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MEASUREMENT OF THE REFLECTION COEFFICIENT OF MOIST MATERIALS AT ULTRAHIGH FREQUENCIES

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ABSTRACT

The paper considers the possibility of increasing the accuracy of the measurement of the reflection coefficient of moist materials in the region of ultrahigh frequencies. By the magnitude of the reflection coefficient, the moisture content of the material is uniquely determined. The solutions proposed by the authors allow adaptively to monitor the minimum value of the reflection coefficient and to intensify the processes of heat treatment of moist materials.

INTRODUCTION

Anomalous absorption of electromagnetic energy in the region of the complex conductivity dispersion occurs in damp materials in the region of ultrahigh frequencies (microwave). The maximum absorption of electromagnetic waves is found at relaxation frequencies when the frequency of the external field coincides with the intrinsic frequency of the dipoles created by water molecules. The reflection coefficient, which has a minimum value at the relaxation frequency, increases with the removal of moisture from the material. Therefore, the value of the reflection coefficient at the relaxation frequency can be determined by the moisture content of the material.

EASE OF USE

Traditional methods of measuring the reflection coefficient in the absorption band [1] consist of irradiating the microwave by fluctuations of the inhomogeneous medium and the distribution of incident and reflected microwave waves. The ratio of their amplitudes allows us to estimate the magnitude of the coefficient of reflection. The problem with using this method is significant measurement errors in the case when the frequency ω of irradiating microwave oscillations does not coincide with the relaxation frequency ω_p of the molecules of the irradiated material. The latter depends on the temperature of the material, the moisture and the form of connection of water molecules with the material. When removing moisture from the material, the frequency difference $\omega-\omega_p$ increases and the measurement error increases.

To eliminate this disadvantage in [2], irradiating microwave oscillations are modulated by amplitude with low frequency oscillations. The low frequency is chosen equal to half of the absorption band. In the reflected from the material of the microwave oscillation, compare the amplitudes of the lower and upper side frequencies, reaching their equality by changing the frequency of irradiating microwave oscillations. After that, the ratio of the amplitudes of incident and reflected microwave oscillations is measured. This method involves frequent selection of microwave oscillations of the side frequencies by two narrowband microwave filters, separate detection of reflected oscillations by two microwave detectors, and the formation of differential voltage with a two-channel comparison device. In this case, due to the lack of identity and instability of the parameters of paired elements inevitably, errors are introduced in determining the equality of the amplitudes of lateral oscillations [3].

Thus, an important task of measuring the coefficient of reflection is to increase the accuracy by adjusting the oscillating oscillator generator to the relaxation frequency of water molecules in the absorption band [4].

DEVICE FOR MEASURING THE RETURN COEFFICIENT

In Fig. 1 shows the functional scheme of the device proposed by the authors for measuring the coefficient of reflection of moist materials.

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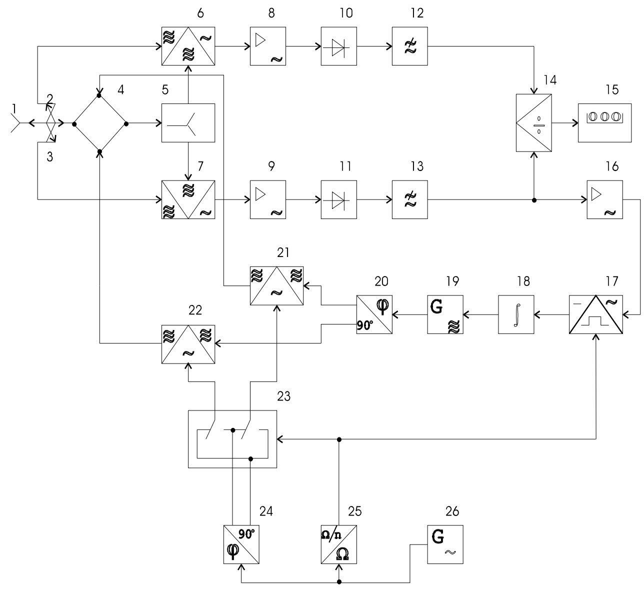


Fig. 1. Functional diagram of the device for measuring the coefficient of reflection of moist materials

The device contains a receiving and transmitting antenna 1, the input-output of which includes directional couplers 2 and 3. The antenna is connected to one of the outputs of the double waveguide duct 4, the second output of which is connected to the power divider 5. Output of the directed coupler 2 of the incident microwave oscillations from connected to the reference channel, and the output of the directional coupler 3 of the reflected microwave oscillations is connected to the measuring channel. Both channels consist of serially coupled balanced microwave mixers 6 and 7, selective amplifiers of a difference frequency of 8 and 9, amplitude detectors 10 and 11, filters of lower frequencies 12 and 13. The second inputs of balanced microwave mixers 6 and 7 are connected to the outputs of the divider of power 5. The outputs of the reference and measuring channels are connected to the inputs of the division unit 14 of the amplitudes of the low frequency signals whose output is connected to the indicator 15. Prior to the output of the low pass filter 13 of the measuring channel connected serially connected switching amplifier 16, a synchronous detector 17 and an integrator 18 whose output is connected to the input of a controlled microwave oscillator 19. A controlled microwave oscillator 19 supplies a quadrature microwave phase-splitter 20 to outputs which are connected to the signal inputs of amplitude microwave modulators 21 and 22. Their modulating inputs via a two-pole switch 23 of coupled to a quadrature low-frequency phase-splitter 24. The control inputs of the bipolar switch 23 and the synchronous detector 17 are connected to the output of the frequency divider 25 connected to the low-frequency generator 26.

The device works as follows. The initial microwave oscillation of the generator 19 (Fig. 1) is separated in phase by a 90° quadrature phase separator 20, creating at its output two orthogonal oscillations:

$$U_1(t) = a_1 cos(\omega_1 t + \varphi_1); \tag{1}$$

$$U_2(t) = a_1 sin(\omega_1 t + \varphi_1), \tag{2}$$

where a_1, ω_1, φ_1, is the amplitude, frequency and phase of microwave oscillations.

Fluctuations (1) and (2) are modulated by amplitude in microwave modulators 21 and 22 by low frequency oscillations of the generator 26, which are also phase-separated by a 90° quadrature phase splitter 24

$$U_3'(t) = A cos(\Omega_1 t + \Phi_1); \tag{3}$$

$$U_4'(t) = A sin(\Omega_1 t + \Phi_1). \tag{4}$$

The low frequency Ω_1 is chosen equal to half the absorption band $\Delta\omega$ of the irradiated medium (fig 2, a), that is, the modulation frequency $\Omega_1 = \Delta\omega/2$.

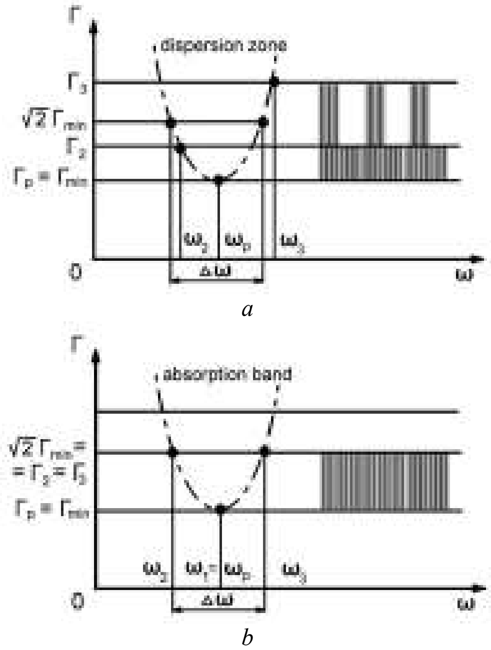
As a result of modulation of microwave oscillations, orthogonal three-frequency oscillations of the form are formed

$$U_5(t) = \{a_H \cos(\omega_1 t + \varphi_1) + 0,5m\cos[(\omega_1 - \Omega_1)t + \\ + \varphi_1 - \Phi_1] + 0,5m\cos[(\omega_1 + \Omega_1)t + \varphi_1 + \Phi_1]\}; \tag{5}$$

$$U_6(t) = \{a_H \sin(\omega_1 t + \varphi_1) + 0,5m\cos[(\omega_1 - \Omega_1)t + \\ + \varphi_1 - \Phi_1] + 0,5m\cos[(\omega_1 + \Omega_1)t + \varphi_1 + \Phi_1]\}, \tag{6}$$

where a_H – amplitude of carrier oscillations; m – depth amplitude modulation coefficient.

Fluctuations of the frequency difference $\omega_2 = \omega_1 - \Omega_1$ with the phase $\varphi_2 = \varphi_1 - \Phi_1$ are oscillations of the lower side frequency relative to the carrier frequency ω_1, and the variations of the total frequency $\omega_3 = \omega_1 + \Omega_1$ with the phase $\varphi_3 = \varphi_1 + \Phi_1$ are the fluctuations of the upper side frequency.



a

b

Fig. 2. Adjust the irradiation frequency to the maximum absorption

Three-frequency oscillations (5) and (6) are formed and subtracted in the double waveguide 4. As a result of these operations, modulated microwave oscillations with only one side frequency are formed at the outputs of the double waveguide tee. When compiling modulated oscillations, a microwave signal with a lower lateral frequency is formed

$$U_7'(t) = a_H'\left[\cos\left(\omega_1 t + \varphi_1 + \frac{\pi}{4}\right) + m\cos(\omega_2 t + \varphi_2)\right], \tag{7}$$

and as a result of subtraction, there is a microwave signal with an upper side frequency

$$U_8{}'(t)=a_H{}''\left[\cos\left(\omega_1 t+\varphi_1-\frac{\pi}{4}\right)+m\cos(\omega_2 t+\varphi_2)\right], \quad (8)$$

where a'_H and a''_H are the amplitudes of the carrier oscillations of the modulated signals.

The microwave oscillation modulation depth is chosen to be small in the range of 5–10% ($m = 0{,}05 - 0{,}1$), so that the power of the microwave oscillations is mainly concentrated in the carrier oscillations of the frequency ω_1 that affect the humid environment. The total microwave oscillations (7) from one output of the double waveguide tee enter the receiving and transmitting antenna 1, and the difference of the microwave oscillation (8) from the second output of the double waveguide tee through the power divider 5 is fed to balanced microwave mixers 6 and 7. With the help of directional couplers 2 and 3, the incident on the inhomogeneous medium and the reflected microwave oscillations are distinguished from it. The amplitude of the reflected vibrations is proportional to the reflection coefficient of the medium, which in the absorption band essentially depends on the frequency of the irradiating oscillations (Figs 2, *a* and *b*). The minimum value of the reflection coefficient occurs when the frequency of the excitatory oscillations ω_i with the frequency ω_p of the relaxation of the water molecules of the wet material coincides ($\omega_i = \omega_p$). The reflection coefficient module, depending on the frequency ratio ω_p and ω_i i can be shown in the following way

$$\Gamma_i=\sqrt{4\Gamma_P^2+(1-\Gamma_P)^2\varsigma_i^2}\,/\sqrt{4+(1+\Gamma_P)^2\varsigma_i^2}\,, \quad (9)$$

where $\Gamma_P=\Gamma_{\min}$ is a coefficient of reflection at the frequency coincidence $\omega_i = \omega_p$; $\varsigma_i=2Q\Delta\omega_i/\omega_P$ is generalized arrangement of the microwave signal relative to the relaxation frequency ω_p; $\Delta\omega=\omega_i-\omega_P$ – detachment at frequencies ω_i of modulated oscillations.

Reflected from the environment, the total microwave oscillations (7) taking into account the reflection coefficient take the form

$$\begin{aligned}U_9{}'(t) = a_H{}'[\Gamma_1\cos(\omega_1 t+\varphi_1+\pi/4+\Delta\varphi_1{}')+\\+\Gamma_2 m\cos(\omega_2 t+\varphi_2+\Delta\varphi_2)],\end{aligned} \quad (10)$$

where Γ_1 and Γ_2 are the modulus of the reflection coefficient of the inhomogeneous medium at frequencies ω_1 and ω_2; $\Delta\varphi_1$ and $\Delta\varphi_2$ is additional phase shifts of the oscillations at the corresponding frequencies.

When mixing 3 reflected microwave oscillations (10) with differing microwave oscillations (8) in the balance mixer 7, low frequency oscillations with different frequencies $\omega_3-\omega_1=\Omega_1$ and $\omega_3-\omega_2=2\Omega_1$. From the spectrum of these oscillations, the selective amplifier 9 allocates oscillations with a doubling frequency of modulation

$$U_{10}{}'(t)=S_1\Gamma_2 K_1 m^2 a_H{}' a_H{}''\cos(2\Omega_1 t+\Phi_2{}'), \quad (11)$$

where S_1 – steplessness of the balance mixer transformation; K_1 – coefficient of selective amplification; $\Phi_2{}'$ – phase of low frequency oscillations when irradiating the environment with total microwave oscillations.

Similarly, in the balance mixer 6, the total incident microwave oscillations (7), separated by directional coupler 2, with varying microwave oscillations (8) are mixed. At the output of the electoral amplifier 8, there are also low-frequency oscillations with a doubling frequency of modulation

$$U_{11}(t)=S_1 K_1 m^2 a_H{}' a_Y{}''\cos(2\Omega t+\Phi_3{}'), \quad (12)$$

where $\Phi_3{}'$ – the phase of low-frequency reference oscillations.

Low-frequency oscillations (11) and (12) are detected by amplitude detectors 10 and 11. Continuous voltage components are isolated by low-pass filters 12 and 13 and fed to the inputs of the division unit 14, where the division operation is performed. The indicator 15 receives a voltage proportional to the fraction from the division of the indicated voltages. From expressions (11) and (12) it follows that the fraction from the division of the amplitudes of low-frequency voltages is proportional to the reflection coefficient of the irradiated medium, that is

$$U_{12}{}'=S_2\Gamma_2(\omega_2), \quad (13)$$

where S_2 is the steepness of the resulting transformation of the reflection coefficient to the voltage; $\Gamma_2(\omega_2)$ is the reflection coefficient of the medium at the frequency ω_2.

The reflection coefficient at the lower side frequency ω_2 has the form

$$\Gamma_2(\omega_2)=\sqrt{4\Gamma_P^2+(1-\Gamma_P)^2\varsigma_2^2}\,/\sqrt{4+(1+\Gamma_P)^2\varsigma_2}\,, \quad (14)$$

where $\varsigma_2=2Q\Delta\omega_2/\omega_P$ – generalized arrangement on the lower side frequency ω_2; $\Delta\omega_2=\omega_2-\omega_P$ – detachment relative to the relaxation frequency of the inhomogeneous medium ω_P.

When changing the position of the contacts of the switch 23 there is a mutual substitution of low frequency modulating oscillations U_3 and U_4, and the transformations of signals similar to given above.

As a result of substitution at the outputs of the double waveguide tees 4 there is also the substitution of total microwave oscillations difference and vice versa.

In this case, the controlled environment begins to be irradiated by difference modulated microwave oscillations, and on the reference inputs of balanced mixers 6 and 7, the total modulated microwave oscillations begin to flow from the outputs of the power divider 5.

The reflection coefficient Γ_3 at the top side frequency ω_3 has the form

$$\Gamma_3(\omega_3)=\sqrt{4\Gamma_P^2+(1-\Gamma_P)^2\varsigma_3^2}\,/\sqrt{4+(1+\Gamma_P)^2\varsigma_3^2}, \quad (15)$$

where $\varsigma_3 = 2Q\Delta\omega_3/\omega_P$ – the general arrangement on the upper side frequency ω_3; $\Delta\omega_3 = (\omega_3 - \omega_P)$ – a breakdown relative to the relaxation frequency.

Modulated microwave oscillations are blended from the medium. In the measuring channel isolated from the mixed oscillations, the low-frequency signal with a doubling frequency of modulation is similar (11).

$$U_{10}''(t) = S_1\Gamma_3 K_1 m^2 a_H' a_H'' \cos(2\Omega_1 t + \Phi_2''), \quad (16)$$

where Φ_2'' – the phase of low-frequency oscillations in the irradiation of the environment difference microwave oscillations.

In the reference channel at the output of the electoral amplifier 8, similar (12) reference low-frequency oscillations

$$U_{11}''(t) = S_1 K_1 m^2 a_H' a_Y'' \cos(2\Omega_1 t + \Phi_3''). \quad (17)$$

At the output of the division unit 14, as a result of the division of the amplitudes of the signals (16) and (17), there is voltage

$$U_{12}'' = S_2\Gamma_3(\omega_3). \quad (18)$$

In the periodic operation of the switch 23 with a lower frequency Ω_2 (in comparison with the modulation frequency Ω_1, $\Omega_2 < \Omega_1$), at the output of the selective amplifier 9, the packets of low frequency signals are alternately allocated $U_{10}'(t)$ and $U_{10}''(t)$ amplitudes are proportional to the reflectance coefficients Γ_2 and Γ_3. With their inequality there is an enveloping amplitude of low frequency signals, the repetition period of which is equal to the switching period of the switch 23. As a result of detecting this signal at the output of the filter 13 lower frequencies, along with a constant component, a variable component of the switching frequency is formed

$$\begin{aligned} U_{13}(t) &= K_2 \frac{U_{10}' - U_{10}''}{2}\cos(\Omega_2 t + \Phi_4) = \\ &= 0{,}5 S_1 K_1 K_2 m^2 a_H' a_H'' (\Gamma_2 - \Gamma_3)\cos(\omega_2 t + \Phi_4), \end{aligned} \quad (19)$$

where K_2 is the coefficient of transformation of low frequency oscillations.

The voltage (19) of the switching frequency is amplified by the amplifier 16 of the switching frequency, straightened by the synchronous detector 17, and changes the frequency of the microwave generator 19. The frequency control of the generator 19 is carried out prior to obtaining a zero voltage of the switching frequency (19).

In case of equality of reflectivities at side frequencies ω_2 and ω_3 (Figure 2, *b*) we receive

$$\Gamma_2 = \Gamma_3 \text{ or } |\omega_2 - \omega_P| = |\omega_3 - \omega_P|. \quad (20)$$

Since the lateral frequencies ω_2 and ω_3 of the modulated microwave oscillations change synchronously with the change of carrier frequency ω_1, equality (25) is satisfied by the condition

$$|\omega_1 - \Omega_1 - \omega_P| = |\omega_1 + \Omega_1 - \omega_P|. \quad (21)$$

From the latter, it can be seen that in this case the carrier frequency ω_1 of the modulated oscillations, which concentrates most of the energy of irradiating microwave oscillations, begins to coincide with the relaxation frequency ω_P.

$$\omega_1 = \omega_P = 2\pi/\tau_P, \quad (22)$$

where τ_P is the time of relaxation of water dipoles in an inhomogeneous medium.

In this case, the output of the division unit 14 produces a DC signal proportional to the reflectance coefficient $\Gamma_{\min}$ (Figure 2, *b*)

$$\begin{aligned} U_{12}'' &= U_{12}' = S_2\Gamma_2(\omega_2) = S_2\Gamma_3(\omega_3) = \\ &= (S_2/\sqrt{2})\Gamma_{\min}(\omega_4) = S_2'\Gamma_{\min}(\omega_P), \end{aligned} \quad (23)$$

where $S_2' = S_2/\sqrt{2}$ normalized steepness of transformation.

CONCLUSION

Thus, the frequency of irradiating microwave oscillations is precisely tuned to the relaxation frequency ω_p, for example, the relaxation frequency of dipoles of water molecules of moist material corresponding to the maximum absorption of electromagnetic energy by moist material. The reflection coefficient takes the minimum value, which is uniquely associated with the moisture content of the material. The relation (26) is not affected by the inequality of the amplitudes of irradiating microwave oscillations ($a_H' \neq a_H''$), instability and inequality of the parameters of mixers, amplifiers, detectors, filters and other paired elements of measuring and reference channels. This is due to the fact that the disappearance of the switching frequency voltage occurs only with the equality of reflection coefficients ($\Gamma_2 = \Gamma_3$) at the side frequencies (ω_2 and ω_3) irrespective of the values of the parameters of the transforming units and the amplitudes of the alternating light oscillations. The considered device can be used in technological processes of light industry (yarn, fabric), agriculture (grain, flour) and other industries where hygroscopic materials are used.

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