Computerized Radiometric System for Measuring Microwave Radiation of Biological Objects

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Abstract

The article deals with the problems of measuring weak microwave signals during studies of electromagnetic radiation (EMR) of biological objects.

The authors proposed a variant of a highly sensitive radiometric system (RS) in the microwave range with modulation conversion of input signals, computer control of the operating mode and processing of measurement results. The use of a computer as part of the system provides the possibility of setting several modes of RS measurement: direct measurement of microwave radiation of a bioobject; comparison of the measured signal level with the reference value; adjustments of the frequency range during measurements; assessment of the presence of a non-equilibrium component in the radiation spectrum, as well as processing and storage of measurement results. To separate the thermal and non-equilibrium microwave components of EMF, an original hardware version of the metal-dielectric converter of the spectrum of the received signal has been developed. Studies were conducted on the selection of individual elements and the operation of the spectrum converter was described. An algorithm for converting input signals in a radiometric channel is proposed and described. The possibility of compensating the internal noise of the PC is shown, which provides the possibility of increasing the integral sensitivity up to $10^{-14}...10^{-15}$ W. This, in turn, makes it possible to measure the non-equilibrium component of microwave radiation caused by the metabolic processes of biological objects.

Keywords

Microwave radiation, biological objects, nonequilibrium radiation, metal-dielectric converter, radiometric system

1. Introduction

The complexity of the task of estimating the non-equilibrium component of electromagnetic radiation is due to the low signal level, which is comparable to the noise level of the radio-thermal radiation of the objects under study. Various types of optical luminescence, microwave radiation of biological structures, microorganisms, and other objects can serve as examples of non-equilibrium EMR [1, 2].

Living organisms, as well as any dielectric object with a temperature higher than that of the environment, have radiothermal radiation of a wide spectrum. Part of the radiothermal radiation lies in the microwave region of the spectrum [3, 4].

The spectral power of such noise radiation correlates with temperature and is described by the well-known Nyquist formula:

$$S = kT\ ,$$

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where: k – Boltzmann's constant ($k = 1{,}38 \cdot 10^{-23}$); T - is the thermodynamic temperature of the object.

At the temperature of a biological object, for example 309,6 K, a human body, the spectral power of microwave radiation is $S = 4{,}27 \cdot 10^{-21}$ W/Hz.

The average noise electromagnetic radiation power is usually measured using a highly sensitive RS in the frequency range limited by the bandwidth (analysis) of the radiometric channel Δf. The integral electromagnetic radiation power of a heated body with radiative power β, which can be measured, is determined by the expression:

$$P = S(f,T)\Delta f = \beta k T \Delta f$$

With the RS bandwidth $\Delta f = 10^8$ Hz and the radiative capacity of the bioobject $\beta = 0.75$, the integral power is $P = 3{,}2 \cdot 10^{-13}\, W$. The fluctuation threshold of RS sensitivity when measuring such small powers should be 5...10 times lower than the measured signal. This causes certain problems when measuring signals of this level [5, 6]. The authors managed to create RS, the sensitivity threshold of which is at the level of $0{,}3 \cdot 10^{-13}\, W$ [5].

The system was used by the authors to study the electromagnetic properties of biomaterials. In this work, RS with extended capabilities is considered, which can be used to isolate and measure the parameters of non-equilibrium signals accompanying the metabolic processes of biological objects.

Non-equilibrium radiation caused by the activity of biological objects, characterized by extremely low intensity, will appear both in the optical and in the radio range. For their selection and assessment, highly sensitive measuring equipment is used: spectrometers, microscopes, optical and microwave radiometers, etc. Usually, the sensitivity of such equipment is limited by the thermal noise of the environment. In addition, the total power of thermal and non-equilibrium electromagnetic radiation is significantly less than the inherent noise power of modern electronic measuring equipment. The radiation of bioobjects in the microwave range can also contain a non-equilibrium component, which is stochastic and much weaker than radiothermal radiation. The allocation of this radiation presents a certain complexity. There are various methods of extracting and measuring the non-equilibrium component of electromagnetic radiation. For example, options for measuring non-equilibrium radiation by isolating it from thermal stochastic noise are proposed. To do this, the radiation of living and non-living bioobjects is compared [7, 8]. At the same time, inanimate objects are heated to the temperature that a living object has. This method is easily implemented in the study of fungi and microorganisms. However, when studying high-level living organisms, for example, humans, it is unacceptable.

The purpose of this work is to create a computerized highly sensitive radiometric system with extended functionality for measuring weak signals in the microwave range of biological objects. Such systems open up opportunities to more objectively conduct research on weak and emitted electromagnetic fields in biology, medicine, materials science, physics, and other areas of science and technology [9].

2. Description of the structural scheme and design features of the RS

In fig. 1 shows the structural diagram of the proposed highly sensitive RS with computer control of the operating modes and the possibility of direct measurement of the non-equilibrium component of microwave radiation.

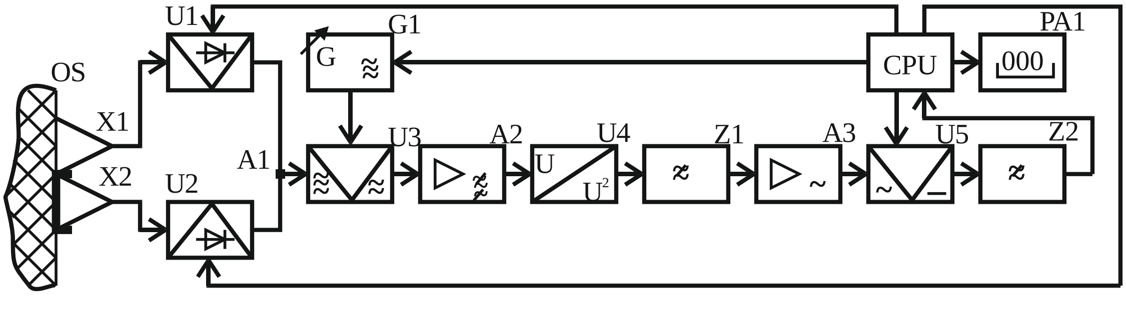

Figure 1: Structural diagram of a computerized RS.

The scheme includes an input part consisting of a dual antenna X1 and X2, two pulse switching modulators U1, U2, a tee A1 and a radiometric conversion channel. The output of the tee is connected to the mixer U3 of the radiometric channel, which consists of a series-connected intermediate frequency amplifier A2, a quadratic detector U4, a selective switching frequency filter Z1 with an amplifier A3, a synchronous detector U5, a low-pass filter Z2, and a digital indicator PA1. The choice of the operating frequency of the RS is carried out by the researcher, and it is implemented by the CPU computer by generating the control voltage on the local oscillator G1. The operation of the switches is controlled by rectangular pulses with a frequency of 1 kHz, which are also used as a reference for the synchronous detector U5.

The receiving combined RS antenna (Fig. 2, a) is made in the form of a rectangular horn 4, in which two antennas are located - an open (measuring) antenna with a waveguide output 6 and a closed copper foil (support) antenna with a waveguide output 5. The antennas are separated from each other by a screen 7. The measuring antenna X1 ensures the passage of the full signal from the object of study. The reference antenna X2 consists of a metal-dielectric converter of the spectrum of the received radiation and ensures the allocation of the microwave power of the thermal component. The design of the support antenna X2 includes a package of metal 1 and dielectric 2 plates located in a radio-transparent passive thermostat 3.

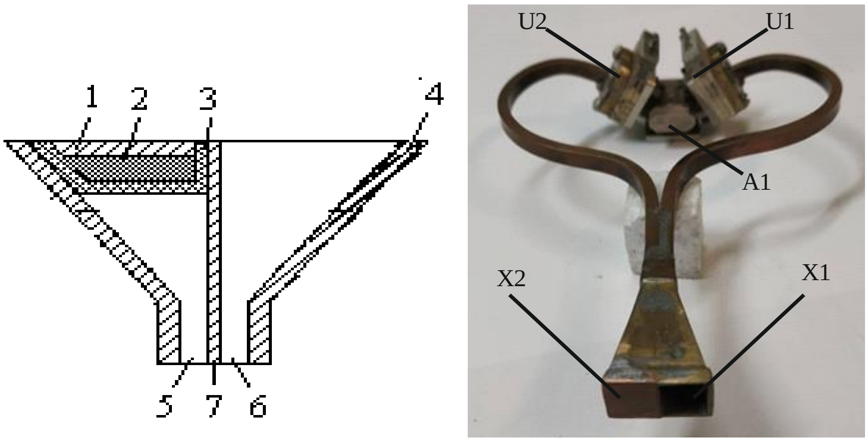

Figure 2: Appearance of the metal-dielectric converter.

For direct measurement of microwave radiation of a biological object, a corresponding control algorithm is installed in the computer. In this mode, only one X1 antenna and U1 modulator are used in the "open-closed" mode. When the antenna is open, the radiometric channel receives a signal from the biological object and noise from the input part of the RS. When the antenna is closed - only noise. As a result, the difference between these signals is isolated at the output of the synchronous detector U5 during the switching period, and the low-pass filter Z2 - the integral value of the measured EMR bioobject, which is entered into the computer's memory and transmitted to the PA1 indicator.

3. Description of the work of RS and the algorithm of transformation of non-equilibrium signals

Isolation and measurement of the non-equilibrium component of bioobjects is a more complicated procedure, which consists of the following.

Antennas X1 and X2 (Fig. 1, a) of the measuring and reference channels are brought into contact with the surface of the biological object under study. In general, a biological object generates equilibrium (radiothermal) radiation and non-equilibrium (bioinformational) radiation. The bioinformational component of electromagnetic radiation is generated by the cells of a living organism, thanks to the metabolic processes occurring in living biological objects. According to the data of a number of authors [10, 11], the non-equilibrium component of radiation performs a regulatory function of the vital activity of cells, organs and the organism as a whole. The radiothermal component of radiation is proportional to the body's absolute temperature and the coefficient of emissivity of each layer. In the microwave range, the emitted signal contains both equilibrium and non-equilibrium components. Therefore, the task of the proposed version of the radiometric system is to separate these signals.

The output signal power of the X1 mm-band antenna is proportional to the total intensity of both radiated

$$P_1 = S_1(I_T + I_\omega) \tag{1}$$

where S_1 - the sensitivity of the antenna; I_T - is the intensity of radiothermal radiation; I_ω – non-equilibrium radiation intensity ($I_\omega < I_T$);.

The input of the X2 antenna is covered by a screen, so direct reception of the object's microwave radiation is impossible.

However, due to the thermal contact of the X2 antenna screen with the surface of a living organism, the screen heats up to the temperature of the surface area. Antenna X2 of the reference channel begins to receive secondary radiothermal radiation from the inner surface of the dielectric plate through a radiotransparent passive thermostat. Assuming that the emissivity of the screen with appropriate selection and treatment of its surface is close to the emissive surface of the body, the output signal power of the X2 antenna is proportional only to the intensity of radiothermal radiation

$$P_2 = S_1 I_T \tag{2}$$

Pulse modulators U1 and U2 work in the key mode (open-closed) and are controlled by anti-phase voltages of low frequency, which are generated by the computer. If the modulator U1, made on p-and-n-diodes, is open, then the modulator U2 is similarly closed, and vice versa.

Therefore, during one half-cycle of the low-frequency voltage, a signal with power is applied to the input of the mixer U3 through the tee A1

$$P_3 = K_1 S_1(I_T + I_\omega + I'_R) \tag{3}$$

where I'_R is the total intensity of the inherent noises of the mixer U3, generator G1 and intermediate frequency amplifier A2, brought to the input of the mixer when the modulator U1 is open; K_1 – transmission coefficient of tee A1.

Accordingly, in the next half-cycle of the low-frequency voltage, a signal with a power is sent to the input of mixer U3 through tee A1

$$P_4 = K_1 S(I_T + I''_R) \tag{4}$$

where I''_R - is the intensity of intrinsic noise when the modulator U2 of the reference channel is open.

Since the receiving antennas X1 and X2 operate at the same temperature and have the same output resistance, it can be assumed that the intensities of their own noises are $I'_R = I''_R = I_R$.

As a result of mixing the oscillating received signals with a wide spectrum and the oscillating monochromatic signal of the G1 mm-band generator, an ensemble of oscillating difference frequencies is created.

If the frequency of the generator G1, performing the role of a local oscillator, is equal to f_1, then the difference frequencies are created from the oscillating components of the emitted mm spectrum that entered the frequency range:

$$f_2 = f_1 + f_4;\; f_3 = f_1 - f_4, \tag{5}$$

where f_4 - is the central frequency of the narrowband amplifier A2 of the intermediate frequency.

Within the bandwidth of the intermediate Δf_4 frequency amplifier A2, the difference frequencies f_{5i} will be in the range

$$\sum_{i=1}^{n} f_{5i} = f_4 \pm \frac{\Delta f_4}{2} \tag{6}$$

where the number *n* is determined by the bandwidth of the intermediate frequency amplifier.

The power of the signal of the intermediate frequencies of equation (6), which consists of a set of oscillations of the difference frequency, will be determined by the state of the modulators U1 and U2.

During one of the half-cycles of the modulators, the signal power will be

$$P_6 = K_1 K_2 S_1 S_2 (I_T + I_\omega + I_R) P_5 \tag{7}$$

and during the second

$$P_7 = K_1 K_2 S_1 S_2 (I_T + I_R) P_5 \tag{8}$$

where K_2 is the power gain of amplifier A2; S_2 – the steepness of the U3 mixer transformation; P_5 – generator power G1.

Video pulses with the following voltages will be generated at the output of the quadratic detector U4 in adjacent half-cycles of switching modulators:

$$U_1 = S_3 P_6 = K_1 K_2 S_1 S_2 S_3 (I_T + I_\omega + I_R) P_5 \tag{9}$$

$$U_2 = S_3 P_7 = K_1 K_2 S_1 S_2 S_3 (I_T + I_R) P_5 \tag{10}$$

where S_3 is the sensitivity of the quadratic detector U4.

From a sequence of video pulses with voltages and a low-frequency U_1, U_2 amplifier A3, an alternating component is isolated and amplified, the amplitude of which is proportional to the polarity of the voltage of the video pulses

$$U_3(t) = K_3 \frac{U_1 - U_2}{2} sign\, sin \Omega t \tag{11}$$

where K_3 is the gain of the low-frequency amplifier A3; Ω is the circular frequency of the low-frequency generator, which is generated by the computer.

The alternating voltage $U_3(t)$ is rectified by the synchronous detector U5 and smoothed by the low-pass filter Z2. As the reference voltage of the synchronous detector U5, anti-phase voltages of the low-frequency generator G2 are used, each of which controls the modulators U1 and U2.

The output voltage of the low-pass filter Z2, taking into account (9) and (10), has the form

$$U_4 = \frac{1}{2} K_1 K_2 K_3 S_1 S_2 S_3 P_5 I_\omega \tag{12}$$

Given that the conversion coefficients of the measuring circuit circuits are constant, we have

$$U_4 = S_0 I_\omega \tag{13}$$

where $S_0 = \frac{1}{2} K_1 K_2 K_3 S_1 S_2 S_3 P_5$ is the resulting sensitivity of the RS to the non-equilibrium component of electromagnetic radiation.

Thus, the introduction of a reference channel with an internal source of secondary radiothermal radiation provides direct measurement of the non-equilibrium component of radiation regardless of intensity I_T, i.e. thermal radiation of the investigated area of the skin of the object, and the level of inherent noise I_R of the receiving equipment.

By retuning the frequency of the G1 generator in the microwave range, it is possible to measure the intensity of the non-equilibrium component in various parts of the spectrum of the millimeter range.

Some error in the measurement results occurs due to the difference in the coefficients of the radiation capacity of each human or animal cover and the radiation of the inner surface of the metal screen of the X2 antenna. To level such an error and increase the reliability of measurements of the non-equilibrium component, the X2 antenna is made in the form of a rectangular horn (Fig. 2 a, b), in the middle of which, on the side of the reference input, a metal-dielectric converter of the spectrum of the received radiation is located. The converter is a two-layer package made of a metal plate and a plate of an organic dielectric, connected to each other by heat-conducting glue or another method that ensures heat transfer without losses.

The fact is that the skin of a person and an animal differs in its emissivity from a completely black body, the emissivity coefficient of which is $\beta = 1$. According to its properties, the skin belongs to the class of gray bodies $\beta < 1$, in which the radiative capacity is much greater than that of metals. The studies carried out by the authors [12] showed that dielectrics made of organic materials are the closest to each cover in terms β of the emissivity coefficient. The selection of materials with the help of a thermal imager showed that ivory in the range of millimeter wavelengths has an emissivity close to the emissivity of each cover (the difference does not exceed 5...7%). Therefore, an ivory plate is used in the above device.

Due to the good reflective ability and the appearance of the skin effect in the metal plate, both components of electromagnetic radiation (I_T, I_ω) are reflected and scattered. For this, the thickness of the metal plate is chosen to be 0,1...0,01 mm. To ensure good thermal contact with the object's skin, the transducer is placed at the receiving end of a rectangular horn of a metal plate at the level of the antenna end. The thickness of the dielectric plate is chosen to be 0,8...1 mm, which ensures its strength and rapid heating from the metal plate. The heated dielectric plate begins to emit mm-waves of radiothermal radiation, the intensity of which is close to the radiothermal radiation of a living organism. Ivory is a "dead" object and does not form non-equilibrium radiation.

4. Conclusions

From the following conclusions can be drawn from this scientific work:

The use of microprocessor technology to control the mode of operation of the developed radiometric system significantly expands the functional measurement capabilities of the system and provides direct measurement of microwave radiation of a bioobject, comparison of the measured signal level with a reference value, adjustment of the research frequency, assessment of the presence of a non-equilibrium component in the radiation spectrum, as well as processing and archiving of research results and measurements.

The high sensitivity of the RS is characterized by a significant fluctuation of the output signal, the use of a computer allows to reduce this deficiency by digitizing and averaging the result, thereby increasing the stability of the readings and the accuracy of the measurements.

When studying microwave-irradiated biological objects, the sensitivity of the radiometric system depends on their temperature and should be 5…10 times less than the level of the signal under investigation. For the analysis of signals of the human body, the authors recommend choosing this ratio within 5...10 times, and the sensitivity at the level of reliable measurement of body thermal radiation of $0,3 \cdot 10^{-13}$ W.

The given values of PC sensitivity and its relationship with thermal microwave radiation make it possible to detect the presence of non-equilibrium radiation, which is 5...8 times less than the level of the total radiation of the bioobject.

The intensity of non-equilibrium radiation is largely an indicator of its vitality.

Non-equilibrium radiation can be used in medical practice as a diagnostic parameter, in agriculture as an indicator of the biological activity of seeds and embryos, in the food industry to control the ripening of hard cheese, wine and other products associated with the use of microorganisms and bioengineering technologies.

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