New Effect in Near-Field Thermal Emission

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A near-field effect has been discovered experimentally in thermal radio emission of an absorbing dielectric medium. It is related to a specific character of the distribution of a quasistationary field component near a radiating surface. The effect consists of the fact that the effective depth of the received emission formation appears to be less than the skin-layer depth and depends on the size of the receiver antenna and its height above the surface. It can be considered as a new source of information about depth temperature distribution. A theory has been developed that allows for determining the relative contribution of wave and quasistationary components to the Plank emission received near the surface.

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I. Introduction.—The near-field (quasistationary) component of thermal radiation was predicted theoretically by Rytov as early as the 1950s (see, for example, [1,2]). This component does not transfer energy and decreases drastically with increasing distance from the surface. Its volume density of energy increases infinitely when approaching the medium surface and exceeds the energy of the wave field component that is independent of distance. This effect was proposed as a method for experimental detection of the near field. But the method has not been realized up to now. The question is, why? Moreover, realization of Rytov's method would mean that it is possible to receive thermal emission energy from a heated medium higher than Plank's emission.

The theoretical analysis carried out in this research shows that the transfer function of the receiving antenna should be taken into account when solving this problem. It was found that the antenna properties inevitably change the dependence of the measured signal on the distance from the surface, which makes it impossible to realize Rytov's method of near-field detection. The total received energy (the sum of the wave P_W and the quasistationary P_Q field components) remains equal to the Plank thermal emission energy $P_0 = P_W + P_Q$ at any distance from the surface. The influence of the near field leads only to the redistribution of energy between P_W and P_Q in the total value of P_0. But it was also revealed that the quasistationary component has its own spatial scale of formation d_{eff} which appears to be less than the absorption skin depth d_{sk}. Moreover, it depends on the effective size of antenna D and its height above the surface h, i.e., $d_{\text{eff}} = d_{\text{eff}}(D, h) < d_{\text{sk}}$. This effect has been detected experimentally, and it is the first evidence of the near-field thermal emission.

The near field tangibly affects a signal measured by a radiometer, if a receiving antenna has a small electric size $D \ll \lambda$ and is situated at height $h \ll \lambda$ over the radiating surface (λ is the wavelength). So, new possibilities are offered to control d_{eff} by varying parameters D and h, which permits one to retrieve a subsurface temperature profile of media by one-wavelength near-field radiometry measurements.

II. Theory.—Let us consider the problem of thermal emission of the half-space $z \leq 0$ with permittivity $\epsilon = \epsilon_1 - i\epsilon_2$, which is measured using an arbitrary antenna with effective size D at height $h \geq 0$ above the medium surface. The thermal emission is related to the fluctuation current $\vec{j}(\vec{r}, z)$ that satisfies the relation

$$\langle j_i(\vec{r}, z) j_k^*(\vec{r}_1, z_1)\rangle = \frac{\omega\theta(z)}{4\pi^2}\epsilon_2\delta(z - z_1), \tag{1}$$

where $\theta(z) = (\hbar\omega/2)\coth[\hbar\omega/2kT(z)]$ is the Plank function, and $T(z)$ is the temperature of the medium that depends on the vertical coordinate z [1,2]. The obtained solution for the received power P can be written as

$$P = \frac{1}{2\pi}\int_{-\infty}^{0}\theta(z)K(h, D, z)\,dz, \tag{2}$$

$$K(h, D, z) = \tilde{K}(h, D, z)\Big/\int_{-\infty}^{0}K(h, D, z)\,dz, \tag{3}$$

$$\begin{aligned}\tilde{K}(h, D, z) = \iint d^2\kappa\left[\frac{\kappa_y^2}{\kappa^2}|T_E(\kappa)|^2 + \frac{\kappa_x^2}{\kappa^2}|T_H(\kappa)|^2|n_\parallel^2|\right]\left|\frac{k_0 + \sqrt{k_0^2 - \kappa^2}}{\sqrt{k_0^2 - \kappa^2}}\right|\exp(2\,\mathrm{Im}\sqrt{\epsilon k_0^2 - \kappa^2}\,z)\\ \times\left\{\begin{matrix}1, & \kappa \leq k_0\\ \exp(-2\sqrt{\kappa^2 - k_0^2}\,h), & \kappa > k_0\end{matrix}\right\}|E_a(\vec{\kappa})|,\end{aligned} \tag{4}$$

where $T_E = 2\sqrt{k_0^2 - \kappa^2}/\sqrt{k_0^2 - \kappa^2} + \sqrt{\epsilon k_0^2 - \kappa^2}$ and $T_H = 2\sqrt{\epsilon}\sqrt{k_0^2 - \kappa^2}/\sqrt{k_0^2 - \kappa^2} + \sqrt{\epsilon k_0^2 - \kappa^2}$ are the

Fresnel coefficients, $|n_{\|}|^2 = (|\sqrt{\epsilon k_0^2 - \kappa^2}|^2 + \kappa^2)/(|\epsilon|k_0^2)$, $k_0 = 2p/\lambda$, and $E_a(\vec{\kappa}) = \iint E_a(\vec{r})\exp(i\vec{\kappa}\vec{r})\,d^2r$. We set in our calculations that the electrical field distribution over antenna aperture $E_a(r) = E_0\exp(-4r^2/D^2)$, where D is the effective antenna size. It was assumed in Eqs. (2)–(4) that the antenna efficiency $\eta = 1$, so the receiver is matched to the medium. The expressions [Eqs. (2)–(4)] take into account the contribution of both the wave and the quasistationary field components in the received power of thermal emission. The effect of the wave component in Eq. (4) is determined by the contribution of the integration range $\kappa \leq k_0$, whereas for the quasistationary component it is the integration range $\kappa > k_0$. Hence, it is possible to express the kernel K of Eq. (2) as a sum of these two components $K = K_W + K_Q$ and, correspondingly,

$$P = P_W + P_Q = \frac{1}{2\pi}\int_{-\infty}^{0}\theta(z)[K_W(h,D,z) + K_Q(h,D,z)]\,dz\,. \quad (5)$$

It is possible to express the wave component in Eq. (5) in terms of half-space emission intensity I and antenna pattern Φ passing over to angle variables $\kappa_x = k_0\sin(\vartheta)\cos(\varphi)$, $\kappa_y = k_0\sin(\vartheta)\sin(\varphi)$:

$$P_W = \lambda^2\int_0^{2\pi}\int_0^{2\pi} I(\vartheta,\varphi)\Phi(\vartheta,\varphi)\sin(\vartheta)\,d\vartheta\,d\varphi\,. \quad (6)$$

The quasistationary (near-field) component P_Q in Eq. (5) cannot be described in terms of the emission transfer theory, but it does make a contribution to the total measured power. One can see this component in relative units in Figs. 1 and 2 at $\lambda = 30$ cm for the water at temperature $T = 293$ K with $\epsilon = 76 - i3$ as a radiating medium. This component can be considerable and, moreover, dominating if (i) the effective size of the aperture is small ($D \ll \lambda$) and (ii) the height of the antenna above the surface is small ($h \ll \lambda$). With an increase in the antenna size or height the relative contribution of the near field decreases.

It should be mentioned that, for a temperature homogeneous medium $\theta(z) = \theta =$ const, the total power of the received thermal emission [Eq. (5)] remains unchanged and does not depend on the antenna size and height. In this case we have

$$P = \frac{\theta}{2\pi} = \lambda^2 J_0 = P_0\,, \quad (7)$$

where $J_0 = k_0^2\theta/(2\pi)^3$ is the brightness of thermal emission. But, as can be seen from Eq. (5), the specific character of the formation of thermal emission in the near-field zone is essentially dependent on the antenna transfer properties. In Fig. 1 $w(h)/w_0$ is plotted, where w is the energy volume density of the thermal emission field calculated according to [1,2], and $w_0 = w(h \to \infty)$. One can see that the contribution of the quasistationary component leads to divergence of $w(h)$ at $h \to 0$, but the antenna transfer function constrains this divergence and leads to the condition $P(h) = P_0$, including the range at $h \to 0$. So, the variation of h leads only to the redistribution of the energy between the wave and the quasistationary components in the total received signal. The fact that the received power of thermal emission does not depend on the size and position of the antenna for a temperature homogeneous medium makes it impossible to detect the effect of the near-field enhancement at $h \to 0$ as it was proposed in [1,2]. Nevertheless, for temperature inhomogeneous media there are some detectable near-field effects.

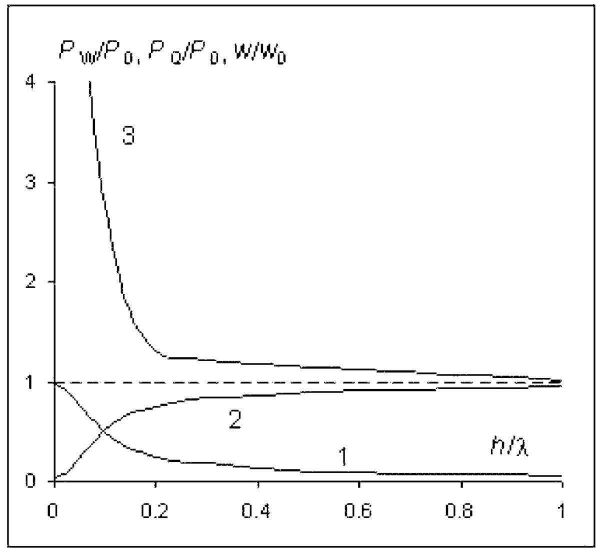

FIG. 1. Normalized power of wave and quasistationary fields as a function of antenna height for $D/\lambda = 0.01$: (1) P_Q/P_0, (2) P_W/P_0, and (3) w/w_0 according to [1,2].

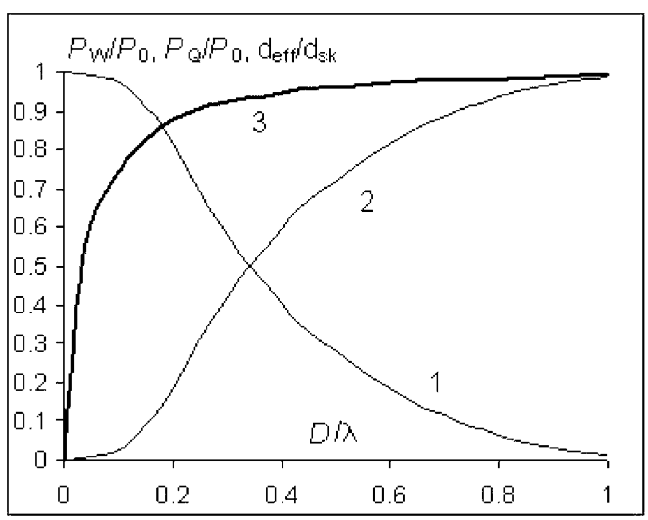

FIG. 2. Normalized power of wave and quasistationary fields versus the antenna aperture size for $h = 0$: (1) P_Q/P_0, (2) P_W/P_0, and (3) $d_{\rm eff}/d_{\rm sk}$.

In particular, the influence of the quasistationary component leads to a new spatial scale of emission formation. Now the effective depth of thermal emission formation becomes a function of antenna size and height:

$$d_{\mathrm{eff}}(h, D) = \left| \int_{-\infty}^{0} zK(h, D, z)\, dz \right|, \tag{8}$$

as can be seen from the calculations in Fig. 2. This effect is more prominent in media with $|\epsilon| \gg 1$, such as water. In this case the wave component of thermal emission is formed by plane inhomogeneous waves propagating in the absorbing medium in the narrow cone near the vertical direction z. So, for the wave component, $d_{\mathrm{eff}} \approx d_{\mathrm{sk}} = 1/(2k_0 \operatorname{Im}\sqrt{\epsilon})$, and does not depend on antenna parameters. The waves propagating outside this cone are totally reflected at the half-space boundary; hence, at $z > 0$ they make a contribution only to the quasistationary component. For this component, one obtains $d_{\mathrm{eff}} < d_{\mathrm{sk}}$. Thus, for the total received power in conditions of strong near-field influence ($D \ll \lambda, h \ll \lambda$), one has $d_{\mathrm{eff}} = d_{\mathrm{eff}}(D, h) < d_{\mathrm{sk}}$.

III. Measurements.—In our research, water was chosen as a very suitable medium because its dielectric parameters can be calculated to a high accuracy at any given value of temperature T and salinity S (see [3]). 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 for the integration constant $\tau = 1$ s. The key element of the receiving system was an electrically small antenna of size $D = 1$ cm ($D/\lambda = 0.03$). The antenna was matched to the radiometer input in close contact with the medium surface ($h = 0$), so that the reflection coefficient R averaged over the radiometer frequency band Δf did not exceed 0.03. The antenna efficiency at $h = 0$ was found to be $\eta = 0.85$. An increase in h leads to a decrease in the efficiency of the antenna η and to its mismatch. Consequently, at $h = h_{\max} \approx 2.5$ mm the sensitivity threshold increases from 0.06 K (at $h = 0$) up to 1 K, so it was impossible to take measurements at $h > h_{\max}$. Besides, an antenna with $D = 4$ cm and efficiency $\eta \approx 1$ at $h = 0$ has been used in our measurements. High-efficiency matched antennas are necessary in the near-field radiometry, unlike active near-field microscopy [4].

IV. Near-field effects.—For measurements of d_{eff}, a stable quasilinear profile $T(z)$ was formed using 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. The expression for the radiometer-measured brightness temperature at a given wavelength λ according to Eq. (5) can be written as

$$T_b(h, D) = \int_{-\infty}^{0} T(z)K(h, D, z)\, dz\,. \tag{9}$$

For a linear $T(z)$, a simple exact expression for the brightness temperature measured by the radiometer can be obtained from Eqs. (8) and (9):

$$T_b = T(z = -d_{\mathrm{eff}})\,, \tag{10}$$

which was used for determining d_{eff} from measurements of T_b. Because the dielectric constant of water ϵ satisfies the condition $|\epsilon| \gg 1$, for the wave component of thermal radiation the value of d_{eff} is equal to the skin depth d_{sk}. For the near-field component, one has $d_{\mathrm{eff}}(D, h) < d_{\mathrm{sk}}$. In our measurements we obtained $d_{\mathrm{eff}}(D = 1\text{ cm}, h = 0) \approx 0.5 d_{\mathrm{sk}}$. Measurements have been carried out for temperature-stratified water at three different values of salinity: $S = 0, 1.8 \times 10^{-3}$, and 5.0×10^{-3} g/cm^3. At the water salinity $S = 1.8 \times 10^{-3}$ g/cm^3, the skin depth at the given frequency is temperature independent and the medium can be considered as a homogeneous dielectric, which is important because the above-mentioned expressions are valid in the case of $\epsilon = \text{const}$. Results of measurements and calculations by Eqs. (3), (4), and (8) are shown in Fig. 3. These results prove the presence and the influence of the near-field component on the measured emission of the medium. Good agreement between the theory and the experiment shows that the predicted dependence of d_{eff} on the size and height of the antenna is really revealed. Results for other values of salinity are also in good agreement with the theory, provided we make a reasonable assumption $\epsilon = \epsilon(T = T_b)$ in Eqs. (3), (4), and (8).

The strongest effects have been observed for distilled water ($S = 0$), but in this case the dielectric constant of water is temperature dependent. Therefore, the discrepancy between measurements and calculations is somewhat greater than for homogeneous water.

V. Retrieval of subsurface temperature profile.—The discovered dependence $d_{\mathrm{eff}}(D, h)$ can be used as a new source of information about subsurface temperature distribution to develop new methods of radio thermal

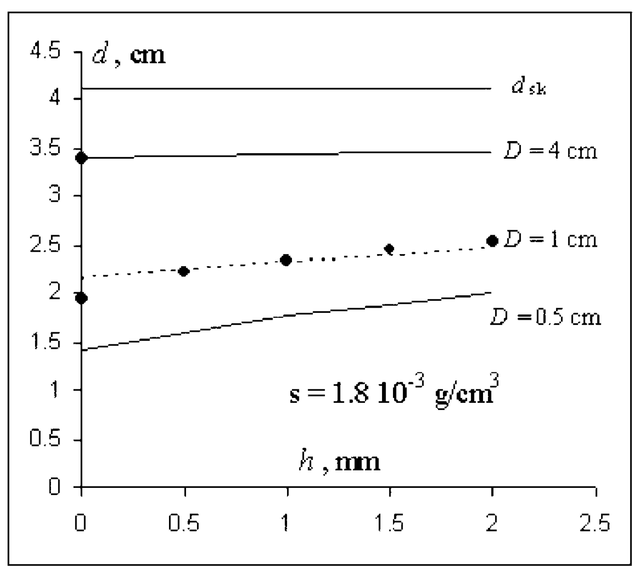

FIG. 3. Effective thickness d_{eff} as a function of antenna height for different antenna sizes. Circles correspond to measurements; lines correspond to calculations.

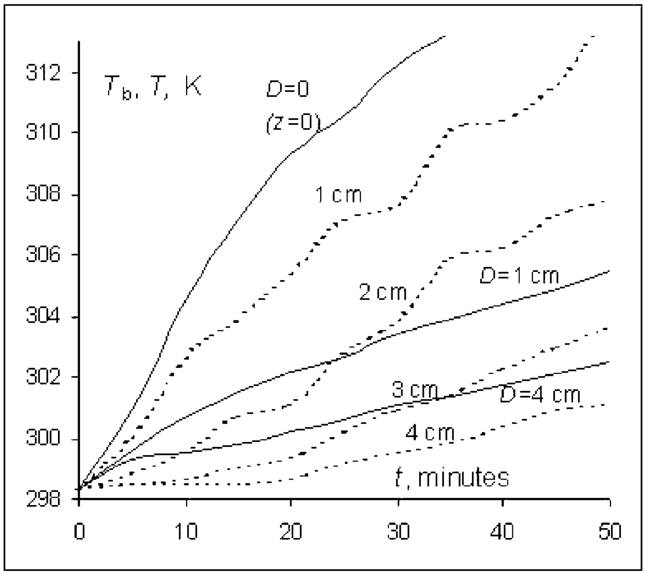

FIG. 4. Measurements of brightness temperature dynamics (solid lines); contact measurements of temperature dynamics at different levels inside water (dashed lines).

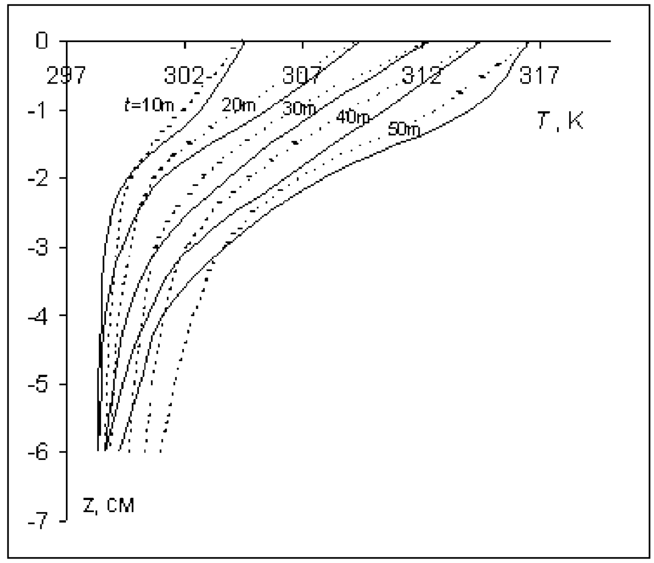

FIG. 5. Profiles $T(z)$ retrieved in the time interval of 10 min by measurements of $T_b(D)$ (dashed lines); profiles $T(z)$ measured by contact thermometer (solid lines).

diagnostics of media. Microwave radiometry measurements of thermal emission are widely used for subsurface diagnostics of media. For temperature measurements these methods are superior to other remote (noninvasive) techniques. The intensity of thermal radiation is proportional to the average temperature of a layer with thickness d_{eff} where this radiation is formed. Controllable variations of d_{eff} allow one to retrieve the subsurface temperature profile $T(z)$. Only the dependence of d_{eff} on wavelength λ has been used earlier for this purpose, i.e., retrieval of $T(z)$ was performed by measurements of thermal emission at several wavelengths (see, for example, [5]). Such a technique has been employed in medical and plasma investigations, for diagnostics of water, soil, etc.

In this Letter we present the first results on the retrieval of a water subsurface temperature profile using the dependence $d_{\text{eff}}(D)$. Two antennas with $D = 1$ and 4 cm have been used in the measurements of the brightness temperature of water in the process of water surface heating (with the help of a wire heater). In addition, because the data set should include at least three different values of D, direct measurements of the surface temperature $T(z = 0)$ by a contact thermometer have been made for $D = 0$ because $T_b(D = 0) = T(z = 0)$.

An algorithm and a program for $T(z)$ retrieval from the integral equation [Eq. (9)] were developed on the basis of the Tikhonov regularization method for the solution of ill-posed inverse problems [6]. The measured dynamics of brightness temperature and water temperature at different depth levels in the course of heating of a water surface (starting with the initially homogeneous temperature distribution) are presented in Fig. 4. The retrieved profiles $T(z)$ are shown in Fig. 5 along with the directly measured temperature profiles. One can see that the accuracy of $T(z)$ retrieval is about (0.5–1) K for $0 < z < d_{\text{sk}} \approx 4$ cm and the quality of retrieval for rather simple temperature profiles is good, taking into account a nonoptimal and very scarce data set.

VI. Conclusion.—In this paper the near-field effect in thermal emission has been discovered, and the theory of this effect has been developed. The effect consists of a decrease of the effective depth of formation of thermal emission received in the near-field zone. This depth can be much less than the absorption skin depth and depends on the size of the antenna and its height above the medium surface. The detected dependence provides an opportunity for developing new near-field radiometry methods of subsurface temperature diagnostics.

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[1] S. M. Rytov, *Theory of Electrical Fluctuations and Heat Emission* (Akademii Nauk SSSR, Moscow, 1953).
[2] S. M. Rytov, Yu. A. Kravtsov, and V. I. Tatarskii, *Principles of Statistical Radiophysics* (Springer-Verlag, Berlin, 1987).
[3] L. A. Klein and C. T. Swift, IEEE Trans. Antennas Propag. **25**, 104 (1977).
[4] E. A. Ash and C. Nicholls, Nature (London) **237**, 510 (1972).
[5] K. P. Gaikovich, M. I. Sumin, and R. V. Troitskii, Radiophys. Quantum Electron. **31**, 786 (1988).
[6] A. N. Tikhonov and V. Y. Arsenin, *Solutions of Ill-Posed Problems* (Wiley, New York, 1977).