Microwave near-field subsurface radiothermometry.

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Microwave radiometry measurements of thermal emission are widely used for subsurface diagnostics of media. For temperature measurements those methods are superior to other remote (noninvasive) techniques. The intensity of thermal radiation is proportional to the averaged temperature of the layer with the thickness d_{eff} where this radiation is formed. Variations of d_{eff} give a possibility to retrieve the subsurface temperature profile $T(z)$. Only the dependence of d_{eff} on the wavelength λ has been used earlier for this purpose, i.e., the retrieval of $T(z)$ was performed by measurements of the thermal emission on several wavelengths. Such a technique has been applied in medical and plasma investigations, for diagnostics of water and soils, etc.

It has been shown theoretically in [1] that the near-field (quasi-stationary) component of the thermal radiation tangibly affects the signal intensity measured by the radiometer if the receiving antenna has a small electric size $D<<\lambda$ and is situated at height $h<<\lambda$ over the radiating surface. In this case d_{eff} is determined not only by λ but also by antenna parameters D, h. So, the new possibilities to control d_{eff} by D, h varying may be realized. This work is devoted to development of a radiometry system for the near-field measurements; investigation of the near-field effects in thermal radiation; retrieval of the subsurface temperature profile of medium by the near-field radiometry measurements.

The thermal radiation was detected by a radiometer with operating frequency $f_0=950$ GHz, frequency band $\Delta f=200$ MHz, and fluctuation sensitivity threshold $\delta_T=0,05$ K at the integration constant $\tau=1$ s. The key element of the receiving system was an electrically small antenna of size $D=1$ cm ($D/\lambda=0.03$) shown in Fig.1. It consisted of two in-phase dipoles connected to a symmetric strip line operating as a matching resonator (a prototype of this system is described in [2]). Water was chosen as the medium for investigation. When the antenna was in close contact with the water surface ($h=0$), it was matched to the radiometer input so that the reflection coefficient R averaged over the radiometer frequency band Δf did not exceed 0.03 (see Fig.2). The antenna efficiency at $h=0$ was found to be $\eta=0,85$. An increase in height leads to both the antenna mismatch (increase in R) and a decrease of η. The sensitivity threshold to the temperature variations increased from 0.06 K at $h=0$ to 1 K at maximum height of measurements $h_{max}=2.5$ mm. Further decrease in sensitivity at $h>h_{max}$ made the measurements at larger heights impossible. Thus, the presence of a matched high-efficiency antenna is a fundamental requirement to a near-field radiometric system, in contrast to similar active-location systems which are usually referred to as near-field microscopes.

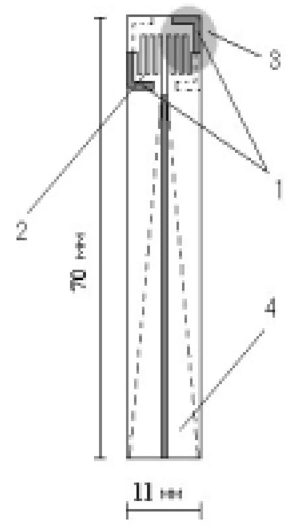

Fig.1. Scheme of the near-field antenna. 1 – electrically-short dipoles; 2 – matching resonator; 3 – dielectric plate for fine tuning; 4 – coaxial to strip-line connector.

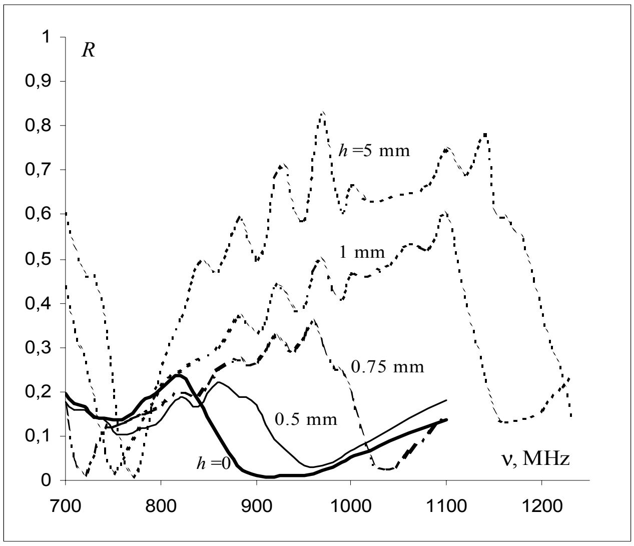

Fig.2. Frequency dependence of antenna reflectivity for different heights above the water surface.

For measurements of d_{eff}, a stable quasi-linear profile $T(z)$ was formed with the use of a heater near the surface and a cooler near the bottom of a cylindrical vessel. The stationary temperature gradient was as large as $dT/dz=2.5\ K/cm$. For linear $T(z)$ a simple exact expression for the brightness temperature measured by radiometer can be obtained: $T_b=T(z=d_{eff})$, which was used for determining the d_{eff}. Because the dielectric constant of water ε satisfies the condition $|\varepsilon|>>1$, for the wave component of thermal radiation the value of d_{eff} is equal to the skin-depth $d_{sk} = \lambda / (4\pi\sqrt{\varepsilon})$ For the near-field component one has $d_{eff}(D,h)<d_{sk}$. We have obtained in our measurements $d_{eff}(D=1cm,h=0)=0,5d_{sk}$. The dependence $d_{eff}(D,h)$ was also determined, which appeared to be in a good agreement with the theoretical calculations (see Fig.3). These experimental results testify to the presence of the near-field component in the thermal radiation of medium [3].

The discovered dependence $d_{eff}(D,h)$ can be used to develop new methods of the radio thermal diagnostics of media. In this study we presents first results of a water subsurface temperature profile retrieval using the dependence $d_{eff}(D)$. The brightness temperature of water has been measured using two antennas with $D=1\ cm$ and $4\ cm$. Also, direct measurements of surface temperature $T(z=0)$ by a contact thermometer have been used. The algorithm and the program for $T(z)$ retrieval from the corresponding integral equation was developed on the basis of the Tikhonoff method of ill-posed inverse problems solution [4]. The retrieved profiles $T(z)$ during the process of heating of the water surface layer are shown in Fig.4. It is seen that the accuracy of $T(z)$ retrieval is about $\sim(0.5\text{-}1)\ K$ for $0<z<d_{sk}\approx 4cm$.

Further development of the proposed technique may go by increasing the sensitivity of the radiometric system at heights $h>h_{max}$ (in this study, $h_{max}=2.5\ mm$) and decreasing the antenna size (in the range $D<1\ cm$). To this end, the antenna should be matched for each height, which is not a difficult problem. At the same time, the efficiency of the electrically small antennas inevitably decreases with increasing of h/λ and decreasing of D/λ. A possible solution to this problem might be improving of a miniature antenna construction and the use of materials with extremely low ohmic losses such as high-temperature superconductors. The effectiveness of using these materials in the problems of miniaturization of antenna devices was examined in [5,6]. Our preliminary calculations show that the near-field radiometric measurements can be accomplished, at least in the height interval $0<h/\lambda<0.1$ and for the antenna sizes $D/\lambda>0.01$. In this case, the effective depth of the radiating layer will vary in the range $0.2d_{sk}<d_{eff}<d$. This single-wave method may prove simpler in implementation than the known multi-frequency methods.

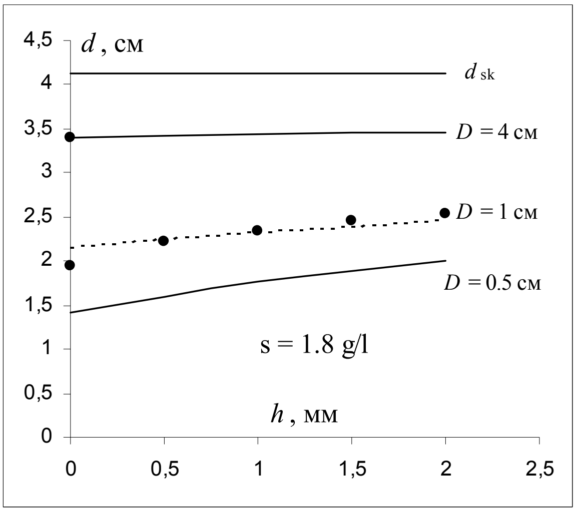

Fig.3. Effective thickness d_{eff} as a function of antenna height for different antenna sizes. Circles – measurements; lines – calculations.

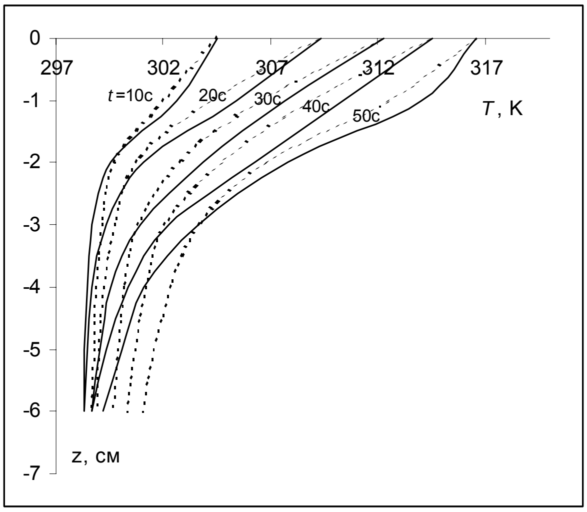

Fig.4. Profiles $T(z)$ retrieved in time interval *10 s* by measurements of $T_b(D)$ – dashed lines; profiles $T(z)$ measured by contact thermometer..

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