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ELECTRONICS AND RADIO ENGINEERING

A Receiving Unit of the Null Modified Microwave Radiometer for Studying Objects in the Antenna Near-Field Zone

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Abstract—A receiving unit of the microwave radiometer, which is based on the modified null measurement method, is described. The application of this unit minimized the influence of the antenna mismatch relative to the studied environment. When the studied object approaches the antenna up to its complete touch, the error in the output signal of the radiometer does not exceed 0.1 K.

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When microwave radiometers (units for receiving electromagnetic waves of thermal radiation of objects) are created for studying media that are located in the immediate vicinity to the antenna (including an applicator-type antenna), variations of the reflection coefficient at the border of the antenna and the studied medium have a significant influence on the measurement accuracy. In [1–3], the influence of the reflection coefficient on the measurement accuracy is decreased by such methods as compensation, additional thermostatting of the antenna system, the accounting of the influence during the signal processing, etc.

In addition, different structural principles of creating input receiving units of radiometric systems are applied, which allow one to decrease the effect of the reflection-coefficient change by circuitry methods, as the antenna approaches the studied object. The reduction in the reflection-coefficient effect on the measurement accuracy is based on the method in which the studied object is additionally noised by a regulated signal of the noise source of the radiometer, which in most cases is carried out as follows [4].

When an electromagnetic signal propagates within the thickness of the studied object to the radiometer, some portion of it is reflected from the surface and arrives back into the object. To compensate signal losses due to the reflection, the radiometer carries out noise pollution of the object.

The adaptive determination by the radiometer of a portion of the useful signal, which is returned to the object, allows one to carry out the principle of reciprocity, symmetry, and uniformity of the reflection coefficient, when signals propagating from the studied object or from the receiving antenna of the radiometer are considered. In the process of the operation, the radiometer regulates an additional noise signal, radiated to the antenna, which after reflection at the border with the object, arrives at the input of the radiometric receiver. As a result, the total useful signal of the object is formed at the input of the radiometric measuring section.

In the radiometer [5], the reference signal, noise-polluting the studied object, is regulated by changing the temperature of the matched load, the thermodynamic temperature of which determines the effective temperature of noises, irradiated into the microwave section. As a result, the zero balance is set at the input of the radiometric receiver. Since the temperature of the matched load varies with some sluggishness, and the zero-balance setting system operates on the tracking principle, this leads to decreasing dynamic characteristics of the radiometer. Another drawback is the narrow dynamic measurement range, since the temperature of the passive noise source (matched load) can vary within small limits.

The receiving unit of the radiometer, whose principle of operation is based on the modified null reception method [6], is considered in this work. The reference noise-polluting signal is usually regulated in value, but in the presented circuit of the receiving unit, the noise-polluting signal level is controlled by changing the duration of arrival of the constant-power reference noise signal into the receiving section. As the noise generator, an active source (noise diode) is used.

The application of the modified null reception method in the radiometer allows one not only to eliminate the influence of the reflection coefficient from the interface between the antenna and object on the measurement accuracy but also to indirectly determine the sought signal from the duration of action of the reference noise-polluting signal and minimize the influence on the measurement accuracy of the drift and fluctuations of the gain of the measuring section at low and high frequencies, including the transfer constant of the square-law detector.

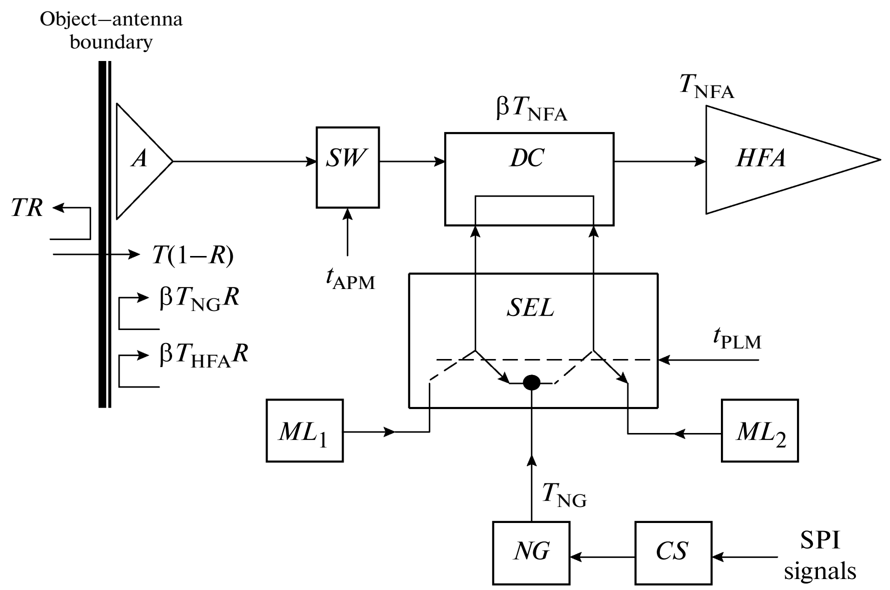

Fig. 1. Block diagram of the receiving unit of the modified null radiometer for studying objects located in immediate proximity to the antenna: (*A*) antenna; (*SW*) ultrahigh-frequency switch; (*DC*) directional coupler; (*SEL*) ultrahigh-frequency selector; ($ML_{1,2}$) matched loads; (*NG*) noise generator; (*HFA*) high-frequency amplifier; (*CS*) current source; and (*TR*) portion of the useful signal of the object, reflected at the boundary with the medium back to the object with reflection coefficient *R*.

Figure 1 shows the block diagram of the input assembly of the radiometer, including antenna *A*, ultrahigh-frequency switch *SW*, and selector *SEL*, two matched loads ML_1 and ML_2, directional coupler *DC* operating in the antidirectional mode, reference noise generator *NG*, power source of the noise generator (current source *CS*), which is controlled by SPI interface signals, and the first high-frequency amplifier *HFA*.

Two kinds of synchronously fulfilled pulse modulations (amplitude and width) are carried out in the input unit (Fig. 2). The amplitude–pulse modulation is symmetric (meander type) and includes two half-periods of the equal duration t_{APM}. In response to signals t_{APM}, the microwave switch *SW* is turned on and off.

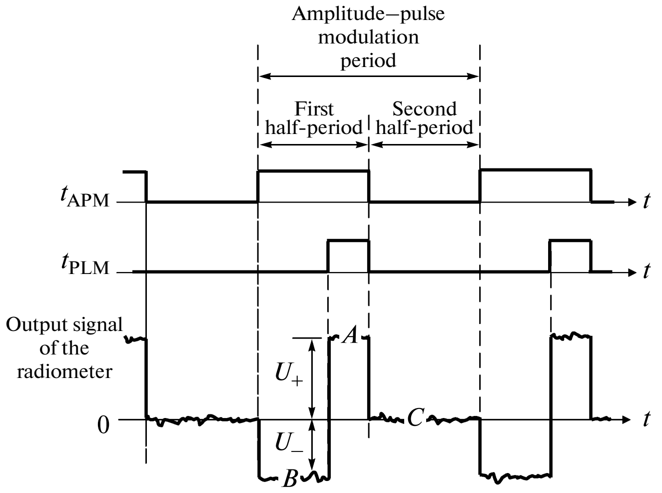

Fig. 2. Time diagrams explaining the synchronous execution of two types of pulse modulations (amplitude and length) in the input unit.

The reflective-type switch is applied in the unit, i.e., in the open state, when the signal t_{APM} is equal to the logic zero (t_{APM} = log. 0), the switch reflects the signal of the noise generator, which arrived from the *DC*, to the amplifier. In the other case, if t_{APM} is equal to the logic one (t_{APM} = log. 1), the switch connects the antenna to the *HFA* input through the *DC*.

The pulse-length modulation is fulfilled only within the first half-period of the amplitude–pulse modulation in response to the control signal with duration t_{PLM}. The pulse logic signal of duration t_{PLM} controls switching in the selector *SEL* and thus changes the direction of arrival of the reference noise signal of the *NG* into the receiving section. If t_{PLM} = log. 1,, the noise signal of the generator arrives after the directional coupler at the input of the high-frequency amplifier; and if t_{PLM} = log. 0, the noise signal is irradiated to the antenna.

Thus, for different combinations of control signals t_{APM} and t_{PLM}, three noise signals will be at the input of the high-frequency amplifier (Fig. 2):

$$\begin{gathered}\text{Signal } A\ (t_{\text{PLM}} = 1, t_{\text{APM}} = 1),\\ \text{equal to } T\,(1-R) + T_{\text{NG}}\beta + T_{\text{HFA}}R + T_{\text{HFA}},\end{gathered} \tag{1}$$

$$\begin{gathered}\text{Signal } B\ (t_{\text{PLM}} = 0, t_{\text{APM}} = 1),\\ \text{equal to } T\,(1-R) + T_{\text{NG}}\beta R + T_{\text{HFA}}R + T_{\text{HFA}},\end{gathered} \tag{2}$$

$$\text{Signal } C\,(t_{\mathrm{PLM}} = 0, t_{\mathrm{APM}} = 0), \quad \text{equal to } T_{\mathrm{NG}}\beta + T_{\mathrm{HFA}} + T_{\mathrm{HFA}}, \tag{3}$$

where T is the measured noise temperature of the object; R is the power reflection coefficient on the object–antenna boundary; T_{NG} is the effective noise temperature of the reference noise generator; β is the signal transfer constant of the noise generator from the primary channel of the directional coupler into the auxiliary channel; and T_{HFA} is the intrinsic noise temperature of the measuring section, reduced to the input of the high-frequency amplifier.

As signals, noise temperatures of thermal noises but not their powers are considered in the course of the analysis. According to [7], they are related to each other through the proportionality coefficient, which is equal to the product of the Boltzmann constant by the band of frequencies, received by the radiometer. Noises of the antenna, noise generator, and intrinsic noises of the amplifier belong to different sources and, hence, are not correlated. Therefore, their effective noise temperatures can be summed up.

In the course of the analysis, we consider that the antenna and microwave switch have no losses and assume the coupler directivity and reflection of the switch in the disabled state to be ideal.

The intrinsic noises of the radiometer, designated as T_{HFA}, should be specially considered. When levels of noise signals A and B are formed, the intrinsic noises are irradiated to the antenna, reflected, and, arriving at the input of the amplifier, being equal to $T_{\mathrm{HFA}}R$, added to the intrinsic noises T_{HFA}. In order that these two noise components should be incoherent and no correlation between them be absent, the following condition should be met [8]:

$$(2s\sqrt{\varepsilon}/C_0) \ge (1/df), \tag{4}$$

where s is the total length of the communication line between the antenna and the input of the high-frequency amplifier; ε is the dielectric permeability of the substrate on which passive elements of the input assembly (a microwave switch and a directional coupler) and sections of signal transmission lines are located; C_0 is the speed of light in vacuum; and df is the frequency band of signals received by the radiometer. For the signal C, the second summand in (3) determines the temperature of intrinsic noises reflected from the open microwave switch. In order to ensure the absence of interference products for this signal level, the distance between the switch and the amplifier input should be larger than or equal to

$$s_{\min} = C_0/2\sqrt{\varepsilon}\,df. \tag{5}$$

According to the used modified zero measurement method [9], the mathematical model of the transfer characteristic of the radiometer, from which the measured signal of the antenna is determined through the duration of the signal, controlling the pulse-length modulation, and changes in the constant component of intrinsic noises and transfer constant do not influence the measurements, can be written:

$$t_{\mathrm{PLM}} = (C - B)t_{\mathrm{APM}}/(A - B), \tag{6}$$

where A, B, and C are the noise signals from (1)–(3). The differences of these noise signals are, respectively,

$$\begin{gathered} C - B\colon\ T_{\mathrm{NG}}\beta + T_{\mathrm{HFA}} + T_{\mathrm{HFA}} - T(1-R) - T_{\mathrm{NG}}\beta R \\ - T_{\mathrm{HFA}}R - T_{\mathrm{HFA}} = T_{\mathrm{NG}}\beta(1-R) + T_{\mathrm{HFA}}(1-R) - T(1-R); \\ A - B\colon\ T(1-R) + T_{\mathrm{NG}}\beta + T_{\mathrm{HFA}}R + T_{\mathrm{HFA}} - T(1-R) \\ - T_{\mathrm{NG}}\beta R - T_{\mathrm{HFA}}R - T_{\mathrm{HFA}} = T_{\mathrm{NG}}\beta(1-R). \end{gathered}$$

After the substitution of these ratios into (6), we obtain:

$$t_{\mathrm{PLM}} = (T_{\mathrm{NG}}\beta + T_{\mathrm{HFA}} - T)t_{\mathrm{APM}}/T_{\mathrm{NG}}\beta. \tag{7}$$

It follows from (7) that the duration t_{PLM} is related to the measured signal T by the linear dependence and, hence, one can indirectly determine the sought signal of the object via it. The obtained formula does not also contain multiplier $(1 - R)$. Hence, the application of the considered unit at the input of the radiometer allows one to exclude the influence of the reflection coefficient on the measurement accuracy, when the antenna and the studied medium are mismatched.

From (7) we find the studied signal T:

$$T = (T_{\mathrm{NG}}\beta + T_{\mathrm{HFA}}) - T_{\mathrm{NG}}\beta t_{\mathrm{PLM}}/t_{\mathrm{APM}}. \tag{8}$$

By substituting into (8) values of the signal duration t_{PLM}, equal to t_{APM} and 0, we will obtain the measurement limits. For $t_{\mathrm{PLM}} = t_{\mathrm{APM}}$, the minimal boundary of the measurement range is equal to $T_{\min} = T_{\mathrm{HFA}}$. For $t_{\mathrm{PLM}} = 0$, the maximal boundary is $T_{\max} = T_{\mathrm{NG}}\beta + T_{\mathrm{HFA}}$.

Thus, the lower border of the measurement range is determined by the noise temperature of the HFA, and the upper border is determined by the additional noise from the noise-polluting channel. The dynamic range is equal to $dT = T_{\max} - T_{\min} = \beta T_{\mathrm{NG}}$.

Based on the block diagram in Fig. 1 for the radiometric receiver described in [10], the decimeter-wavelength input unit with a central frequency of 2.27 GHz and a 200-MHz received-signal band is designed.

When the input unit was designed, requirements for minimizing losses in microwave components were taken into account to decrease intrinsic noises of the system and mass-and-size indices. The wave-leading structures of the input unit are based on asymmetric microstrip lines using the ФЛАН-2.8 0.5-mm thick material.

The directional coupler on microstrip lines with the end-wall coupling has a small transfer constant between the basic and auxiliary channels and thus decreases the branching of the useful signal of the antenna into the channel of the noise generator. The calculation was performed for the coupling coefficient $\beta = 0.003(-25.2\ \mathrm{dB})$. The substrate material with a low dielectric permeability ($\varepsilon = 2.8$) is selected from

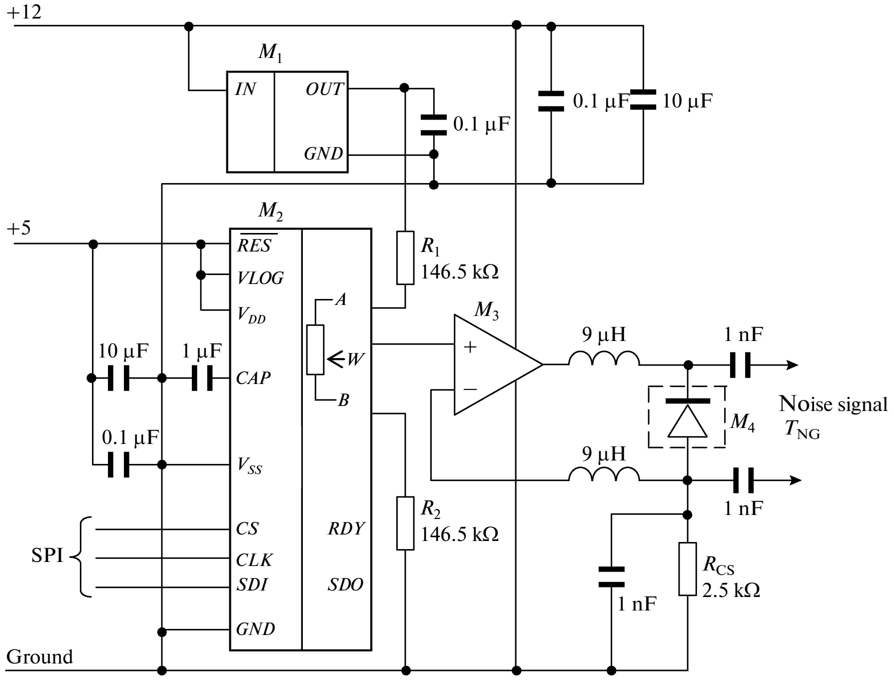

Fig. 3. Schematic diagram of the controlled current source of the noise generator: (M_1) ADR445B, (M_2) AD5292BRUZ-20, (M_3) OP1177, and (M_4) NC301.

requirements of designing a coupler with a high directivity (–23 dB).

The solid-state ultrahigh-frequency switch and reflective selector for two directions are based on HMC545 chips. The direct losses at the working frequency of the radiometer are 0.3 dB. The switch and the selector are controlled by the amplitude–pulse and pulse–length signals arriving at the control inputs through galvanic decoupling circuits on an ADUM1300 microcircuit.

As the noise generator, an NC301 semiconductor avalanche transit-time diode is used. The power of the noise signal of the generator is regulated by the value of the current flowing through its active zone. When the current varies from 0 to 2 mA, the generated noise power varies from 0 to 2×10^6 K.

Figure 3 shows the schematic diagram of the voltage-controlled current source, powering the avalanche transit-time diode M_4 of the noise generator of the input unit. The semiconductor diode of the generator is used in the backfire mode with a breakdown voltage of 6 V. The source is based on operational amplifier M_3. In addition to the operational amplifier, the source also includes a reference voltage source M_1, a variable potentiometer M_2, which is regulated in response to signals of the 10-bit digital interface SPI, and a current sensor R_{CS}.

For rated values of divider resistors R_1 and R_2 (indicated in the scheme) and current sensor R_{CS}, the signal of the noise generator, arriving at the measuring channel through the directional coupler, is equal to 300 K and is regulated within ±19.2 K with an increment of 75 mK. When the output power of the noise generator is adjusted, it is necessary to meet the condition: the change of the digital code of the potentiometer by one lower-order bit and the thus caused increment of the noise reference signals in the antenna section must not exceed the fluctuation sensitivity of the receiver of the radiometer.

The input unit is maintained at a constant temperature of +45°C with an accuracy of ±0.031°C, when the ambient temperature changes from –20 to +30°C with a speed below and equal to 15°C/h. The time of reaching the operation condition at an ambient temperature of 0°C is ~6 min.

In the course of experiments, it was obtained that, when the studied flat object with a reflection coefficient of 0.3, the surface of which during the movement remained parallel to the antenna aperture plane, approached the antenna to the full contact with it, the radiometer output signal changed by a value of at most 0.1 K.

Thus, the application of the considered unit in the radiometer input allows one to significantly decrease the influence of the interface between the antenna and the studied medium on the measurement accuracy by circuitry methods.

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