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Interaction Between Millimeter Oscillations and Monocrystal Hexagonal Ferrites with Modulated Resonance Frequency

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Keywords: monocrystal hexagonal ferrite resonator, arbitrary oriented crystallographic anisotropy axis, tensor of magnetic susceptibility, stable non-linear resonance effects

Introduction

Investigation of non-linear stable effects taking place at ferromagnetic resonance (FMR) in monocrystal arbitrary oriented hexagonal ferrite resonators (HFR) with controlled (modulated) resonance frequency is an urgent problem. This problem arises at frequency-selective mm-wave ferrite devices design for measuring energetic (power) parameters of irradiations (spectrum power density, width of the spectrum, intensity and carrier frequency of irradiation harmonics), especially in multi-signal regime of active devices operation. Application of high anisotropy HFR allows to operate in mm-wave band and its short-wave part without massive magnetic systems due to the internal magnetic field of the HFR.

The HFR resonance frequency can be controlled in two ways: the “field” control is connected with external magnetization field modulation (“cross-multiplication regime” [1]), and the “angular” control is based on variation of angle between the internal anisotropy field and external constant magnetic field in vicinity of some initial position (this can be realized by means of piezoelectric slab connected with the HFR [2]).

One of the theoretical problems arising at such devices design is connected with the analysis of the HFR microwave magnetization vector components, transmission and reflection coefficients for the waveguide containing HFR with modulated resonance frequency, because these parameters carry information on the electromagnetic signal intensity at the HFR resonance frequency.

The presented analysis is based on two approaches: the “quasistatic” approach using static tensor of the HFR magnetic susceptibility [3] and the “dynamic” one based on the solution of magnetization vector motion equation (MVME) with varying in time coefficients due to modulated magnetization field or the HFR angle of orientation [4]. The first approach is valid at the low modulation frequencies (in comparison with the relaxation frequency of the HFR) and the second one in general case can be used for “rapid” variation of resonance frequency.

“Quasistatic” approach to the analysis of the HFR magnetization vector components

At “slow” HFR resonance frequency variation we can use 9-component static tensor of magnetic susceptibility of arbitrary oriented HFR $\chi$ [3]. The direction of equilibrium magnetization vector $M$ with respect to the external constant magnetic field $H_0$ and field of anisotropy $H_A$ is determined on base of the minimum magnetic energy of the hexagonal ferrite crystal [5]. At low frequencies of modulation $\Omega$ the relation of angles between these directions can be assumed to remain the same as in static case.

$$\sin \theta_M = \frac{H_A}{2H_0} \sin 2\theta_0,$$

$$\theta_H = \theta_M + \theta_0.$$
For “field” or “angular” control of resonance frequency each tensor component \( \chi_{ij} \) absolute value can be represented in the following form:

\[
\left| \chi_{ij} \right| = \frac{a^{ij}_{\Delta} + a^{ij}_{s} \cos \Omega t}{\sqrt{\sum_{n=0} b_{n} \cos n\Omega t}},
\]

where \( a^{ij}_{\Delta}, b_{n} \) depend on the parameters, which determine \( \chi_{ij} \), such as \( H_A, H_0, \theta_{M, H, 0} \), relaxation frequency \( \omega_{r} \), saturation magnetization \( M_{s} \). The HFR magnetization vector components are represented as signals with slowly varying envelope and phase,

\[
m_{x,y,z} = G_{x,y,z} \cos(\omega t + \varphi_{x,y,z})
\]

For mm-wave magnetic field in the waveguide with amplitudes \( h_{xm}, h_{ym} \) it is necessary to take into account only \( x \) and \( y \) components of mm-wave magnetization. Each envelope \( G_{x,y,z} \) can be expanded in Fourier series at modulation frequency \( \Omega \) harmonics. For certain field of the HFR crystallographic anisotropy \( H_A \) and external magnetic field \( H_0 \) there is certain angle of orientation \( \theta_{H} \) at which the amplitude of the certain harmonic being maximum.

“Dynamic” and “quasidynamic” approach to the analysis of the HFR magnetization vector components

When modulation frequency \( \Omega \) is comparable to that of the HFR relaxation one \( \omega_{r} \), it is necessary to use the magnetization vector motion equation (MVME) [5],

\[
\frac{d\tilde{M}}{dt} = -\mu_0 \gamma [\tilde{M} \times \tilde{H}_{ef}] + \tilde{R},
\]

where \( H_{ef} \) - effective magnetic field and \( R \) - dissipative term in modified Blokh’s form. But we cannot use the static relation between the angles (1)-(2) in this case. The MVME can be represented by 3 of equations correspondent to 3 Cartesian coordinates. The rigorous solution of the problem can be obtained for the case of zero angles of the HFR orientation (i.e. when the directions of \( M_0, H_0, H_A \) coincide). In this case the results of analysis can be reduced to the case of the ferrite with low internal magnetic field, i.e. “isotropic” ferrite (ferrogarnet, for instance), considered previously [4]. The envelopes \( G \) of the magnetization vector mm-wave components \( m_x \) and \( m_y \) (they coincide) and longitudinal component \( M_z \) contain the harmonics of the modulation frequency \( \Omega \), described by well calculated functions \( \Psi_{a,p,q}(a,p,q) \) and phases \( \Phi_{a}(a,p,q) \), where \( a \) - is relative detuning from the FMR frequency, normalized by the HFR half-width of resonance curve for the HFR with spherical form \( \delta = \omega_0 (1 + \chi_0 / 3 \mu_0) \), \( \chi_0 \) - is the static HFR susceptibility, \( p = \Omega/\delta \) and \( q = \omega_{mod}/\Omega \) - are normalized frequency and amplitude of modulation [4,6].

\[
G = \frac{h_{xm}}{2\delta} \sqrt{b^2 + \omega_M^2} J_0(\Delta \theta_{M}) \times \sqrt{\Psi_0(a,p,q) + \sum_{n=1} \Psi_n(a,p,q) \cos(n\Omega t + \Phi_n)},
\]

with \( J_0 - \) Bessel function of the angle deviation \( \Delta \theta_{M}, \omega_M = \mu_0 \gamma M_z, b = \omega_0 \chi_0 / \mu_0 \).

At the arbitrary HFR orientation the system of differential equations for mm-wave components of magnetization with parametric coefficients cannot be solved rigorously without introducing some simplifications, leading to “quasidynamic” approach (when we can use static relation
between angles of orientation at rather low frequencies of modulation. In this case the solution is also can be represented through the \( \Psi_n(a,p,q) \) functions for both "field" and "angular" cases of the resonance frequency control (6).

\[
G = \frac{h_{xm} + h_{ym}}{2\delta} \sqrt{b^2 + \omega_M^2 \cos^2 \theta_M J^2_0(\Delta \theta_M)} \times \sqrt{\Psi_0 + \Psi_n \cos(n\Omega t + \Phi_n)}
\]  

(7)

There is good coincidence of the calculated results in "quasistatic" and "quasidynamic" cases at rather low frequencies of modulation \((p<0.1)\) with the accuracy of 1% for the harmonics up to the 3-rd order. At higher frequencies of modulation it is necessary to take into account dynamic phenomena, connected with the distortion of resonance line at rapid variation of the parameters determining the HFR resonance frequency.

Coefficients of reflection, transmission and modulation in the waveguide section with the HFR having modulated resonance frequency

The magnetization vector components determine reflection and transmission coefficients in the waveguide containing HFR. As the dimensions of the HFR being fairly less comparable to the wavelength, the effects of propagation can be neglected, and the HFR is represented as elementary magnetic dipole, excited by the falling electromagnetic wave and irradiating in the waveguide. Its density of the "magnetic current" is determined by the magnetization vector components. As the HFR usually absorbs about 20 dB of the falling power in the waveguide, there is strong link between the HFR and the waveguide, and there must be used the "self-matched magnetic field" approach [5], when the components of the mm-wave magnetic field irradiated by the HFR into the waveguide determine HFR magnetic moment, being in its turn acted by the irradiated waves.

The reflection, transmission and modulation coefficients in the waveguide, containing the HFR can be also represented as Fourier series with the harmonics of the modulation frequency. For modulation factor we obtain the following formula:

\[
Q = \frac{(\omega \mu_0 V_f)^2}{8\delta^2 N_w^2} (h_{xm} + h_{ym})^2 (b^2 + \omega_M^2 \cos^2 \theta_M J^2_0(\Delta \theta_M)) \times \{\Psi_0 + \Psi_n \cos(n\Omega t + \Phi_n)\},
\]  

(8)

\((N_w\) is the norm of the wave in the waveguide, proportional to its power). The modulation factor increases with the reduction of the HFR resonance line width, it reaches its maximum value at the maximum of correspondent function \(\Psi_n(a,p,q)\).

Results There can be found optimum regime of modulation and optimum angle of the HFR orientation for getting maximum coefficient of modulation in the signal which has passed the HFR. The optimum angle of orientation depends on the ferrite parameters and lies somewhere near 50 degrees. The optimum parameters of modulation for the first harmonic of modulation are \(a=1.7, p=1, q=1.2\). But this regime in not "quasistatic" or "quasidynamic". With \(p=0.01\) and \(q=135\) one can also get the maximum modulation coefficient. The theoretical results agree with experimental results, showing the possibility of nearly 100% modulation (Fig. 1).
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Dependence of modulation factor 1-st harmonic versus detuning a

Fig.1.

Conclusion

Interaction between mm-wave signals and monocrystal HFR with modulated resonance frequency has been studied using two approaches: "quasistatic" and "dynamic" (transformed into "quasidynamic" one for arbitrary oriented HFR at low frequencies of modulation). The formulae of the microwave magnetization vector components have been represented as signals with slowly varying amplitude and phase, their envelopes containing harmonics of the modulation frequency. Each harmonic carries information on the mm-wave signal intensity at the HFR resonance frequency, and this has practical application for the design of measuring frequency-selective devices.