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INCREASED ACCURACY OF MEASUREMENT OF HIGH-SENSITIVITY mm-RANGE RADIOMETRIC EQUIPMENT INTENDED FOR MEDICAL-BIOLOGICAL APPLICATION

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Abstract – The paper considers the methods of improving the accuracy of measurements of low-intensity electromagnetic radiation of the bio-objects in mm- range carried out with the use of high-sensitivity radiometric equipment with the reference noise generator included into its structure. The main sources of uncertainty of measurement are determined. It is shown that with the help of a reference noise generator having the power comparable with radiation power of bio-objects, it is possible to decrease essentially the uncertainty of measurement and to register accurately the peculiarities of radiation spectrum of the living objects.

Keywords: radiometric system, uncertainty of measurement, reference noise generator

1. INTRODUCTION

Electromagnetic radiation generated by the living organisms or exerting influence on them is widely used in biological and medical investigations. The values of wavelength may lie within a wide spectrum. However of special interest is a millimeter (mm) wavelength range. Theoretical substantiation of possibility of these waves generation by cellular structures way given by Fröhlich [1, 2]. Later on, this trend of science has gained the further development and found practical application both in biology and medicine [3, 4]. Its distinguishing feature is a low level of acting power: 10^{-6}–10^{-12} W for monochromatic signals and 10^{-14}–10^{-20} W/Hz for noise signals. But the level of the registered inherent-radiation of bio-objects is still lower, as a rule: 10^{-12}–10^{-13} W and 10^{-20}–10^{-21} W/Hz. However, medical practice and biological research showed that such low-intensity signals within frequency range 37,5–78,3 GHz were rather efficiently influencing the living organisms and their inherent radiation carried valuable information about the state of an organism [3, 5].

Existence of the great number of the devices intended for acting upon the living objects [6], as well as for registration of the inherent radiation [5], stipulated the necessity of designing the high sensitivity radiometric system (*RS*) capable of solution of the problems of metrological support of the devices and also suitable for scientific investigations in medicine and biology. For this purpose, the specialists of the head organization of the Ministry of Public Health of Ukraine specializing in electrical and radiotechnical measurements of Scientific Research Center of Quantum Medicine (SRC QM) "VIDHUK" have designed and certified two radiometric systems in frequency ranges 37,5–53,6 and 53,5–78,3 GHz. Due to implementation of the new engineering solutions [7] there was attained sensitivity not lower than 10^{-22} W/Hz.

However, in the process of maintenance of both systems the necessity arose to specify their metrological characteristics and to reduce uncertainty of measurement. One of the ways to solve this problem is to improve the parameters of the high-frequency input channel of the system and also to design and use the reference noise generator (*RNG*) with the level of spectral noise power density (*SNPD*) close to the level of biological objects radiation within the *RS*'s operating frequencies band. As can be seen from practice, for the optimal solution of the stated problem the two approaches should be used in mutual interrelation. It makes it possible not only to carry out the reliable metrological monitoring of the respective equipment but also to determine more exactly the radiation parameters of the living objects and to understand in a better way its nature.

2. THE MAIN REQUIREMENTS TO THE REFERENCE NOISE GENERATOR

The absence of the reference noise generator essentially enhances the uncertainty of measurement as soon as in this case it should be estimated proceeding from metrological characteristics of measuring units forming a composite part of the *RS*. For the mm-range systems such calculation of uncertainty is objectionable since it essentially restricts the domain of their application. The well-known standard noise generators of high as well as low-temperature [8-12] are intended for operation within frequency ranges below 37,5 GHz and have operating temperature differing drastically from the temperature of biological objects (35–40°C).

That is why one of the main requirements to *RNG* was setting of its operating temperature in the vicinity of 40°C and here, by Nyquist's formula the value of *SNPD* ($I_\omega = kT$) comprises $4{,}3\cdot 10^{-21}$ W/Hz, that is 10 times as much as the value of the *RS* threshold sensitivity. Thus the *RS*'s high sensitivity allows us to use the thermal noise generator with operating temperature approximately the same as that of the objects being measured. It results in simplification of the requirements to the *RNG*, which, as will be shown further, gives the possibility to lower uncertainty of measurement.

The generator construction is schematically shown in Fig. 1. It consists of short-circuited length of a rectangular waveguide 1 inside which there is a load in the form of a wedge made of radio absorbing material 2 (electromagnetic noise source). The heating element 3 is connected to the load. To provide the temperature stability, the noise source is placed in thermostat 4. The temperature control is realized with the help of the sensor 5. Thermo-isolating filter 6 provides power transfer from the noise source to the generator output 7. The heater temperature is assigned with the use of a control unit 8.

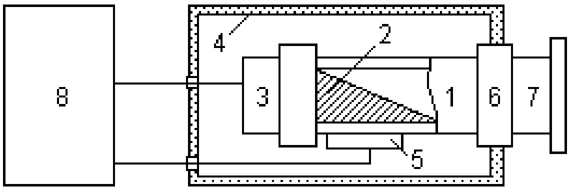

Fig. 1. Block diagram of reference noise generator

The total uncertainty of assigning the level of output power is expressed through the standard deviation

$$u_C(P_S) = \sqrt{u^2(P_A) + u^2(P_C) + u^2(P_V) + u^2(P_W)}\ ,$$

where

$u^2(P_A)$ is variance related to errors in the scheme of automatic temperature control;

$u^2(P_C)$ is variance caused by instability of the parameters of a temperature sensor;

$u^2(P_V)$ is variance obtained owing to non-uniformity of the load temperature;

$u^2(P_W)$ is variance related to uncertainty of the waveguide parameters with due regard for power losses owing to attenuation and also instability of temperature distribution.

The following requirements to the reference generator result from analysis of formula (1):

a) the improved accuracy of initiation of a circuit of the noise source temperature regulation, i.e. the enhanced circuit sensitivity without loss of stability of its operation;

b) the reliable contact of a thermocouple with the load body of the noise source;

c) the improved uniformity of temperature distribution over the load body;

d) since it is rather difficult to make accurate calculations of attenuation stipulated by the finite conductivity of the walls of the waveguide, so it is expedient to shorten the transitional section length, i.e. the section of a waveguide from the wedge end 2 to the output flange.

Among the above-enumerated reguirements the most difficult to implement are the points *a* and *b*, since owing to small dimensions of the wedge load in the mm-wavelength range, it is difficult to insert a temperature sensor (for example, a thermocouple) into it. As a result, it is necessary to place the noise source together with a waveguide into a thermostat, as a rule.

The requirement of point *c* is much easier fulfilled in mm-range, since linear dimensions of a load construction are reduced. Estimation of temperature nonuniformity in this case is an order of magnitude lower than in centimeter range (± 0,5 K versus ± 5 K).

To ensure fulfillment of the point *d* requirement, related to the maximal reduction of a transitional section length and decreasing of a temperature gradient, it is necessary to introduce a thermo-isolating filter into the generator construction.

It should be also taken into account that a transitional section is an additional noise source whose power can be defined just approximately. Thus the section length reduction improves measurement accuracy when using the *RNG*.

In the process of its designing it is necessary to take into consideration the requirements *a–d*, since the remaining uncertainty in assigning of the level of output power leads to the increased uncertainty of the final measurement.

Also, it is worth observing, that while operating within mm-range, the special attention should be paid not only to the choice of the measurement method but also to matching of the high-frequency channel units, since the accuracy of the fulfilled measurements strongly depends on this.

3. METHOD AND SCHEME OF MEASUREMENTS

One of the most widely spread methods of measurement is the substitution method with the use of the reference noise generator and precise attenuator. And here, at first the *RNG* is connected to the *RS* input port, followed by the noise source being measured, and with the help of the precise attenuator the same signal level is set at the *RS* output.

The block diagram of measurement is given in Fig. 2. The upper part of the figure corresponds to *RNG* connecting to *RS* input and the lower to the measured object connecting to *RS* input.

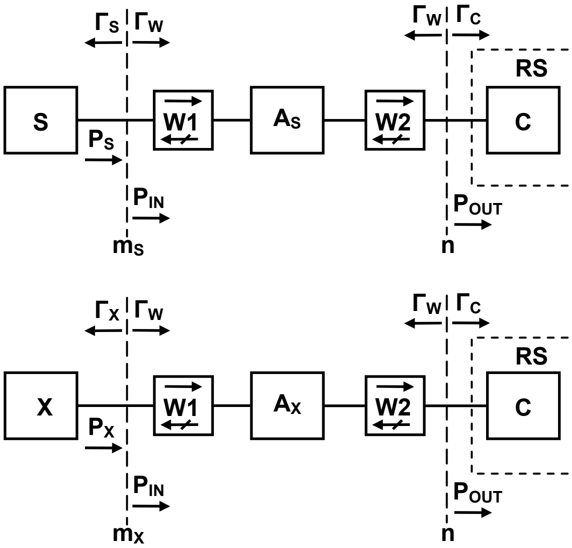

Fig. 2. Block diagram of measurement of low-intensity radiation power

The following designations are introduced here: *RS* is a radiometric system; *S* is the reference noise generator; *X* is the measured object; *A* is the precise attenuator with attenuation A_S (or A_X), when *RNG* (or the measured object) is connected to the *RS* input; *W1* and *W2* are isolators connected to attenuator input and output and having a reflection coefficient $\varGamma_W \le 0{,}1$; *C* is the converter unit of the radiometric system *RS*.

The powers of the *RNG* and the measured object connected to the input of the isolator *W1* are equal to:

$$P_S = kT_S \Delta f \tag{1}$$

and

$$P_X = kT_X \Delta f , \tag{2}$$

where

$k = 1{,}38 \cdot 10^{-23}$ J/K is Boltzman's constant,

T_S is *RNG* temperature,

T_X is the measured object temperature;

Δf is a band of the analyzed *RS* frequencies.

It is assumed that spectral noise power density of the generator and one of the measured object are constant within the frequency range Δf .

The mismatch coefficients defining a portion of power of the signal entering the attenuator's input through the isolator W1 are equal to:

$$m_S = \frac{\left(1-|\varGamma_S|^2\right)\cdot\left(1-|\varGamma_W|^2\right)}{|1-\varGamma_S \varGamma_W|^2} \tag{3}$$

and

$$m_X = \frac{\left(1-|\varGamma_X|^2\right)\cdot\left(1-|\varGamma_W|^2\right)}{|1-\varGamma_X \varGamma_W|^2} , \tag{4}$$

where

$\varGamma_S$ is a reflection coefficient of the *RNG*;

$\varGamma_X$ is a reflection coefficient of the measured object.

The mismatch coefficient at the input of the *RS'*s converter is equal to:

$$n = \frac{\left(1-|\varGamma_C|^2\right)\cdot\left(1-|\varGamma_W|^2\right)}{|1-\varGamma_W \varGamma_C|^2} . \tag{5}$$

where

$\varGamma_C$ is a reflection coefficient of the input of the converter.

The efficiency of the attenuator and the isolators connected to its input and output can be determined by formula:

$$\eta = \frac{P_{OUT}}{P_{IN}} = \frac{A\left(1-|\varGamma_C|^2\right)\cdot A_W^2}{\left(1-|\varGamma_W|^2\right)\cdot|1-\varGamma_C \varGamma_W|^2} , \tag{6}$$

where

P_{OUT} and P_{IN} are powers at the input and output of the indicated part of the scheme (Fig. 2);

A is one of the values of A_S or A_X ;

A_W is the losses at the isolator *W1* (or *W2*).

With due regard for mismatch coefficients (3), (4) and (5) it is possible to receive the total attenuation value of sequentially connected precise attenuator and the two isolators:

$$\alpha = \frac{\left(1-|\varGamma|^2\right)\cdot A \cdot A_W^2}{\left(1-|\varGamma_W|^2\right)\cdot|1-\varGamma \varGamma_W|^2} \tag{7}$$

where

$\varGamma$ equals $\varGamma_S$ or $\varGamma_X$.

The power applied to the isolator *W1* input with due regard for mismatch is defined by the expression:

$$P_{IN} = mP ,$$

and the power at the system's converter input is equal to nP_{OUT} , where m is one of the values of m_S and m_X and P is one of the values of P_S and P_X . Proceeding from thermodynamic equilibrium condition, one can obtain:

$$\begin{aligned} nP_{OUT} &= m\eta P + nP_A\left(1-\alpha\right) = \\ &= n\left[P\alpha + P_{AW}\left(1-\alpha\right)\right] \end{aligned} \tag{8}$$

where

$$P_{AW} = kT_{AW} \Delta f$$

is thermal noise power generated by a two-port network consisting of the attenuator and two isolators.

Assuming that the *RS* is very sensitive, one can write down the equation of power balance for substitution method using (8):

$$n\left[P_S\alpha_S + P_{AW}\left(1-\alpha_S\right)\right] = nP_{OUT} =$$

$$= n\left[P_X\alpha_X + P_{AW}\left(1-\alpha_X\right)\right] \quad (9)$$

Hence

$$P_X = \left(P_S + P_{AW}\right)\frac{\alpha_S}{\alpha_X} + P_{AW}. \quad (10)$$

Taking account of (7) we can obtain:

$$\frac{\alpha_S}{\alpha_X} = \left|\frac{1-\Gamma_W\Gamma_X}{1-\Gamma_W\Gamma_S}\right|^2 \cdot \frac{1-|\Gamma_S|^2}{1-|\Gamma_X|^2} \cdot \frac{A_S}{A_X} \quad (11)$$

From (10) it is possible to obtain the uncertainty estimation stipulated by uncontrolled thermal noise of the power P_{AW}, which is generated in the precise attenuator *A* and two isolators *W1* and *W2*:

$$u_T\left(P_X\right) \le \left|1-\frac{\alpha_S}{\alpha_X}\right| u_T\left(P_{AW}\right) \approx$$

$$\approx \left|1-\frac{A_S}{A_X}\right| u_T\left(P_{AW}\right) \quad (12)$$

The expression (11) makes it possible to find two more reasons influencing upon the measurements accuracy, each one of them is characterized by the multipliers included into the right-hand part of the given equality.

It is rather difficult to determine very accurately the phases of reflection coefficients Γ_X, Γ_S and Γ_W in practice, and the more so, within the mm-range of wavelength. As a result, there occurs uncertainty of measurement caused by mismatch of the system units (Fig. 2). Using the expression (11) we can obtain its estimate:

$$u_M\left(P_X\right) \le \left[1-\left(\frac{1+|\Gamma_W\Gamma_X|}{1-|\Gamma_W\Gamma_S|}\right)^2\right]\times$$

$$\times\frac{1-|\Gamma_S|^2}{1-|\Gamma_X|^2}\cdot\frac{A_S}{A_X}\left(P_S-P_{AW}\right) \quad (13)$$

Taking into account that the value of Γ_S and Γ_W is small, the estimate for uncertainty can be obtained from the more simple formula which follows from (13):

$$u_M\left(P_X\right) \le 2|\Gamma_W||\Gamma_X|P_X. \quad (14)$$

The given uncertainty can be reduced due to additional matching of the receiving antenna, which takes into account the peculiarities of the measured object.

The second reason causing the uncertainty of the measurements resides in inaccuracy of calibration of the precise attenuator. It is determined by the third multiplier into the right-hand part of (11):

$$u_A\left(P_X\right) \le \left|\frac{1-|\Gamma_W\Gamma_X|}{1-|\Gamma_W\Gamma_X|}\right|^2 \cdot \frac{1-|\Gamma_S|^2}{1-|\Gamma_X|^2}\times$$

$$\times\left(P_S-P_X\right)\cdot u\left(\frac{A_S}{A_X}\right) \approx \left(P_S-P_X\right)\cdot u\left(\frac{A_S}{A_X}\right). \quad (15)$$

And finally, the estimate of uncertainty caused by uncertainty of the *RNG* power level can be obtained from (10):

$$u_S\left(P_X\right) \le \frac{\alpha_S}{\alpha_X}u_C\left(P_S\right) \approx P_X\frac{u_C\left(P_S\right)}{P_S}. \quad (16)$$

The carried out analysis of the scheme of measurements confirms the expediency of interconnected solution of the two problems related to the improvement of the measurement accuracy, i.e. design optimization of the *RNG* and of the high-frequency input channel of the radiometric system. In this case, uncertainty of measurement due to mismatch will be minimized and its estimation can be done by (14).

Since the device is intended for biological and medical researches, so operating temperature of the *RNG* must be chosen near 40°C. As follows from (15) and (16), the small value of operating temperature and, consequently, of the *RNG* output power also reduces the uncertainty of measurement. Besides, when stabilizing the temperature of the radiometric system and precise attenuator, the uncertainty related to their thermal noises is reduced.

4. MAIN RESULTS

In accordance with the requirements stated in points *c* and *d* of section 2, we have designed the reference noise generator characterized by smooth regulation of noise power due to operating temperature changes. For the sake of matching improvement at small attenuation values of precise attenuator, the isolator *W1* is introduced additionally (Fig. 2) and voltage standing-wave ratio (VSWR) of the *RNG* output is essentially reduced. Experimental study of the suggested generator design confirmed expediency of its utilization as the reference noise generator. The dependence of spectral noise power density (*SNPD*) at a generator's output on its operating temperature is plotted in Fig. 3. It has a linear character, which allows for high-precision generator's scale adjustment and regulation of its power within the 10% limits. This creates additional capability of increasing the measurement accuracy.

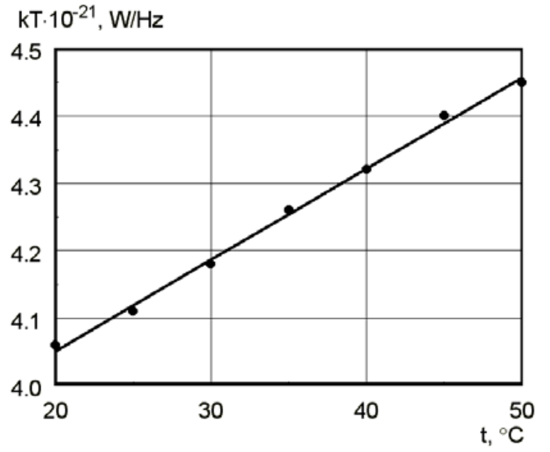

Fig. 3. Dependence of spectral noise power density of the RNG on temperature

The designed reference noise generator was certified by Scientific Research Institute "Metrology" (Kharkov, Ukraine) and it has the following characteristics:

Operating frequency range, GHz	37,5-78,3
Temperature of noise generator, °C	27-48
Uncertainty of setting of operating temperature of generator, °C	0,7
Spectral density level of noise power at generator output, W/Hz	$(4{,}2\text{-}4{,}5)\cdot10^{-21}$
Uncertainty of setting of spectral density of noise power, W/Hz	$1\cdot10^{-23}$

Application of the designed generator in the measurement of low-intensity radiation of biological as well as physical objects enabled us to reduce the uncertainty of measurement from 35–40% to 5–15% due to calibration of the radiometric system and statistical processing of the results of measurements.

The typical dependence of the relative experimental standard deviation of *SNPD* of the input signal on the value of *SNPD* measured at one the operating range frequencies is given in Fig. 4. From the represented dependence it follows that uncertainty of measurement is growing with lowering of the level of input *SNPD*. However, even with the values close to threshold sensitivity, the ratio of standard deviation to the mean value is approximately 3-4 times less than for measurements without *RNG*.

The data were obtained as a result of statistical processing of 20 observations at each point. It should be noted that for *SNPD* values close to threshold sensitivity of a radiometric system, uncertainty of measurement with respect to the mean value drastically increases, so while carrying out the measurements by substitution method, it is necessary to do our best to avoid the situations involving operation with such levels of power.

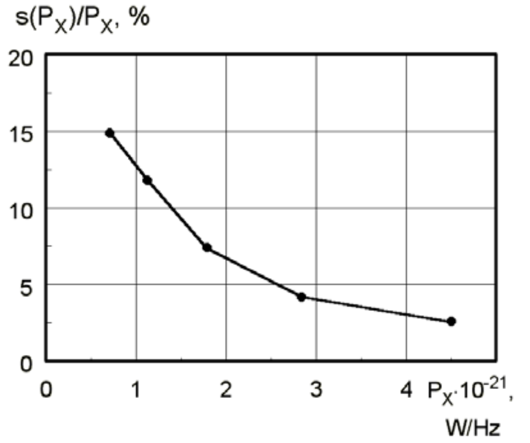

Fig. 4. Dependence of relative experimental standard deviation of *SNPD* on *SNPD* level at *RS* input for 45 GHz frequency

The use of the reference noise generator ensures the improvement of the RS's metrological characteristics and makes it possible to more accurately measure the parameters of mm-range low-intensity generating equipment whose level of spectral density of noise power does not exceed 10^{-21} W/Hz.

It should be noted that improvement of the RS accuracy allowed for revealing of a number of interesting peculiarities in medical-biological investigation of bio-objects. For example, the peculiarities are revealed of the inherent microwave radiation of a human depending on the conditions of life and nutrition, the state of his organism. Also the influence of diseases, stresses, and physical strain on radiation intensity was discussed. The radiation peculiarities of various simple bio-objects were marked: fungi, bacteria, seeds of plants which also characterize one or another state.

At the same time, it should be noted that the considered methods of uncertainty reduction are related to the measurements of the inherent noise radiation of biological or physical objects.

5. CONCLUSION

1. The method of improving the accuracy of measurement of radiation power of biological objects within mm-range of wavelength with the use of the reference power source was considered.
2. For this purpose there was designed and certified the reference noise generator specifically adapted to the radiation level of biological objects.
3. It is shown that the problem of improvement of quality of measurements must be solved on all-round basis, i.e. it is necessary to develop the reference noise source and to improve high-frequency input channel of a radiometric system by interrelated process.
4. The use of the approaches represented in the paper allows decreasing uncertainty of measurement of spectral density of the noise power for the bio-objects.

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