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Marina Koledintseva

Missouri University of Science and Technology

L. K. Mikhailovsky

Alexander A. Kitaytsev

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Advances of Gyromagnetic Electronics for EMC problems

Marina Y. Koledintseva*
University of Missouri-Rolla, EMC Lab, EECH, Rolla, MO, 65409 USA

Leonard K. Mikhailovsky
Moscow Power Engineering Institute (Technical University), Krasnokazarmennaya, 14 111250 Moscow RUSSIA

Alexander A. Kitaytsev
Moscow Power Engineering Institute (Technical University), Krasnokazarmennaya, 14 111250 Moscow RUSSIA

Abstract - A number of EMC problems at microwaves – detection and measurement of power (spectrum) parameters of signals and suppression of unwanted radiation - can be solved owing to the results obtained in the field of gyromagnetic (spin) electronics. The latter deals with the unique properties of gyromagnetic media (GM) based on microwave ferrites, including high-anisotropy hexagonal ferrites that do not need intense magnetization field for their operation at ferromagnetic resonance. Approaches to the study of interaction of GM with electromagnetic field and ways of modeling frequency-selective measuring devices, absorbing coatings and all-mode filters of harmonics on base of GM are discussed. Results of experiments and practical application of the elaborated GM devices for EMC problems are represented.

Introduction

EMC of radioelectronic equipment and electromagnetic ecology at microwaves demand elaboration of methods and devices for detection, spectrum analysis, and measurement of parameters of various signals, as well as design of coatings and filters suppressing unwanted radiation. These devices must operate in wide frequency band and range of power, satisfy demands on reliability, low cost and technological simplicity. All the mentioned above problems can be solved on base of the advances of *gyromagnetic (spin) electronics* – branch of modern microwave electronics that deals with *gyromagnetic media* (GM), i.e. media containing microwave ferrites. GM have a unique spin mechanism of interaction with electromagnetic field (Lande factor is g=2) [1], and exhibits frequency selectivity at microwaves due to substantial magnetic losses at ferromagnetic or antiferromagnetic resonance (FMR or AFMR). Stable non-linear resonance effects (SNRLE) [2] at the microwave power levels less than that of spin-wave instability take place near the resonance frequency. These effects are used for the design of various functional devices on base of high-quality ferrite resonators (FR) – frequency and power converters, tunable bandpass and stopband filters, mixers, modulators, detectors, etc. [3].

* The results were obtained when the co-author was working in Moscow Power Engineering Institute (Technical University)

GM could be accounted as "non-current" media, because their conductivity current losses are negligible. This makes it possible to use these media for the design of absorbing coatings of various application, waveguide filters of harmonics, matched loads.

The other peculiarity of the GM is their tensor permeability in general. They exhibit non-reciprocal interaction with electromagnetic waves of various polarization, and they are used in microwave isolators and circulators.

The significant success in basic and applied research of gyromagnetic media at microwaves is achieved in the Ferrite Lab of Moscow Power Engineering Institute (Technical University) – MPEI (TU). There are two main topics of research and development in the field of gyromagnetic electronics directly aimed at the solution of the mentioned EMC problems [4]:

- Physical bases of elaboration of frequency-selective methods and devices for microwave and mm-wave signal detection, spectrum analysis, and power parameters measuring using monocrystalline garnet and hexagonal ferrite resonators;
- Physics and technology of composite absorbing materials, study of their chemical and physical, including microwave, properties, and design of coatings and devices of absorbing type - filters of harmonics on base of dispersed (powder) polycrystalline hexagonal ferrites.

Frequency-selective measuring devices design using stable non-linear effects in microwave ferrite resonators

The first of the mentioned above topics mainly uses the phenomenological model of the magnetization vector precession in the vicinity of ferromagnetic resonance [5]. Description of the interaction of the GM with electromagnetic fields employs harmonic functions used in classical field theory. Interaction between FR and various types of microwave signals (continuous, pulse, noise) has been studied both theoretically and experimentally (see the references in the review [6]). The FR magnetization vector variation contains information on the microwave signal

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acting on the FR. Using an element sensitive to the FR magnetization vector variation the *resonance detection* is realized. So-called *magnetic detector* invented in 60-ies by Professor of MPEI(TU) L.K. Mikhailovsky contains a spiral micro-coil surrounding the FR [7], but it may be a Hall-element [12]. The FR resonance frequency can be controlled not only by varying the field of magnetization for tuning in the certain frequency range. It can be varied by the RF modulation signal applied locally tó thé FR the certain along with the external magnetization field ("field" control of resonance frequency). This modulation can be realized by the same micro-coil that is used for resonance detection, or some semiconductor or piezoelectric element that can cause sufficient variation of the resonance frequency of the FR. Then the output harmonics of the magnetization vector variation has information what is the microwave signal frequency and power (spectrum power density). It is so-called *cross-multiplication regime* [8].

Application of monocrystalline Ba- and Sr- hexagonal ferrite resonators (HFR) with high value of the internal magnetic field of crystallographic anisotropy allows the control of the resonance frequency of the HFR in two ways [12]. It is variation of the magnitude (H_0) of the external magnetization field ("*field control*"), and variation of the orientation this field in respect to the HFR internal crystallographic field of magnetic anisotropy (H_A) axis ("*angular control*").

The longitudinal component of any FR magnetization vector M_z is proportional to the sum of squares of the transversal components ($m_x^2 + m_y^2$), and it is determined by the formula, generalized from that valid for the ferrogarnet with zero crystallographic field of magnetic anisotropy [9]:

$$M_Z = M_S - A^2 \times \sum_{n=0}^{\infty} \Psi_n(a,p,q)\cos(n\Omega t - \varphi_n);$$
$$A^2 = (\frac{\omega_M^2 \cos\theta_M J_0(\Delta\theta_M) + b^2}{2M_S})(\frac{h_{xm} + h_{ym}}{2\delta})^2, \quad (1)$$

where

$$q = \omega_m / \Omega;$$
$$p = \Omega / \delta;$$
$$a = \frac{\omega - \omega_0}{\delta}.$$
$$\delta = \omega_r(1 + N_t\chi_0 / \mu_0);$$
$$b = \omega_r\chi_0 / \mu_0$$

$$\Psi_n = \sqrt{A_n^2 + B_n^2};$$
$$\varphi_n = arctg\frac{B_n}{A_n};$$
$$A_n = \sum_{n=-\infty}^{+\infty} J_n(q)\frac{\cos\Delta\omega_n t + a_n \sin\Delta\omega_n t}{a_n^2 + 1};$$
$$B_n = \sum_{n=-\infty}^{+\infty} J_n(q)\frac{\sin\Delta\omega_n t - a_n \cos\Delta\omega_n t}{a_n^2 + 1};$$
$$a_n = \frac{\Delta\omega + n\Omega}{\delta}.$$

These formulae use the following notations: M_s is the saturation magnetization of the FR, $\omega_M = \mu_0\gamma M_S$; $J_0(\Delta\theta_M)$ is Bessel function of the zero order of argument $\Delta\theta_M$, deviation of the FR angle of crystallographic axis orientation (for the uniaxial hexagonal ferrite resonator at 'angular' modulation of the resonance frequency); δ determines the half of the FR line width, ω_r is the ferrite relaxation frequency, χ_0 is the FR static susceptibility, N_t is the FR transversal demagnetization factor; $h_{xm,\ ym}$ are the amplitudes of the transversal microwave magnetic field; p is the relative frequency of modulation; q is the normalized amplitude of modulation (with ω_m - amplitude of the FR resonance frequency modulation at either 'field' or 'angular' control), a is the relative detuning of the FR resonance frequency ω_0 from the carrier of the microwave signal ω

Thus, in the vicinity of the FMR the longitudinal component of the FR magnetization vector contains the harmonics of the modulation frequency $\Psi_n(a,p,q)$, 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 intermediate frequency. The amplitude of the harmonic depends on the microwave signal and the FR parameters, as it is seen from the listed above formulae.

SNLRE in ferrite monocrystalline resonators determine the operation of the devices elaborated in MPEI(TU): gyromagnetic converter (GC), ferrite-diode converter, filter-preselector, ferrite mixer and a number of measurers on their base [3,12].

The devices using SNRLE exhibit stable functioning at high power levels admissible for the transmission line path. Frequency selectivity of the devices is determined by the width of FMR of the employed ferrite resonator, usually 1-10 MHz. It's necessary to underline that only frequency-selective methods allow getting the most full and adequate information on the radiation under test.

GC (see fig.1) working in the cross-multiplication regime fulfills non-heterodyne frequency conversion. It is important that the GC is free from parasitic combination channels of conversion typical for ordinary mixers. The GC provides the output signal at the intermediate frequency, which is usually the second harmonic of modulation frequency. Since the modulation can be provided by a stable RF oscillator, then for further intermediate frequency signal processing it is possible to use a minimum possible narrow-band amplifier to increase the signal-to-noise ratio.

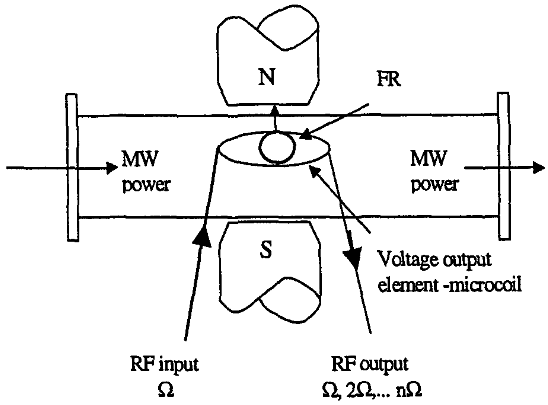

Fig.1. Gyromagnetic converter

The *"panoramic" measurer of power parameters* (spectrum power density, width of spectrum; integral power of wide-band signals, and peak power of pulsed signals) (fig.2) designed in MPEI (TU) was designed for testing intense wide-band noise signals. The measurer uses a GC with monocrystalline ferrite (YIG, Ca-Bi-Va garnet) resonator as a non-linear resonance scanning element (for the frequency range 300 MHz-30 GHz) [10]. The typical conversion coefficient of the GC is 10 mV/W. The measurer operates with signals having spectrum width more than 10 MHz (the minimum achieved width of resonance line of the employed YIG resonators is about 1 MHz). With the second channel (a narrow-band amplifier of the converted signal) added, the device can fulfill a function of detection of comparatively narrow band ('harmonic') signals at the background of intense wide-band noise. The narrow-band channel should be switched on simultaneously with cross-multiplication regime in the GC of the measurer [11].

Another device using SNRLN in FR is the *wattmeter of peak and average power of pulse signals* of microsecond duration. It uses the ferrite-diode converter (FDC), containing FR with the modulating microcoil inside the transmission line loaded with the crystalline (diode) detector (see fig. 3). The signal from the detector contains information on the input microwave signal. Depending on the design (type of the transmission line) it can operate in wide dynamic range – from 10^{-8} W up to 1 MW power level in the frequency band 1-40 GHz.

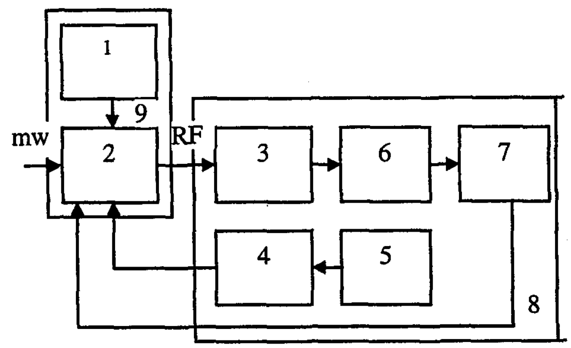

Fig.2. Functional scheme of microwave measurer of power parameters:

1- magnetic system; 2- magnetic detector; 3-high-pass filter; 4-low-pass filter; 5-RF modulating oscillator; 6-amplifier of converted signal; 7-scanning and displaying block; 8- measuring block; 9-gyromagnetic converter.

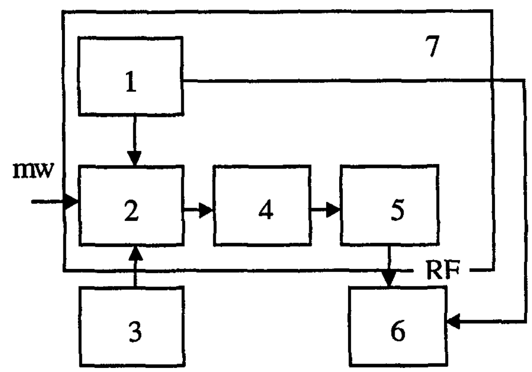

Fig.3. Functional scheme of microwave wattmeter of pulse signals:

1-magnetic system; 2- magnetic detector; 3- RF modulating oscillator; 4- attenuator; 5-crystalline detector; 6- scanning and displaying block; 7- ferrite-diode converter

Application of high-quality hexagonal ferrite resonators (HFR) along with elaboration of the new principles of frequency and power conversion on their base allows to prolong the frequency range of this measurer to mm-waveband (30–170 GHz) without massive external magnetic field [12]. Thus, semiconductor elements (Hall-elements, unpackaged diodes and transistors) having contact with the HFR and sensitive to its magnetic moment, resistance or temperature variations, is perspective for measuring the parameters of the signals at mm-waves [12].

Frequency-selective absorbing coatings and filters using gyromagnetic composite materials

The second topic (see Sec. *Introduction*) employs both classical approach operating with averaged in space constitutive parameters of media – ε and μ [1], and non-classical, based on axiomatic quantum field theory and gyrovector formalism with discrete counting out in space-time for quantification of both electromagnetic field and GM [13-15]. This formalism was introduced by L.Mikhailovsky in 70-ies. GM particles with inner spin magnetic moment are represented as "point" centers of electromagnetic energy absorption and radiation where instantaneous transition from one discrete energy level to the other takes place due to the particles spin turn over. The macroscopic characteristic of the electromagnetic field – phase of the wave – does not influence the process of "energy" interaction, unlike it takes place at Lorentz "force" interaction. This "non-current", "non-inertial", and "non-phase" mechanism determines the effect of all-directional and all-wave matching of the gyromagnetic media impedance with the free-space.

This theory forms a novel trend in microwave electronics - *Spin-Electronics and Non-Phase Electrodynamics* (see Reviews [6, 15]).

Non-classical approach clears up the picture of interaction at microcosm level, while the classical one allows by introducing effective constitutive parameters of powders or composite gyromagnetic absorbing materials to treat them as homogeneous media and apply methods of modern computational electromagnetics for the design of the devices on their base.

Maxwell Garnett's model [16] can be applied for determining the effective permittivity and permeability of a composite gyromagnetic material:

$$\varepsilon_{ef} = \varepsilon_A \frac{1+\frac{2}{3} f_B \alpha_e}{1-\frac{1}{3} f_B \alpha_e}, \tag{2}$$

$$\alpha_e = \frac{1}{3}\sum_{i=1}^{3} \frac{\varepsilon_B - \varepsilon_A}{\varepsilon_B + L_i(\varepsilon_B - \varepsilon_A)}, \tag{3}$$

where ε_A, μ_A are parameters of the host material, and $\varepsilon_B, \vec{\mu}_B$ are the parameters of the gyromagnetic particles as a filler. Volumetric fractions of the materials are f_A and f_B, correspondingly, where $f_B << f_A$; $f_A + f_B = 1$. $\{L_i\}$ is a triplet of depolarization form factors along axes x, y, z for the particles in the form of spheroids.

The analogous formulae for permeability (with taking into account tensor character of $\vec{\mu}_B$ in general case of the material with the arbitrary texture) are the following:

$$\vec{\mu}_{ef} = \mu_A(\vec{I} + \frac{2}{3} f_B \vec{\alpha}_m)(\vec{I} - \frac{1}{3} f_B\, \vec{\alpha}_m)^{-1}, \tag{4}$$

$$\vec{\alpha}_m = \frac{1}{3}\sum_{i=1}^{3}\left(\vec{\mu}_B - \mu_A \vec{I}\right)\left(\vec{\mu}_B + N_i(\vec{\mu}_B - \mu_A \vec{I})\right)^{-1}, \tag{5}$$

where $\{N_i\}$ is a triplet of demagnetization form factors along axes x, y, z; $\vec{I}$ is a unit tensor. The averaged permeability tensor $\vec{\mu}_B$ for the single hexagonal ferrite particle is related to the susceptibility tensor:

$$\vec{\mu}_B = \vec{I} + \vec{\chi}_B. \tag{6}$$

Each component χ_{ij} of tensor $\vec{\chi}_B$ can be represented via distribution functions for crystallographic anisotropy field scatter both in magnitude H_A and in orientation θ_C in respect to the chosen axis of the material texture [17].

When the material is non-textured by the application of the external magnetic field ($H_0=0$), the susceptibility tensor is diagonal with components equal to the corresponding components of preliminary magnetized up to saturation hexagonal ferrite,

$$\vec{\chi}_B = \begin{vmatrix} \chi & 0 & 0 \\ 0 & \chi & 0 \\ 0 & 0 & \chi \end{vmatrix}, \tag{7}$$

where

$$\chi = \frac{\chi^+ + \chi^-}{3}, \qquad \chi^{\pm} = \frac{f_B \cdot M_S \mu_0 \gamma}{\mu_0 \gamma H_A \mp \omega + j\omega_{loss}}$$

with H_A being the mean value of anisotropy field scatter, and the 'loss' parameter ω_{loss} is determined mainly by the width of the anisotropy field scatter ΔH_A.

Wideband composite GM using a mixture of high-anisotropy hexagonal ferrite (HF) powders of various chemical structure are elaborated in MPEI(TU). At present fillers for such GM are designed and studied for the application in the frequency range from 2.5 to 170 GHz [18]. Due to the phenomenon of *natural ferromagnetic resonance (NFMR)* in HF particles, coatings and devices operating without external magnets are designed on their base.

Desirable frequency characteristic of the absorption could be formed (see, for example, fig.4), and filters of harmonics with the necessary parameters could be designed by varying the contents of the composite material, geometry and position of layers – gyromagnetic composite thick films [19]. Such materials were used, for example, for suppressing the 5th harmonic of magnetron radiation of microwave oven that falls into the frequency band of telecommunication systems (fig.5) [20].

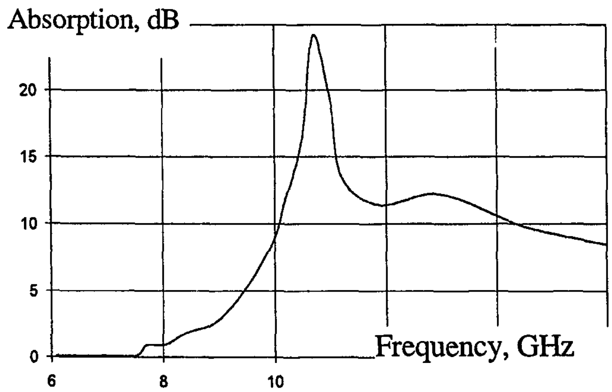

Fig.4. Absorption characteristic of composite gyromagnetic material with doped hexagonal ferrites

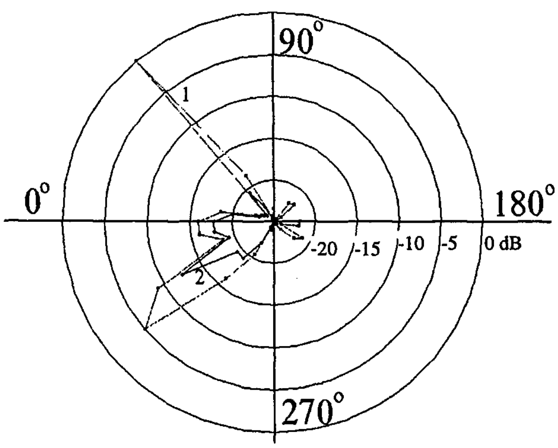

Fig. 5. Radiation diagram from the microwave oven
1- without absorber; 2- with absorber. 0° corresponds to the direction normal to the microwave oven door.

Conclusion

Basic and applied research in the field of gyromagnetic media carried out in recent years in MPEI (TU) yielded in the design of microwave equipment having new principles of functioning and construction. The "panoramic" equipment aimed at testing and measuring power parameters of microwave signals operates in the frequency band 0.3-75 GHz. Due to frequency selectivity at FMR and low "current" conductivity losses in gyromagnetic media the devices are resistant to high-power overload. All-directionally matched with free space spin (non-current) absorbing materials have been elaborated and tested for frequency band 2.5-170 GHz. All-mode waveguide filters of harmonics of intense sources of microwave radiation using gyromagnetic composite thick films have been designed. The elaborated devices and coats can be used for the solution of various problems of electromagnetic compatibility and ecology:

- In all the branches of industry using microwaves for harmful radiation suppression;
- In radio electronics for EMC problems that require the suppression of spurious radiation in transmitting devices, and that require noise immunity in receiving devices; one example would be suppression of the 5th harmonic in microwave oven radiation, which causes interference in satellite telecommunication systems;
- For domestic (everyday) life to protect people from harmful radiation (microwave ovens, medical equipment; portable hand-phones);
- For protection of human beings in outer space conditions;
- For optimal design of modern computers that have microprocessors operating at near-microwave frequencies.

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