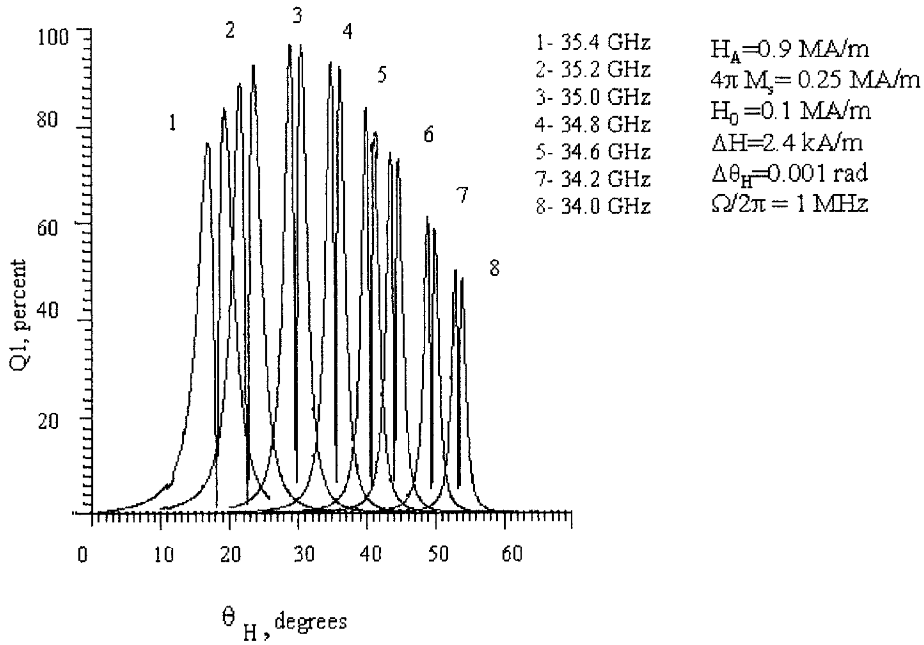

Fig. 2. Amplitude of the first harmonic of modulation frequency versus the HFR angle of orientation.

B. Interaction of the Modulated Signal with the HFR—Demodulation

Now let us consider the case with the HFR excited by the modulated millimeter wave signal having the following components of the magnetic field:

$$\begin{cases} h_x = h_{xm}(1+Q)\cos(\omega t + \Phi) \\ h_y = h_{ym}(1+Q)\sin(\omega t + \Phi) \end{cases} \tag{14}$$

where $Q(t)$, $\Phi(t)$—modulated amplitude and phase, correspondingly.

Let us find voltage induced in spiral microcoil, surrounding the HFR due to the variation of the longitudinal component of the magnetization vector. Since the relation between the variation of the longitudinal component of the magnetization vector and its transversal components is nonlinear [8], [14] then, following from the geometry of the problem, the variation of the M_z is

$$\Delta M_z = \frac{m_x^2 + m_y^2}{2M_0}\cos\theta_M \tag{15}$$

and voltage E induced in the microcoil is

$$\begin{aligned} E &= -Z\frac{dM_z}{dt} \\ E &= \frac{Z}{M_0}\cos\theta_M\left(m_x \cdot \frac{dm_x}{dt} + m_y \cdot \frac{dm_y}{dt}\right) \end{aligned} \tag{16}$$

where Z is the coefficient depending on the geometry and parameters of the microcoil.

Taking into account the relation between millimeter wave components of the magnetization vector and the millimeter wave magnetic field via the tensor of magnetic susceptibility, we can obtain the expression for the voltage E in microcoil. Derivation of the formulas is represented in the Appendix [see (A.11), (A.15a), (A.15b)]

$$E = \frac{Z}{2M_0}\cos\theta_M Q(1+Q')\left(h_{xm}^2 g_x^2 + h_{ym}^2 g_y^2\right) \tag{17}$$

where

$$g_x^2 = \frac{(\omega\omega_M\alpha)^2 + (\omega_M\omega_1)^2 + (\omega\omega_M\cos\theta_M)^2}{(\omega\omega_1 - \omega^2(1+\alpha^2))^2 + (\omega\alpha(\omega_1+\omega_2))^2} \tag{18}$$

$$g_y^2 = \frac{(\omega\omega_M\alpha)^2 + (\omega_M\omega_2\cos^2\theta_M)^2 + (\omega\omega_M\cos\theta_M)^2}{(\omega\omega_1 - \omega^2(1+\alpha^2))^2 + (\omega\alpha(\omega_1+\omega_2))^2}. \tag{19}$$

This output voltage E has resonance character and achieves maximum at the FMR by choosing proper external field of magnetization H_0 and angle of orientation θ (Fig. 3). The voltage increases with the reduction of the parameter α, i.e., with the decrease of the FMR line width. If the millimeter wave signal is unmodulated, the output voltage is equal to zero. If the signal has amplitude modulation with the depth m and frequency Ω

$$Q(t) = m\cos\Omega t \tag{20}$$

then the voltage E contains the first and the second harmonics of the modulation frequency, because the component $Q'(t)(1+Q(t))$ in (17) is

$$Q'(1+Q) = -\Omega m\sin\Omega t + (m^2\Omega/2)\sin 2\Omega t \tag{21}$$

and with the increase of the modulation frequency Ω the voltage E rises linearly (in the limits of "quasi-static" approximation at relatively low-modulation frequencies). With the growth of the depth of modulation m the amplitudes of the voltage harmonics also increase: the first one linearly, the second one as a square.

It is important to note that there is no dependence on phase of millimeter wave signal acting on the HFR, because of the

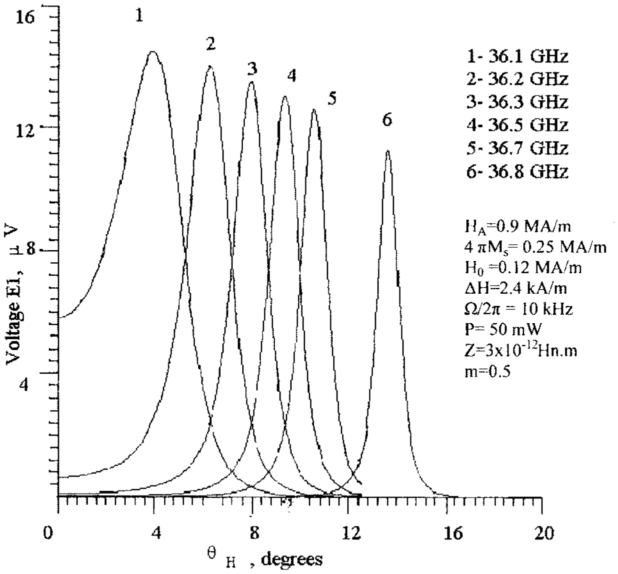

Fig. 3. Dependence of the output voltage in the microcoil on the angle of the HFR orientation.

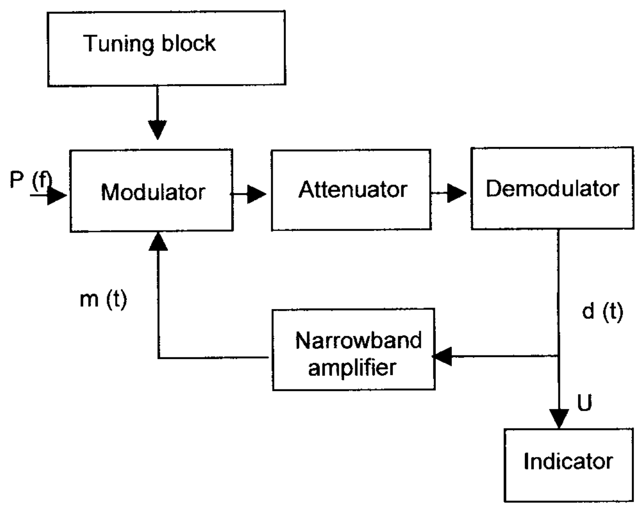

Fig. 4. Scheme of automodulation measuring system.

square-law character of dependence between the longitudinal and transversal components of the magnetization vector. Harmonics of the voltage contain information on the millimeter wave power at the certain frequency. These results coincide with the solution of the same problem for "isotropic" ferrite at low values of frequency Ω and depth of modulation m [15].

III. Design of the Measuring System

The processes of modulation and demodulation considered above provide the design principles of an automodulation measuring system on HFR with feedback on the intermediate (RF) frequency and narrow-band amplifier in the feedback loop (see Fig. 4) [16].

The envelope of the millimeter-wave signal modulated by the HFR modulator is detected by means of the demodulator (either any conventional, rather wide-band millimeter wave detector or frequency-selective HFR demodulator) and it contains harmonics of the intermediate modulation frequency. One of these harmonics can be used as the feedback signal so that the system has automodulation. This system can be used for frequency-selective threshold tolerance control of millimeter wave radiation, i.e., it allows the detection of millimeter wave signal if its power exceeds certain normalized level in the vicinity of the HFR FMR frequency.

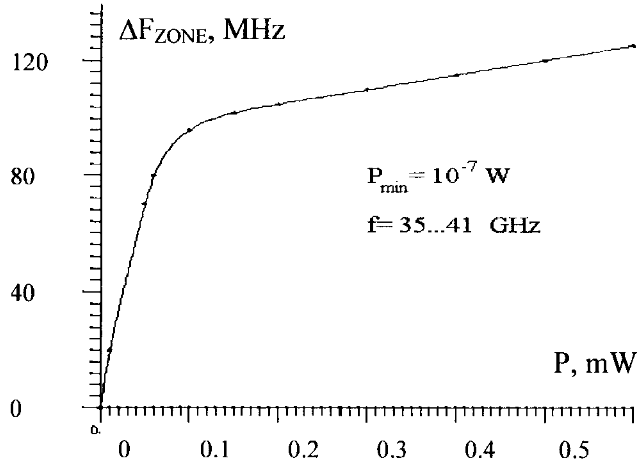

Fig. 5. Oscillation zone bandwidth versus input microwave power.

When tuning the HFR by slow linear variation of its bias magnetic field H_0, we realize that RF oscillations in the closed loop are automatically sustained only in a limited interval of bias field ΔH_{zone}, or in the corresponding millimeter wave frequency range ΔF_{zone}. This frequency range ΔF_{zone} we call an *oscillation zone*. Self-sustained oscillations take place if the millimeter wave signal falls at one of the HFR resonance curve slopes (phase balance) and if the input power is more than the certain threshold level (amplitude balance). Frequency of oscillation in the loop is determined by the narrow-band amplifier central frequency.

The dependence of the oscillation zone bandwidth ΔF_{zone} upon the input power P at corresponding frequencies has linear sections (Fig. 5). This permits frequency-selective measurements.

Some details of this system analysis (choosing the elements of the feedback loop, amplitude and phase relations in the circuit, threshold power level of signal detection, analysis of the oscillation zone bandwidth versus input microwave power) and experimental results are described in papers [17], [18]. The device has a number of advantages in comparison with the conventional GC and cascade junction of the GC with the crystal detector in millimeter wave band: high sensitivity (10^{-7} W), high selectivity, due to the automodulation comparable to that realized in the GC on base of YIG resonators with narrow line width—about 5 MHz), larger linear dynamic range (about 50 dB), independence of the output voltage amplitude on the input power, leading to better measurement reliability.

IV. Conclusion

Application of high-anisotropy monocrystal HFR in frequency-selective measurement devices allow the measurement of power at millimeter wave frequencies in multifrequency regimes of active device operation and tolerance control of power levels at certain frequencies. Modulation and demodulation of millimeter signals using stable nonlinear resonance effects of HFR resonators have been discussed. The measurement system design using the automodulation scheme on base of the HFR modulator and demodulator leads to increased sensitivity, selectivity, and the dynamic range of the device when comparing to the HFR frequency and power converters with spiral microcoils and with conventional crystal detectors. Tolerance control and power measurements become more reliable. The described system application reduces design constraints of the preselectors at the input of millimeter wave measuring devices and, thus, eliminates difficulties connected with the technology of their production.

APPENDIX

Let us consider the case when millimeter wave magnetic field acting on the HFR has the following components h_x and h_y:

$$\begin{cases} h_x(t) = h_{xm}(1+Q(t))\cos(\omega t + \Phi(t)) \\ h_y(t) = h_{ym}(1+Q(t))\sin(\omega t + \Phi(t)) \end{cases} \tag{A.1}$$

where the modulating oscillation amplitude is expanded into Fourier series

$$Q = Q_0/2 + \sum_{n=1}^{\infty} Q_n \cos(n\Omega t) + \sum_{n=1}^{\infty} P_n \sin(n\Omega t). \tag{A.2}$$

The longitudinal magnetization vector component variation is connected with the transverse microwave magnetization components by the approximate formula, following from the geometry of the problem [8], [14]

$$\Delta M_z = \frac{m_x^2 + m_y^2}{2M_0}\cos\theta_M. \tag{A.3}$$

Complex amplitudes (denoted by points) of the microwave magnetization and magnetic field are related via susceptibility tensor components

$$\begin{cases} \dot{m}_x = \chi_{xx}\dot{h}_x + \chi_{xy}\dot{h}_y \\ \dot{m}_y = \chi_{yx}\dot{h}_x + \chi_{yy}\dot{h}_y \\ \dot{m}_z = \chi_{zx}\dot{h}_x + \chi_{zy}\dot{h}_y. \end{cases} \tag{A.4}$$

Longitudinal magnetization vector component variation ΔM_z can be rewritten as

$$\Delta M_z = \frac{\cos\theta_M}{2M_0}(1+Q)^2\{(k_1\cos\omega t + k_2 \sin\omega t)^2 + (k_3\cos\omega t + k_4\sin\omega t)^2\} \tag{A.5}$$

where

$$\begin{cases} k_1 = \chi'_{xx}h_{xm} + \chi''_{xy}h_{ym} \\ k_2 = -\chi''_{xx}h_{xm} + \chi'_{xy}h_{ym} \\ k_3 = \chi'_{yx}h_{xm} + \chi''_{yy}h_{ym} \\ k_4 = -\chi''_{yx}h_{xm} + \chi'_{xy}h_{ym}. \end{cases} \tag{A.6}$$

Let us find voltage induced in the microcoil surrounding the HFR

$$E = -Z\frac{dM_z}{dt}. \tag{A.7}$$

Then

$$E = \frac{Z\cos\theta_M}{2M_0}Q'(t)(1+Q(t))\left(k_1^2+k_2^2+k_3^2+k_4^2\right). \tag{A.8}$$

According to (A.6),

$$k_1^2+k_2^2+k_3^2+k_4^2 = h_{xm}^2(|\chi_{xx}|^2 + |\chi_{yx}|^2) + h_{ym}^2(|\chi_{xy}|^2+|\chi_{yy}|^2). \tag{A.9}$$

With notations

$$\begin{cases} g_x = |\chi_{xx}|^2 + |\chi_{yx}|^2 \\ g_y = |\chi_{xy}|^2 + |\chi_{yy}|^2 \end{cases} \tag{A.10}$$

we get the formula for the voltage E

$$E = \frac{Z}{2M_0}\cos\theta_M Q(1+Q')\left(h_{xm}^2 g_x^2 + h_{ym}^2 g_y^2\right). \tag{A.11}$$

The formulas for $g_{x,y}$ are derived below.

Each susceptibility component module can be represented as

$$|\chi_{\alpha\beta}| = \frac{\sqrt{(\omega F_{\alpha\beta})^2 + K_{\alpha\beta}^2}}{\sqrt{B^2+C^2}} \tag{A.12}$$

where with Landau–Lifshits damping [8] we have

$$B^2 + C^2 = (\omega_1\omega_2 - \omega^2(1+\alpha^2))^2 + (\omega\alpha(\omega_1+\omega_2))^2. \tag{A.13}$$

Coefficients $F_{\alpha\beta}$, $K_{\alpha\beta}$ for the components of $\chi_{\alpha\beta}$ at the equilibrium vector $\vec{M}_0 \in (yz)$ are the following:

$$\begin{cases} K_{xx} = \omega_M\omega \\ F_{xx} = \omega_M\alpha \\ K_{xy} = K_{yx} = 0 \\ F_{xy} = -F_{yx} = \omega_M\cos\theta_M \\ K_{yy} = \omega_2\omega_M\cos^2\theta_M \\ F_{yy} = \alpha\omega_M\cos^2\theta_M. \end{cases} \tag{A.14}$$

Substituting these expressions into (A.10), we finally get

$$g_x^2 = \frac{(\omega\omega_M\alpha)^2 + (\omega_M\omega_1)^2 + (\omega\omega_M\cos\theta_M)^2}{(\omega\omega_1 - \omega^2(1+\alpha^2))^2 + (\omega\alpha(\omega_1+\omega_2))^2} \tag{A.15a}$$

$$g_y^2 = \frac{(\omega\omega_M\alpha)^2 + (\omega_M\omega_2\cos^2\theta_M)^2 + (\omega\omega_M\cos\theta_M)^2}{(\omega\omega_1 - \omega^2(1+\alpha^2))^2 + (\omega\alpha(\omega_1+\omega_2))^2}. \tag{A.15b}$$

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