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SENSITIVITY OF MICROWAVE RADIOMETER FOR TISSUE SCREENING

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Abstract. This article analyzes theoretically and simulates numerically radiometric temperature measurement of female human breast tissues by the 4.5 GHz Dicke radiometer. The balance method of radiometric measurement of tissue temperature is used. The Final Difference of Time Domains method is applied to calculate the spatial distribution of antenna's receiving pattern. The calculated radiometric signal has the temperature resolution better than 1 K for tumours of 6 mm in diameter. It is shown that the balance method of measurement makes possible the use of the Dicke radiometer with body-contacting waveguide antennas for early cancer detection.

Key words: microwave radiometry, breast cancer detection.

1. INTRODUCTION

Microwave radiometry is a technique that provides practically the only passive, non-invasive method for the exploration of subcutaneous cancer tumours. The method is based on the measurement of temperature differences between healthy and cancerous tissues as the differences of thermal emission from the tissues at microwave frequencies [1–3].

The sensitivity of the microwave radiometer, aimed at tissue screening for cancer exploration, depends on two different aspects:

– sensitivity of the receiving system for electromagnetic energy registration;

– detectability of temperature anomalies inside an inhomogeneous tissue.

Even at very high electromagnetic sensitivity of the radiometer, it is not possible to detect all temperature anomalies inside tissues due to other factors, such as background radiation from tissues, multiple reflections, and absorption of the signal on different kinds of tissues (skin, fat, and muscle).

The first aspect has been thoroughly investigated for radio astronomy receivers [4–6]. The well-known radiometric formula for the estimation of the equivalent output noise level [4] is expressed as

$$\Delta T = T_n \sqrt{\frac{1}{\Delta f \tau}}, \tag{1}$$

where T_n is input noise temperature, Δf is the bandwidth at the microwave frequency, and τ is the integration time of the system. This formula determines the detectability of the input signal by the radiometric device. In this case, the input energy of the radiometer is assumed related to the signal and the internal noise T_n of the radiometer only. It is true when radiometric measurements are used in space investigations where the level of external background radiation is not high.

In the case of tissue screening radiometer, the useful radiation signal is not related to the total level of input radiation, but only to the variations in this level at different tissue points (1–2 K). However, the level of background radiation emitted by tissues is much higher (about 310 K).

Another difference between the astronomic and the tissue screening radiometer is matching of the radiometer input and the object under investigation. The latter case is characterized by a significant level of reflection at the tissue-input surface. The reflection of internal and external noise due to the input mismatch causes a significant change of the input radiation level that may be more substantial than the useful signal level.

The second aspect is related to the generation and propagation processes of the electromagnetic radiation inside inhomogeneous biological tissues. This problem can be solved by the calculation of the signal and background electromagnetic radiation generation, absorption and reflection in tissues, taking into account the spatial distribution of electrical parameters.

To solve this problem, different authors have proposed and used analytical methods to calculate electromagnetic radiation propagation and absorption in a homogeneous or an inhomogeneous lossy medium, such as the integral equation method, the plane wave method, the Fourier integral method, and the Green's function method [7–9]. Most of the calculations of the radiometer input weighting factors have involved the homogeneous biological tissue. Weighting factors have been calculated also in a three-layered tissue by the unbounded plane wave approximation. In [7], the effect of one layer, i.e., skin, in the radiometric signal was calculated by the exact image theory.

Analytical methods always include some kind of approximation. The direct numerical Final Difference of Time Domains (FDTD) method of solving Maxwell's field equations provides a more reliable result. Therefore, the FDTD method was selected and the program package MAFIA, based on this method, was used in our previous work [10] for the modelling of the system, consisting of the radiometer input and the planar three-layered skin–fat–muscle human body.

The radiometer input transfer function was calculated using the principle of reciprocity.

In this work, we discuss the sensitivity of the radiometric system for electromagnetic energy registration, taking into account input reflections and the background tissue radiation. The detectability of temperature anomalies inside the inhomogeneous tissue is calculated using the FDTD method.

2. THEORETICAL BACKGROUND OF THE RADIOMETRIC MEASUREMENT OF SUBCUTANEOUS TEMPERATURE

A microwave radiometer is used to measure the electromagnetic energy of thermal radiation. According to Plank's radiation law, a physical object with the physical temperature higher than zero degrees radiates at all frequencies. The spectral density of the energy P_i radiated by an arbitrary point of the object is determined by the physical temperature of the source located at this point T_i and its radiation coefficient A_i

$$P_i = A_i\, kT_i = kT_e\,, \tag{2}$$

where k is Boltzman's constant. The radiation coefficient A_i is equal to the absorption coefficient of electromagnetic power at this point at the same frequency. The equivalent or radiation temperature T_e represents the spectral density level of the radiation energy.

The electromagnetic energy emitted from the object is collected by the input antenna of the microwave radiometer. The effective temperature of the object seen by the antenna depends on the contribution of different parts of the volume of the object under investigation. Let us assume that in the volume V under test there is a sub-volume V_i with the effective temperature $T_{ei} = A_i T_i$. In the case of ideal matching between the homogeneous human tissue and the antenna, the temperature seen by the receiving antenna that is contributed by the sub-volume V_i is

$$T_{vi} = D_i A_i T_i L(\alpha) + [1 - L(\alpha)] T_0\,, \tag{3}$$

where L is the factor of propagation losses, which depends on α, the field absorption constant in the tissue; T_0 is the physical temperature of the surrounding tissue. Factor D_i determines the coupling between the point and the radiometer input and has the meaning of the transfer function from an arbitrary point to the radiometer input. Parameters $A_i = A_i(\varepsilon, \sigma)$ and $\alpha = \alpha(\varepsilon, \sigma)$ are the functions of the dielectric permittivity ε and the conductivity σ of the tissue. The transfer function D_i depends on the electrical parameters of the tissue as well as on the location of the point relative to the radiometric input and input properties.

In the case of mismatch between the radiometer input and the tissue, in addition to the object's effective temperature, the signal power received by the radiometer depends on the reflection coefficient R on the tissue-input surface. The equivalent temperature generated by the object on the radiometer input T_{viR} is

$$T_{viR} = \{D_i A_i T_i L(\alpha) + [1 - L(\alpha)]T_0\}(1 - R). \quad (4)$$

The temperature of the object seen by the antenna depends on the contribution of different parts of the volume of the object under investigation.

Real biological tissues are inhomogeneous, comprising several layers which have different electromagnetic parameters. Multiple reflections and complex attenuation occur on the path of the energy transfer between the contributing sub-volume V_i and the object surface. In real conditions, the analytical expression for the equivalent temperature generated by the object on the radiometric input appears very complicated.

3. METHOD OF MEASUREMENT AND PARAMETERS OF THE RADIOMETER

As calculations and measurements in [10–12] show, the radiometric signal very strongly depends on even slight variations of the human tissue parameters. The parallel reference signal can be used to take into account the properties of tissues. Therefore, we have applied the balanced measurement method with the two-reference radiometer input, consisting of two identical waveguide antennas. The distance between the two probe-antennas is small, and the signal port and the reference port are in contact with the human body in different regions with and without the tumour. This method enables measurement of temperature gradients between two adjacent points, thus automatically taking into account possible changes in the background tissue parameters.

The 4.5 GHz Dicke radiometer has been designed. Figure 1 shows the block diagram of the radiometer. Its input consists of two identical open-ended rectangular waveguides. The geometrical size of the waveguide and the dielectric constant of the medium inside the waveguide were determined by the analysis of the numerical calculation results [10,11]. Different antenna configurations and sizes were measured on the water phantom. Our experimental investigations showed that the most effective waveguide antenna size is 23×10 mm. The waveguide was filled with pressed titanium oxide powder with the dielectric constant of about 10. The measured transfer losses and matching curves of the two input antennas are presented in Figs. 2 and 3, respectively. The losses in the operating band are less than 0.7 dB, and the reflected power level is less than –5.5 dB. The reflection was measured in the case of direct contact between the antennas and the tissue.

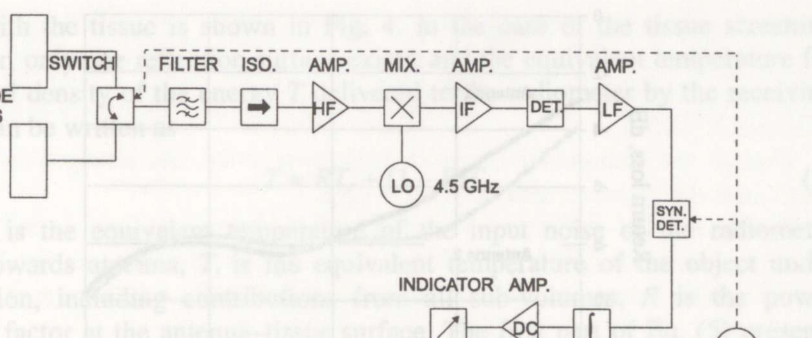

Fig. 1. Block diagram of the radiometer.

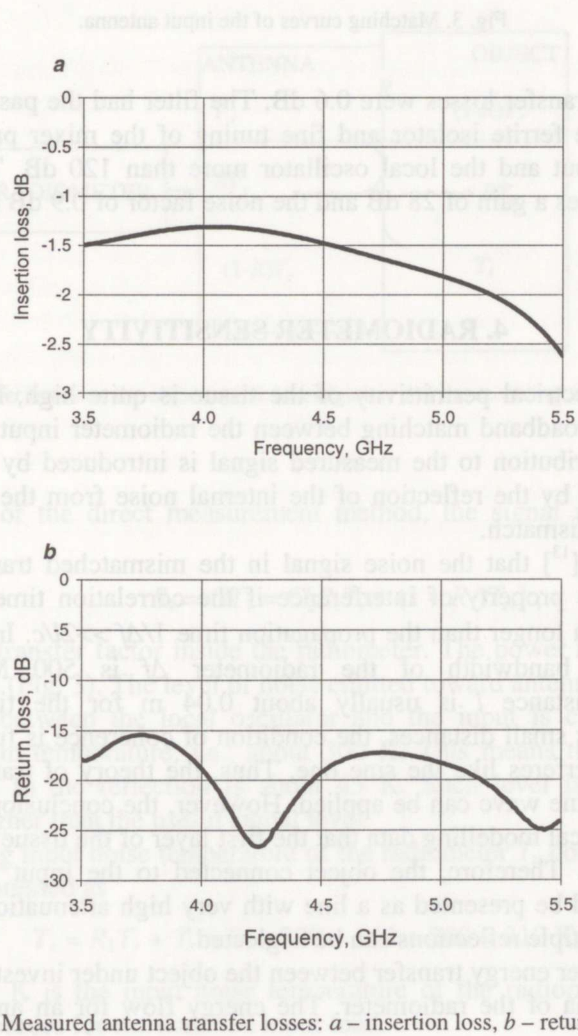

Fig. 2. Measured antenna transfer losses: *a* – insertion loss, *b* – return loss.

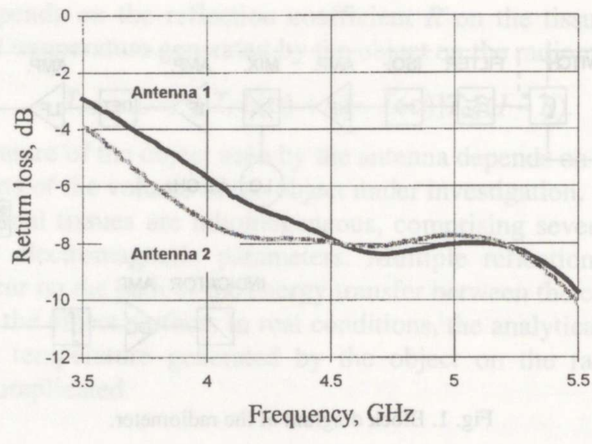

Fig. 3. Matching curves of the input antenna.

The switch transfer losses were 0.6 dB. The filter had the passband of 3500–4500 MHz. The ferrite isolator and fine tuning of the mixer provide isolation between the input and the local oscillator more than 120 dB. The microwave amplifier provides a gain of 28 dB and the noise factor of 0.9 dB in the operating band.

4. RADIOMETER SENSITIVITY

Since the electrical permittivity of the tissue is quite high, it is difficult to provide good broadband matching between the radiometer input and the tissue. Additional contribution to the measured signal is introduced by the radiometer itself, generated by the reflection of the internal noise from the antenna–tissue contact due to mismatch.

It is known [13] that the noise signal in the mismatched transmission lines should have the property of interference if the correlation time of this signal $\tau = 1/\Delta f$ is much longer than the propagation time $1/\Delta f >> 2l/c$. In this work, the high-frequency bandwidth of the radiometer Δf is 500 MHz, and the measurement distance l is usually about 0.04 m for the tissue screening radiometers. For small distances, the condition of coherence is fulfilled, and the noise signal interferes like the sine one. Thus, the theory of transmission lines excited by the sine wave can be applied. However, the conclusion can be drawn from the numerical modelling data that the first layer of the tissue (skin) has very high absorption. Therefore, the object connected to the input antenna of the radiometer could be presented as a line with very high attenuation. In this case, the effect of multiple reflections can be neglected.

Let us consider energy transfer between the object under investigation and the receiving antenna of the radiometer. The energy flow for an antenna in direct contact with the tissue is shown in Fig. 4. In the case of the tissue screening radiometer, only one reflection surface exists, and the equivalent temperature for the spectral density of the energy T delivered to the radiometer by the receiving antenna can be written as

$$T = RT_r + (1 - R)T_t\,, \tag{5}$$

where T_r is the equivalent temperature of the input noise of the radiometer emitted towards antenna, T_t is the equivalent temperature of the object under investigation, including contributions from all sub-volumes, R is the power reflection factor at the antenna–tissue surface. The first part of Eq. (5) presents the unwanted contribution of the internal noise reflected from the tissue. It is easy to see that this unwanted effect disappears when the equivalent temperatures T_r and T_t are equal. Unfortunately, this condition cannot be fulfilled.

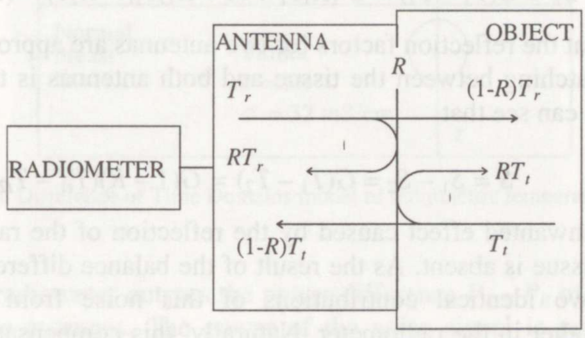

Fig. 4. Energy transfer between the object under investigation and the receiving antenna of the radiometer.

In the case of the direct measurement method, the signal received by the radiometer is

$$S_1 = GT_1 = G[R_1T_r + (1 - R_1)T_{t1}]\,, \tag{6}$$

where G is the transfer factor inside the radiometer. The power reflection factor R_1 is about 0.15 (Fig. 3). The level of noise emitted toward antenna in the case of good isolation between the local oscillator and the input is close to thermal radiation at room temperature, i.e., about 300 K. This means that the possible uncertainty due to the reflection is about 45 K. Such level is approximately twenty times higher than the useful signal level.

The operating input noise temperature of the radiometer T_n consists of several components expressed as

$$T_n = R_1T_r + T_t + T_i = 300 + 310 + 200 = 810 \text{ K},$$

where $T_i = 200$ K is the input noise temperature of the radiometer caused by internal noise sources for the matched input load.

According to (1), the sensitivity of the radiometer for 1 s integration time of the registrator is 0.02 K. This value does not account for the gain instability caused by technical reasons. The sensitivity measured with the warm-cold water phantom is 0.05 K.

Though the radiometer has such high sensitivity, the changes in reflection may cause the measurement error up to 45 K.

In the case of the balance method of measurement, the signal from the reference antenna should be added. Let us assume that the transfer factors are equal for both antennas. The radiometric signal from the reference port is

$$S_2 = GT_2 = G\,[R_2T_r + (1 - R_2)\,T_{t2}]. \quad (7)$$

The two-reference radiometer compares these signals and outputs the difference

$$S = S_1 - S_2 = G(T_1 - T_2) = G\,[R_1T_r + (1 - R_1)T_{t1} - R_2T_r - (1 - R_2)T_{t2}]. \quad (8)$$

If we suppose that the reflection factors for two antennas are approximately equal ($R_1 = R_2 = R$, matching between the tissue and both antennas is the same), then from Eq. (8), we can see that

$$S = S_1 - S_2 = G(T_1 - T_2) = G(1 - R)(T_{t1} - T_{t2}). \quad (9)$$

In Eq. (9), the unwanted effect caused by the reflection of the radiometer input noise from the tissue is absent. As the result of the balance difference method of measurement, two identical contributions of this noise from two antennas annihilate each other in the radiometer. Naturally, this compensation of noise is perfect only in the case of absolutely symmetrical input channels and in that of equal reflection factors for both antennas. Because the highest reflection takes place at the first tissue layer, i.e., skin [10], we can assume that variations of the reflection factors are insignificant for the parts of the tissue with and without tumour and that the compensation of the reflected input noise works well.

5. CALCULATION OF DETECTABILITY OF THE TEMPERATURE ANOMALIES

Radiometric measurement of the temperature anomalies can be simulated inside the arbitrary complex structure using the numerical FDTD method [14,15]. In that model, the error in the radiometric measurement, originating from the reflections and attenuation of the signal, can be taken into account.

Let us assume that the antenna used as the receiver antenna in the radiometer radiates at the central frequency of the radiometer. The radiated microwave energy is absorbed in the object under radiometric investigation. Based on the reciprocity principle, we can state that the same portion of energy that is absorbed in sub-volume V_i of the object will be contributed to the received signal of the radiometer by that sub-volume during the radiometric measurement.

The model adopted for calculations is shown in Fig. 5. It consists of two dielectric-filled waveguide antennas that are in contact with the multi-layered model of the breast. Under the centre of one antenna, there is a tumour. Thus, two structures are considered: one with the presence of the tumour and the other without it.

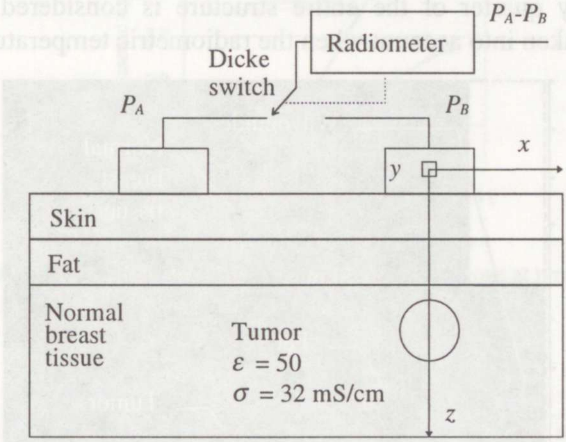

Fig. 5. The Final Difference of Time Domains model of radiometric temperature measurement.

The Dicke radiometer outputs the power difference $P_A - P_B$ of the noise signals received by the antennas. The power of the noise signal is proportional to the temperature of the radiating source in the receiving pattern of the antenna. If the radiating source is divided into n cells, then the temperature seen by the antenna is

$$T = \sum_{i=1}^{n} \xi_i T_i + RT_{ant}, \qquad (10)$$

where ξ_i is the portion of the noise power contributed by the i-th cell, T_i is the temperature of this cell, T_{ant} is the physical temperature of the antenna, R is the reflection factor from the antenna–tissue interface.

Having calculated the weighting coefficients of the source cells for two cases – with the tumour and without it, the temperatures seen by the antennas can be calculated, using (10) and taking into account the discontinuity of the temperature in the case of the tumour.

For the FDTD calculations, the antennas are modelled as infinite 23 × 10 mm waveguides filled with the dielectric $\varepsilon = 10$. The fundamental TE_{10} mode at 4.5 GHz is used as the incident field at the waveguide opening. The power absorbed in the tissues is then calculated. The weighting coefficients ξ_i are evaluated, taking into account the reflection R at the antenna–tissue interface, using the following relation:

$$\sum_{i=1}^{n} \xi_i = 1 - R. \qquad (11)$$

The resulting field of the weighting coefficients is shown in Fig. 6 at the cross-section in the middle of the waveguide. Only half of the cross-section is shown because of the symmetry of the structure and the field. In the FDTD calculations, only quarter of the entire structure is considered. However, the symmetries are taken into account when the radiometric temperature is evaluated.

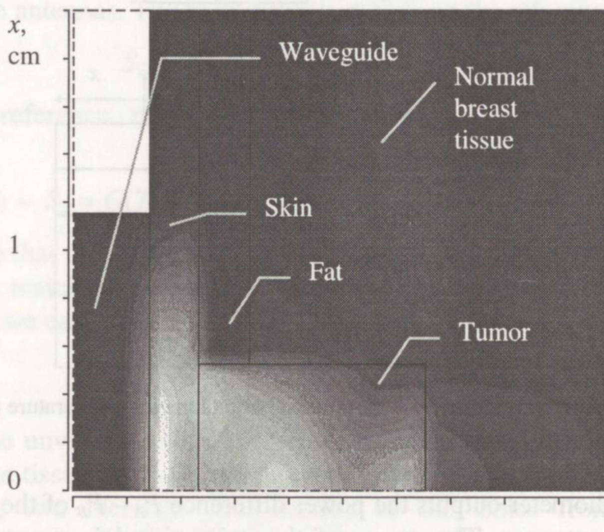

Fig. 6. Antenna's receiving pattern. Cross-section at the middle of the waveguide normal to *Y* axis.

Calculations were made for several angles between the axis of the waveguide and the normal to the tissue interface. For each angle, two cases are considered: 1) space between the antenna and the tissue is a free space; 2) space is filled with the dielectric $\varepsilon = 10$. Additionally, one series of calculations were made for the conductivity of the muscle and skin $\sigma = 2$ and permittivity $\varepsilon = 46$. This was done because the parameters may vary from one tissue sample to another.

The temperature seen by the antenna is evaluated using (10). When the tumour is present, temperature discontinuity is taken into account as follows. It is assumed that tumour's temperature is 3 K higher than that of healthy tissues, and furthermore, that the tissues extended for 1 mm from the tumour are heated at 2 K and the tissues extended for 2 mm from the tumour are heated at 1 K in comparison with the temperature of healthy tissues (36 °C).

Calculations were made for different combinations of the tissues and different dimensions of the tumour. The results are the differences of temperatures seen by the antennas, if one of them is positioned over the centre of the tumour. Figure 7 shows the simulated radiometer output for different tumour dimensions if the tumour depth is 4 mm.

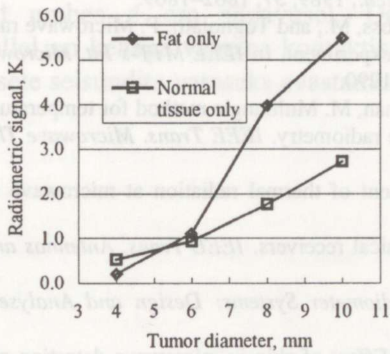

Fig. 7. Calculated radiometric signal for different tumour dimensions at tumour depth of 4 mm.

6. CONCLUSIONS

The results of the calculation of the sensitivity to the registration of the electromagnetic energy of the radiometric system show that sensitivity is high (0.05 K), but in the temperature measurements of tissues it is degraded by the measurement error of about 45 K. The application of the balance method of measurement eliminates errors that arise from the background tissue radiation and antenna mismatch.

The numerical modelling of the radiometric measurement of the tissue temperature shows that the Dicke radiometer, which has the temperature resolution better than 1 K, can be used with two dielectric-filled body-contacting waveguide antennas for the exploration of tumours which are at least 6 mm in diameter. The results of numerical modelling also show that

– small variations in the dielectric properties of the tissue cause significant changes in the transfer function value;
– the spatial resolution decreases with an increase in the observation angle;
– the effective operating antenna size is close to the wavelength in it, the parts of the antenna far from its centre do not give a significant contribution to the summary field pattern;
– the highest input transfer function corresponds to the direct contact between the antenna and the tissue without air slot;
– the highest absorption takes place in skin, and this layer cannot be neglected.

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REFERENCES

1. Carr, K. Microwave radiometry: Its importance to the detection of cancer. *IEEE Trans. Microwave Theory Tech.*, 1989, **37**, 1862–1869.
2. Bardati, F., Brown, V., Ross, M., and Tognolatti, P. Microwave radiometry for medical thermal imaging: theory and experiment. In *IEEE MTT-s Int. Microwave Symposium Digest.* New Mexico, 1992, 1287–1290.
3. Mountreuil, J. and Nachman, M. Multiangle method for temperature measurement of biological tissues by microwave radiometry. *IEEE Trans. Microwave Theory Tech.*, 1991, **39**, 1235–1239.
4. Dicke, R. The measurement of thermal radiation at microwave frequencies. *Rev. Sci. Instr.*, 1946, **17**, 268–275.
5. Tiuri, M. Radio astronomical receivers. *IEEE Trans. Antennas and Propagation*, 1964, **12**, 7, 264.
6. Skou, N. *Microwave Radiometer Systems: Design and Analyses*. Artech House, Norwood, 1989.
7. Alanen, E. and Lindel, I. Effect of skin in microwave detection of breast cancer. *IEEE Trans. Microwave Theory Tech.*, 1986, **34**, 584–588.
8. Martens, L., Fache, N., De Zutter, D., and De Wagter, C. Electromagnetic modelling of a parallel-plate waveguide applicator irradiating an inhomogeneous lossy medium. In *IEEE MTT-s Int. Microwave Symposium Digest.* New Mexico, 1992, 243–246.
9. Hinrikus, H. Calculation of microwave radiometric signals in a lossy biologic tissue. *Trans. Tallinn Tech. University*, 1994, **736**, 68–81.
10. Hinrikus, H., Riipulk, J., Beilenhoff, K., and Hartnagel, H. Calculation of microwave radiometric signal in multilayered biological tissue. In *Proc. IEEE Engineering in Medicine and Biology Annual Conf.* Montreal, 1995, 1583–1584.
11. Hinrikus, H., Krasavin, J., and Põdra, H. Microwave radiometry for cancer detection. In *Proc. 7th Int. IMEKO TC-13 Conf. on Measurement in Clinical Medicine Model Based Biomeasurements.* Stará Lesná, 1995, 221–225.
12. Hinrikus, H., Riipulk, J., and Põdra, H. Design of microwave radiometer for early detection of cancer. *Physica Medica*, XIII, Dec. 1997, 324–325.
13. Troitskij, V. S. Fluktuatsii v nagruzhennoj linii. *Zhurn. Tekh. Fiz.*, 1955, **25**, 8, 1426–1435 (in Russian).
14. Hinrikus, H., Riipulk, J., Beilenhoff, K., and Hartnagel, H. Simulation of breast tissues temperature measurement using Dicke radiometer by FDTD method. *Medical & Biological Engineering & Computing*, 1996, **34**, 1, 135–136.
15. Riipulk, J. and Hinrikus, H. Interpretation of radiometric signal for tumor detection. *Proc. 19th Int. IEEE/EMBS Conf.* Chicago, 1997, 2509–2511.

MIKROLAINERADIOMEETRI TUNDLIKKUS KUDEDE LÄBIVAATAMISEL

Hiie HINRIKUS, Jevgeni RIIPULK, Tarmo NEEMELA ja Harri PÕDRA

Radiomeetrilist meetodit temperatuurianomaaliate avastamiseks rinna kudedes on uuritud teoreetiliselt ja simuleeritud numbriliselt. Kasutusel oleva 4,5 GHz diapasoonis töötava Dicke'i radiomeetri diferentsiaalne sisend võimaldab maha suruda peegeldustest ja foonikiirgusest tekkivad vead. Numbrilist ajadomeenide lõplike vahede meetodit kasutati radiomeetri sisendi ülekandefunktsiooni

ruumilise jaotuse modelleerimisel kolmekihilises mittehomogeenses kehas. Arvutatud radiomeetrilise signaali eraldusvõime on parem kui 1 K, kui tuumori diameeter on 6 mm. Radiomeetri tundlikkus 0,05 K võimaldab avastada temperatuurianomaaliaid umbes 4 cm sügavusel. Diferentsiaalse sisendiga Dicke'i radiomeeter, millel on kehaga vahetus kontaktis olevad antennid, sobib vähkkasvaja või vähieelsete seisundite varaseks avastamiseks.