Frequency-selective Power Transducers “Hexagonal Ferrite Resonator—Semiconductor Element”

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Abstract—The transducers studied herein allow for frequency-selective measurement of mm-wave power parameters. Frequency selectivity is assured by a monocrystalline hexagonal ferrite resonator (HFR). The HFR is in direct contact with a semiconductor element (SE)—an unpackaged Hall-element, or a chip transistor (or diode). Power absorbed by the HFR at the ferromagnetic resonance converts to heat, and the heat flux penetrates through the current-carrying SE. A number of thermo/electro/magnetic phenomena accompany the Hall-effect in a semiconductor and cause a voltage in addition to the Hall-effect voltage. The conversion coefficient of a transducer is analyzed using the power balance equation. Some experimental results using the designed power transducers in the 8-mm waveband are presented.

1. Introduction

Many applications require an adequate information about mm-wave (30–300 GHz) spectra of signals, e.g., spectral power density, peak power of pulse signals, integral power in the given frequency band, width and central frequency of spectrum [1, 2]. Equipment for measuring power parameters of electromagnetic signals contains a primary measuring transducer and a secondary processing/display unit. A primary transducer in this case converts the energy associated with electromagnetic oscillations into a different form of energy (e. g., thermal, mechanical, etc.), or into voltage which is convenient to register and quantify. Most of microwave and mm-wave power meters and detectors are not frequency-selective. Their application for “fine” spectra measurements needs additional high-Q filters and cumbersome calibration of the receiving path. Heterodyne-type spectrum analyzers and measuring receivers typically have numerous parasitic channels of reception, which is an especially difficult problem for the analysis of mm-wave spectra of signals of middle and higher intensity levels (more than 1 mW of continuous power).

The transducers proposed herein allow for frequency-selective measuring of mm-wave power parameters. Frequency selectivity is assured by incorporating a monocrystalline hexagonal ferrite resonator (HFR) with a narrow ferromagnetic resonance (FMR) line. An advantage of an HFR is its high intrinsic field of magnetic crystallographic anisotropy, so it does not need massive bias magnetic systems for achieving FMR [2]. In the transducer, the HFR is in direct contact with a semiconductor element (SE). The SE may be an unpackaged Hall-element (HE) slab, or chip transistor (or diode). The mm-wave power absorbed by the HFR at the FMR converts to heat, and the heat flux from the HFR penetrates through the body of the current-carrying SE. Since this structure is in the bias magnetic field, there are a number of thermoelectric, thermomagnetic, galvanomagnetic, and thermoelectromagnetic phenomena, along with the Hall-effect in the SE. In fact, there are over 560 different known effects accompanying the Hall-effect [3]. These phenomena cause a voltage in addition to that of the Hall-effect. This happens only when the frequency of the mm-wave signal falls into the ferromagnetic resonance curve of the HFR, thereby assuring frequency selectivity of power conversion.

2. Mathematical Model for the Conversion Coefficient of the Transducer

The conversion coefficient of a frequency-selective power transducer is defined as a ratio of the amplitude of the converted signal to the power of the input microwave signal at the given frequency [1],

$$K_p = \Delta V / P(f_0). \tag{1}$$

If the thermal coefficient of voltage in a semiconductor element

$$K_T = \Delta V / \Delta T \tag{2}$$

is known, then the conversion coefficient of a transducer operating on the basis of thermal effects is

$$K_p = K_T \Delta T_{stat} / P(f_0), \tag{3}$$

where ΔT_{stat} is the stationary temperature increase in the system “HFR-semiconductor element”.

Consider the case when a microwave oscillation of power $\mathrm{P}(f_0)$ acts on the HFR continuously, and the HFR absorbs this power due to the FMR. Inside the HFR there is a constant source of heat, and the surface temperature of the HFR remains constant. Suppose that heat radiation is absent. Let us also neglect semiconductor heating when current flows in it, and further assume there is no difference in the temperature of the contacts (no thermal electromotive force). The result of the semiconductor heating is the variation in the charge carrier mobility, which leads to the variation of the thermal coefficient K_T. Then the equation for thermal balance can be written in terms of power,

$$P_{abs} = P_{FS} + P_{SM} + P_{FA} + P_{SA}, \tag{4}$$

where $P_{abs} = \alpha P(f_0)$ is the mm-wave power absorbed by the ferrite at the FMR (α is the absorption coefficient); P_{FS} is the heat power transferred by the ferrite to the semiconductor element (conduction heat exchange); P_{SM} is the heat power transferred from the semiconductor element to the metal contacts (conduction heat exchange); P_{FA} is the heat power transferred by the HFR surface to air (convection heat exchange); and P_{SA} is the heat power given to air by the semiconductor (convection heat exchange).

The Cauchy problem describing the transient thermal regime in the system "HFR-SE" with a heat source inside the ferrite is analogous to that considered in [4] for a YIG bolometer,

$$C_\Sigma \frac{dT}{dt} + \Psi_{T\Sigma} T = P_{abs}; \quad T(0+) = T_r, \tag{5}$$

where C_Σ [J/K] is the total heat capacity of all the elements of the thermal system, and $\Psi_{T\Sigma}$ [W/K] is the total heattransfer factor of all the system. The initial condition is the room temperature T_r. The solution of the Eq. (5) is an exponential function

$$T(t) = T_r + \Delta T_{stat}(1 - e^{-t/\tau_\Sigma}), \tag{6}$$

where $\Delta T_{stat} = P_{abs}/\Psi_{T\Sigma}$ is the increase of the stationary temperature, and $\tau_\Sigma = C_\Sigma/\Psi_{T\Sigma}$ is the response time of the system.

The absorption coefficient α depends on the HFR rate of coupling with the transmission line where it is placed. This coupling is described by the coupling coefficient η_c [5], and in turn, it depends on the geometry of the transmission line or waveguide, operating mode structure, the point where the HFR is situated, and the physical parameters of the HFR (its resonance line width ΔH, saturation magnetization M_S, anisotropy field H_A, and orientation of the HFR crystallographic axis in respect with the bias magnetic field H_0), as well as on the detuning $|f_{res} - f_0|$ of the FMR frequency from the mm-wave signal carrier frequency. The absorption coefficient can be obtained through solving the self-matched field problem and electromagnetic power balance equation, as described in [1, 5]. From this analysis, the absorption coefficient relates to the coupling coefficient as

$$\alpha = 2|\eta_c|/|1 + \eta_c|. \tag{7}$$

For a transmission line or waveguide operating with only a single mode having transverse microwave magnetic field components $h_{x,y}$, and with the bias magnetic field for the HFR directed along z-direction, the coupling coefficient can be calculated as

$$\eta_c = j\frac{\omega\mu_0 V_f}{2N_1}(\chi_{11}^{ext} h_x^2 + \chi_{22}^{ext} h_y^2), \tag{8}$$

where $\chi_{11,22}^{ext}$ are the complex diagonal components of the external magnetic susceptibility tensor for an ellipsoidal (general case) HFR [1, 5] for any arbitrary orientation of the HFR crystallographic axis with respect to the bias magnetic field. In (8), V_f is the volume of the HFR, and N_1 is the norm of the corresponding transmission line or waveguide mode, as calculated in [5].

3. Calculations and Experimental Data

The calculations were performed for a uniaxial monocrystalline HFR resonator made of M-type Ba ferrite doped with Ti and Zn ions. It was placed in a metal waveguide with a cross-section of 7.2 mm× 3.4 mm, in the point with the right circular polarization of the mm-wave magnetic field. The HFR in this case was a spheroid with the axes 0.585 mm×0.557 mm. Its magnetic parameters were the following: the field of crystallographic magnetic anisotropy was $H_A = 11.3$ kOe, saturation magnetization was $4\pi M_S = 3.5$ kG, and the unloaded resonance line width was $\Delta H = 31.1$ Oe. The density of the hexagonal ferrite was $\rho_f = 4900\,\text{kg/m}^3$; the specific heat was $c_f = 1100$ J/(kg.K); and thermal conductivity was $\lambda_f = 4.1$ W/(m.K). The measured input average power of the mm-wave continuous signal at the frequency $f_0 = 39.5$ GHz was $P(f_0) = 60$ mW; the HFR absorbed 5 dB at the FMR ($P_{abs}^{meas} = 41.1$ mW).

The Hall-element (HE) X511 (Russia) measured 1.5 mm×2.0 mm×0.1 mm. It was made of a monocrystalline InSb, the density was $\rho_s = 5770\,\text{kg/m}^3$, the specific heat was taken as $c_s = 700$ J/(kg.K); the thermal conductivity was $\lambda_s = 18$ W/(m.K); and the thermal coefficient of voltage K_T was 1.5 mV/K (according to the technical passport for the X511). An active region of contact with the HFR was assumed to be 0.01 mm^2. Heat transfer coefficients for natural convection (room temperature $T_r = 20°C$ and normal atmosphere pressure of 760 mm of mercury) for both HFR and SE are about 30 W/(m^2·K).

The total heat transfer factor was calculated as $\Psi_{T\Sigma} = \Psi_{conv} + \Psi_{cond} = 1.2 \cdot 10^{-3}$ W/K. The total heat capacity is $C_\Sigma = C_f + C_s = 0.9 \cdot 10^{-3}$ J/K. The calculated response time of the system is $\tau_\Sigma^{calc} = 750$ ms, and the calculated stationary temperature increase in the system is $\Delta T_{stat}^{calc} = 25°C$. The transition time for the temperature increase is $t_{stat} = 4.6 \cdot \tau_\Sigma = 3.45$ s. The calculated voltage at the SE is $\Delta V^{calc} = 37.5$ mV, and the conversion coefficient is $K_p^{calc} = 0.625$ V/W. The measured data are $\Delta T_{stat}^{meas} = 21°C$ and $\tau_\Sigma^{meas} \approx 1$ s.

4. Design and Experimental Data of the Frequency-selective Thermal Transducers

4.1. HFR-two Hall-elements

The structure of the frequency-selective electronically tunable power transducer is shown in Fig. 1. It contains two identical Hall elements: one is inside the waveguide, having direct contact with the HFR, and the second is on the outer side of the waveguide. Both transducers are exposed to the same uniform bias magnetic field. The Hall elements are connected so that it is possible to obtain a differential signal at the comparator. When there is no FMR absorption, the signals of the Hall elements are the same and correspond to the pure Hall-effect voltage in the given magnetic bias field. When the HFR is at the FMR, it heats up because of the resonance absorption, and there is an additional voltage that is induced on the contacts of the internal Hall element. Its value is proportional (with the coefficient K_P) to the average power of the mm-wave signal at the resonance frequency of the HFR, through the equation $\Delta V_H = K_p P_{av}(f_{res})$.

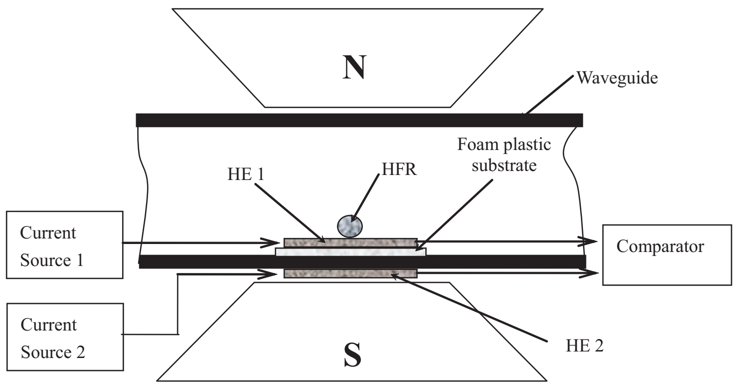

Figure 1: Schematic of the transducer based on the HFR and two Hall-elements.

When experimental structures based on the HFR and semiconductor elements were exposed to nanosecond pulses with pulse repetition frequency of 1 kHz, an off-duty factor of 2, and an average power of 10–100 mW, the mechanism of interaction was mainly inertial, of a thermal nature. Low-inertial effects, such as the magnetoresistive effect, the microwave Hall-effect in semiconductor, direct electromagnetic field detection by the SE, and magnetic detection by the SE due to variation in the magnetic flux from the HFR are negligibly small at average power levels of a few dozen mW. This inertial mechanism of interaction between the HFR and the mm-wave field is determined by heating of the HFR at the FMR power absorption and the corresponding heat flux acting on the Hall element.

Suppose that the total voltage induced in the semiconductor plate carrying a current I placed in a transverse magnetic field H_{0z} consists of a Hall-effect voltage V_H and a number of additional terms, corresponding to the most important effects accompanying the Hall-effect [3]:

$$V = V_H + V_{neq} + V_{mr} + V_{temf} + V_E + V_{NE} + V_{PNE} + V_{RL} + V_{PRL}. \tag{9}$$

In (9), V_{neq} is the non-equipotentiality voltage, V_{mr} is the magnetoresistive voltage, V_{temf} is the thermoelectromotive force voltage, V_E is the Ettingshausen galvanomagnetic voltage, V_{NE} is the Nernst- Ettingshausen thermomagnetic voltage, V_{PNE} is the Peltier-Nernst-Ettingshausen thermomagnetic electrothermal/ thermogalvanomagnetic voltage, V_{RL} is the Righi-Leduc thermomagnetic voltage, and V_{PRL} is the Peltier-Righi- Leduc electrothermal/thermogalvanomagnetic voltage. In the proposed design, the contribution of V_H and V_{mr} is compensated by the second Hall-element. The voltages V_{neqv} and V_{temf} are independent of the bias magnetic field, and can be taken into account and compensated. It is impossible to separate the remaining five contributions. However, the Nernst-Ettingshausen effect might be dominant. It is a thermomagnetic effect, and appears as a transverse voltage with respect to the current I flowing in the semiconductor slab, assuming the latter is in the magnetic field and is affected by the heat flux.

In the experiment, two Hall elements were used. The first one was an X511 characterized by $R_{in} = 2.0$ Ohms, $R_{out} = 1.6$ Ohms, $I_{oper} = 100$ mA, and having a thermal sensitivity of 1.05 V/(A·T). The second was X211. The characteristics of the X211 differ only in the output resistance ($R_{out} = 1.9$ Ohms) and the thermal sensitivity 1.38 V/(A·T). The slope with respect to the magnetic field is $S = \Delta V/\Delta H = 10^{-2}$ mV/Oe for both Hall-elements. The minimum measured magnetic field for both Hall elements was 0.1 Oe. Identical operation of both Hall-elements was assured by proper choosing of their operation currents.

In the transducer, the first Hall-element was placed in the rectangular waveguide with cross-section 7.2 mm × 3.4 mm, in the point of the circular polarization of the mm-wave magnetic field. The off-resonance loss factor in the section was 1.1 dB, and the standing wave ratio in this section was SWR=1.2. The HFR was the same as discussed above. The FMR absorption was 5 dB. Fig. 2 shows the resonance dependence of the differential signal ΔV as a function of the applied bias magnetic field H_{z0} for a continuous mm-wave signal at $f_0 = 40.7$ GHz. The minimum stable measured signal was about 10 μW. The conversion coefficient was $K_P^{meas} = 0.6$ V/W, which is close to the calculated value ($K_P^{calc} = 0.625$ V/W). The discrepancy can be explained by the mm-wave loss in the section of the waveguide. The 50% alcohol solution of the glue BF-2 (Russia) was used to fix the HFR on the unpackaged HE, and the resonance absorption in a high-Q ferrite resonator could have decreased by about 1 dB due to the glue. The simplifying assumptions in the model, such as neglecting the heat loss on metal contacts, might also adversely influence the accuracy of computations. Also, the reference input data for the parameters of a transmission line, ferrite resonator, and InSb HE might have some tolerance. Furthermore, instrument error in the mm-wave measurements might yield another 1 dB of uncertainty.

4.2. HFR—Unpackaged Chip Diode or a Transistor

The Hall-element contacting with the HFR was replaced by a chip transistor (CT) used as a diode. The voltage thermal sensitivity of the CT (2TC398A-1 manufactured in Russia) was 3.0 mV/K, which is higher than the voltage thermal sensitivity of the HE. The HFR anisotropy field was $H_A = 10.6$ kOe, and the FMR line width was $\Delta H = 30$ Oe. The HFR absorbed 3 dB of power at the FMR ($f_0 = 40.7$ GHz, $P(f_0) = 60$ mW). The conversion coefficient is 1.2 V/W, which is two times greater than that of the transducer "HFR-2 Hall elements". The minimum measured signal was about 1 μW. The shortcoming of the transducer is the presence of a "pedestal" at the level of 1 mV due to the off-resonance heating of the semiconductor element directly from the mm-wave signal power. However, this "pedestal" can be removed by a calibration in the off-resonance regime. A further improvement of the transducer can be realized by using a more thermosensitive semiconductor element. Linear volt-watt characteristics of the transducers with two Hall-elements and the chip transistor are shown in Fig. 3.

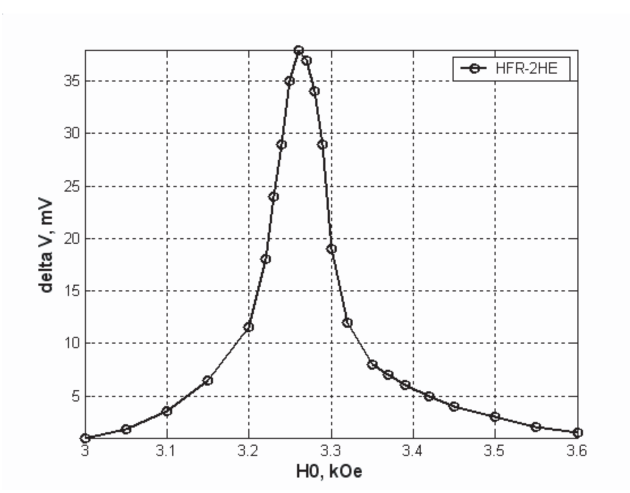

Figure 2: Resonance dependence of the converted voltage (HFR-2 Hall elements).

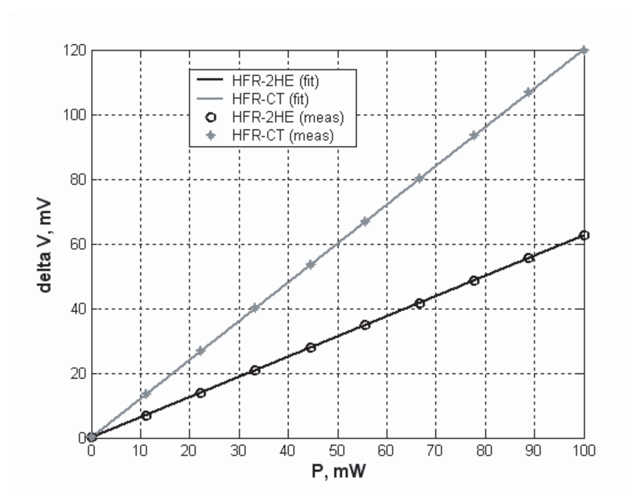

Figure 3: Linear volt-watt characteristics for transducers.

5. Conclusion

The transducers based on a high-Q hexagonal ferrite resonator in direct contact with a thermosensitive semiconductor element allow for frequency-selective measurement of mm-wave power parameters over a wide frequency range. The physical mechanisms of power conversion are analyzed, and it is shown that the conversion coefficient of a transducer can be calculated using the equation of power balance. To increase the sensitivity and conversion coefficients of a transducer based on the approach, it is necessary to use an HE with a higher thermal coefficient of voltage, assure the best possible heat contact between the HFR and the semiconductor element (increase the surface of their contact, for example, using a disk HRF), and employ a microvoltmeter with higher sensitivity to register smaller converted signals.

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