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MILLIMETER WAVE SIGNALS DETECTION BY MEANS OF MONOCRYSTAL HEXAGONAL FERRITE ELLIPSOID

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Frequency-selective 'panorama' devices on base of gyromagnetic converters (GC) for detection, visualization and measurement of power parameters of middle and high-intense microwave signals in wide frequency band (several octaves) have found application [1].

The principle of the GC operation is based on stable nonlinear resonance effects (SNLREs) at ferromagnetic resonance (FMR), taking place in ferrite resonators (FR) at power levels less than that of spin-wave instability. At interaction of microwave irradiation and FR with unmodulated resonance frequency ("resonance detection") or modulated resonance frequency ("cross-multiplication") nonlinear relations between transversal and longitudinal components of the FR magnetization vector are evident [1]. 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.

SNLREs have been already studied in crystallographically 'isotropic' ferrogarnet FR [2], employed in the frequency range of 300 MHz to 30 GHz. Application of prospective hexagonal monocrystal ferrites with large field of crystallographic magnetic anisotropy leads to the possibility of the GC design for mm waveband (from 30 to 200 GHz) without massive external magnets. This paper deals with the analysis of a more general case with taking into account both crystallographic H_A and form H_F anisotropy of HFE as well as its arbitrary orientation of the main crystallographic axis θ with respect to the constant field of external magnetization H_0.

Let us consider the HFE to be a single-domain, magnetically uniaxial saturated small (compared to wavelength) ellipsoid. For an arbitrarily oriented HFE with arbitrary modulation frequencies the solution of the problem is intractable. So we make some simplifications, which correspond to real situation in GC design: (1) $H_A > H_0$; and modulation frequency is essentially less than relaxation one $(\Omega \ll \omega_r)$. (2) We consider small angles of magnetization vector precession and small deviations of the HFR resonance frequency, $\omega_m \ll \omega_{res}$.

The HFE resonance frequency can be controlled ('modulated') 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 The second way is specific for the HFE, it is 'angular' control via deviation of the angle θ of H_A orientation.

The resonance frequency of the uniaxially anisotropic HFE with arbitrary oriented crystallographic axis and ellipsoid axis in respect to the external magnetic field H_0 is determined by method of effective demagnetization factors (sum of demagnetization tensors of form and crystallography),

$$\tilde{N} = \tilde{N}_F + \tilde{N}_C$$

and the solution of a static problem for the equillibrium magnetization moment M_0 [3].

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

$$\omega_{res} = \omega_{r0} + \omega_m \cos\Omega t, \tag{1}$$

ω_m is proportional to the magnitude of bias magnetic field variation h_z at "field" control and to the deviation of the HFE crystallographic anisotropy field orientation $\Delta\theta$ at "angular" control.

The mm-wave magnetization vector components have slowly varying amplitude and phase [4],

$$m_\alpha = G_\alpha \cos(\omega t + \varphi_\alpha), \text{ at } \alpha = x, y \tag{2}$$

where
$$G_\alpha = \sqrt{\left|\chi_{\alpha x}\right|^2 h_{xm}^2 + \left|\chi_{\alpha y}\right|^2 h_{ym}^2 + 2h_{xm}h_{ym}\Delta_\chi} \tag{3}$$

and h_x, h_y are components of mm-wave field (for instance, mode H_{10} in rectangular waveguide), each component of the HFE susceptibility tensor $\chi_{\alpha\beta}$ written in Cartesian coordinates in 9-component form with Landau-Lifshits dissipation term [3, 5], contains real and imaginary parts, $\Delta_\chi = \chi'_{\alpha x} \chi''_{\alpha y} - \chi''_{\alpha x} \chi'_{\alpha y}$.

The amplitude G_α can be expanded into Fourier series,

$$G_\alpha = g_0^\alpha / 2 + \sum_{n=1}^{\infty}(g_n^\alpha \cos n\Omega t + f_n^\alpha \sin n\Omega t) \qquad (4)$$

Harmonics of the envelopes of mm-wave signals, coupled by the HFE into the waveguide (transfer and reflection coefficients), also carry information on the input power at the certain frequency. They are determined via the HFE representation as an elementary magnetic dipole radiating into the waveguide, using the technique of eigenwaves and the solution of 'self-matched field' problem [3]. Then the modulation coefficient of the transferred wave approximately is [4],

$$Q \approx 0.5(\frac{\omega\mu_0 V_f}{N})^2 (G_x h^2{}_{xm} + G_y h^2{}_{ym}), \qquad (5)$$

where V_f is ferrite resonator volume, N is the main wave norm, $h_{xm,ym}$ are amplitudes of the mm-wave magnetic field components.

Spectra of $G_{x,y}$ determine the spectra of modulation coefficient Q. The form of the modulation coefficient harmonic amplitudes versus the relative detuning $a=(\omega-\omega_0)/\delta$ coincides with the form of correspondent harmonics of the susceptibility tensor components and with the forms of analogous dependencies for the 'isotropic' case [2]. The harmonic amplitudes almost linearly increase with the normalized amplitude of modulation $q=\omega_m/\Omega$ growth at low modulation frequency Ω. Amplitudes of the harmonics in the envelope of the transferred signal are proportional to the intensity of the input signal. They also depend on the HFE physical parameters: anisotropy field, relaxation frequency, orientation, value of the external field of magnetization, waveguide path parameters, point of the HFE placement in the waveguide, etc. Maximum amplitude of any harmonic is achieved at certain combination of H_0 and angle of orientation θ for the ferrite with given H_A. Computations for the spherical HF resonator (which has the only resonance response due to the only main magnetostatic type of precession) show that at the 'field' control maximum modulation depth on the 1-st harmonic of modulation frequency corresponds to the 'zero' orientation, $\theta=0$. And at the 'angular' control with the fixed angular deviation the optimum angle of orientation this angle lies in the interval 30-70 degrees [6].

Now let us assume the HFE to be excited by the modulated mm-wave signal having the following components of the magnetic field

$$\begin{cases} h_x = h_{xm}(1+Q)\cos(\omega t + \Phi) \\ h_y = h_{ym}(1+Q)\sin(\omega t + \Phi) \end{cases}, \qquad (6)$$

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

Since the variation of the M_z follows from the geometry of the problem (see [5]):

$$\Delta M_z = \frac{m_x^2 + m_y^2}{2M_0}\cos\theta_M , \qquad (7)$$

then taking into account the relation between mm-wave components m_α amd h_α via susceptibility tensor voltage, we get E induced in spiral microcoil with the constructive coefficient Z :

$$E = \frac{Z}{2M_s}\cos\theta_M Q'(1+Q)(h_{xm}^2 g_x^2 + h_{ym}^2 g_y^2) , \qquad (8)$$

where

$$g_x^2 = \frac{(\omega\omega_M \alpha)^2 + (\omega_M \omega_1)^2 + (\omega\omega_M \cos\theta_M)^2}{(\omega\omega_1 - \omega^2(1+\alpha^2))^2 + (\omega\alpha(\omega_1 + \omega_2))^2} , \qquad (9)$$

$$g_y^2 = \frac{(\omega\omega_M \alpha)^2 + (\omega_M \omega_2 \cos^2\theta_M)^2 + (\omega\omega_M \cos\theta_M)^2}{(\omega\omega_1 - \omega^2(1+\alpha^2))^2 + (\omega\alpha(\omega_1 + \omega_2))^2} . \qquad (10)$$

This output voltage has resonance character and reaches maximum at the FMR by choosing corresponding external field of magnetization and angle of orientation. The voltage increases with the reduction of the parameter

α, i.e. with the decrease of the HFE FMR width line. If the signal is non-modulated, the voltage is equal to 0. If the signal has amplitude modulation

$$Q(t) = m\cos\Omega t, \tag{11}$$

then the voltage E contains the 1-st and the 2-nd harmonics of the modulation frequency, because

$$Q' \ (1+Q) = -\Omega m \sin\Omega t + (m^2\Omega/2)\sin 2\Omega t, \tag{12}$$

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

There is no dependence upon the phase of mm-wave signal, because of the square-law relation between the longitudinal and transversal components of the magnetization vector. Harmonics of the voltage contain information on the mm-wave power at the certain frequency. These results coincide with the solution of the same problem for 'isotropic' ferrite at low frequency and depth of modulation [2].

The processes of modulation and demodulation considered above lay the principles of design of an automodulation measuring system on HFE with feedback on the intermediate frequency and narrow-band amplifier in the feedback loop. This system operation and analysis (choosing the elements of the feedback loop, amplitude and phase relations in the circuit, threshold power level of signal detection, analysis of the generations zones width versus input microwave power) and experimental results on getting zones of generation are described in our paper [7].

The device has a number of advantages in comparison with the conventional GC and cascade junction of the GC with the crystal detector in mm-waveband: 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. Tolerance control and power measurements become more reliable. The described system application reduces strictness of demands to the preselectors at the input of mm-wave measuring devices and thus eliminates difficulties connected with the technology of their production.

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