

The prospects of creating of microwave radiothermography based on monolithic integrated circuits

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Abstract. A new approach to the creation of microwave radiothermography is shown. Scientific and technical barriers preventing the creation of relatively inexpensive devices for early diagnosis of tumors, as well as painless and safe monitoring during treatment were identified. An optimal principle of construction of microwave radiothermography based on monolithic integrated circuits is offered.

1 Introduction

The great interest of physicians, biologists and biophysicists to microwave radiometry (MR) is due to the fact that it is a non-invasive method of measuring the deep temperatures of the internal areas of the human body based on their own thermal radiation. This method has received deserved recognition in medicine in the diagnosis of damages of the central and peripheral nervous system, assessment of local inflammatory, traumatic, oncological, vascular and dystrophic diseases of various localization [1-6].

The method of microwave radiometry is not widely used in practical medicine despite the high diagnostic potential. This is due to the imperfection of diagnostic equipment and lack of visibility of the results, which slowed down the implementation of the method in clinical practice.

The results obtained earlier should be developed and used in the development of new methods of diagnosis and the development of appropriate medical techniques. This task is quite doable at the modern level of technology. By solving this task it is possible to obtain information about the nature of the temperature distribution in depth by constructing layered images or three-dimensional temperature fields. The great advantage of the system will be to obtain information about the internal temperatures and dynamics of its changes in several points of the body at the same time and in time, and at different depths. Existing devices can not provide it. This will allow to go to dynamic microwave thermography of internal tissues and organs and evaluate their condition under the influence of various loads and functional problems. We believe that it is possible to expand the functionality and significantly reduce the size by combining the principles of multichannel, multifrequency and microminiaturization in one radiometric complex. One of the tasks is to determine the optimal number of channels and frequencies, as well as to simplify the scheme by reducing the number of elements.

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The purpose of the article is to study the possibility of combining in one radiometric complex the principles of multichannel, multifrequency and microminiaturization, which will lead to the expansion of its functionality and a significant reduction in size.

2 Main part

Research on the early diagnosis of cancer has recently become of great scientific interest. The annual review of March 31, 2017 presents a statistical analysis of the state of Affairs in the field of Oncology based on the results of statistical data processing in several US States [1]. The analysis shows that despite significant scientific and financial efforts to improve five-year survival, statistics for a lot of types of cancer are improving slightly. This applies to cancer of the bronchus, lung, esophagus, stomach, pancreas, liver, bile ducts, brain. According to the results of American authors, the minimum tumor size diagnosed using nuclear medicine methods is 15 mm in diameter on average in clinics [2]. The inability of early detecting is the main cause of failures in the treatment of tumors that begin to metastasize at smaller sizes. Therefore, an important task is to find sensitive methods and tools to diagnose tumors of minimal size. This is important for the diagnosis of tumors in the early stages. These methods include microwave radiothermy.

Recently, there have been a lot of new results by using of MR in medicine. MR is used to detect cancer and monitor the course of treatment of various diseases of the mammary glands in mammology (Fig. 1) [3-6].

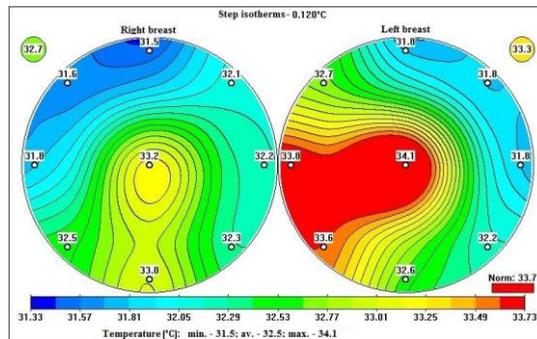


Fig. 1. Temperature field of the breast without pathologies and with oncology.

In emergency medicine, the method is used to measure brain temperature in the treatment of stroke and traumatic brain injuries [7-10]. A number of studies related to the detection of inflamed atherosclerotic plaques and estimation of stroke risk were carried out [11, 12]. MR is also used in studies of non-invasive diagnosis of arthritis [13], the study of brown fat activity [14], in studies of the brain, spine and joints [15]. Interesting results were obtained in the field of phlebology, experimental oncology, gynecology and urology [16, 17]. In addition, MR was also used to study of microwave radiation of enzymes [18, 19].

Further development of MR is restrained by a number of scientific and technological limitations. Devices used in medicine are single-channel and single-frequency, and also have considerable size. Multichannel systems are needed that would allow in real-time to evaluate temperature changes in depth and examine significant areas of the body. In addition, it will allow to realize long-term monitoring of internal tissue temperature. Mechanical expansion of the number of channels is low-tech and it is need to use new models of radiometers, allowing to drastically reduce their sizes. This requires combining in one measurement complex principles of the multi-channels, multifrequency and miniaturization without reducing necessary functionality. Obviously, using of monolithic integrated circuits can significantly reduce the size of the device and its components [20,

21]. In general, the development of MR requires the development of special antenna designs and their optimal location in the antenna array, the optimal choice of the number of channels and operating frequencies, as well as the introduction of additional filtering of the received signals. The development of special forms of medical antennas and the device will be required for using of radiothermography in case of examination of the human body through the skin and through a natural cavities.

The above scientific problem can be presented in the form of two: the first scientific problem is the search for a method to diagnose diseases, including cancer, at an early stage; the second scientific problem in this project is the development of a non-invasive method for monitoring and evaluating of tumors development.

Every physical body, including biological objects, radiates electromagnetic fields into the surrounding space in a wide frequency range. The study of the characteristics of these fields allows to obtain information about the object, in particular information about the state of the deep structures of radiating bodies. It should be noted the works of R. H. Dicke, A. H. Barrett and a number of other foreign researchers from the works that determined the development of the theory and technology of systems for measuring the intrinsic electromagnetic radiation of biological objects, [22-28].

According to the well-known Raylei-Jeans law, the energy density of thermal radiation of biological tissues in the microwave range is proportional to the absolute temperature. Therefore, body's temperature can be determined by measuring of the radio emission intensity [22-28].

The current state of the problem reviews in the article [29].

In [10, 30] the features of dynamic thermal patterns obtained by microwave radiothermography after various functional tests were studied in detail, which significantly expand the diagnostic capabilities of the method (Fig. 2).

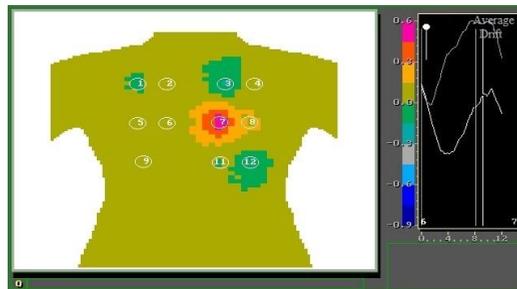


Fig. 2. Diagnosis of the left lung pathology (glucose test in oncology).

However, it should be noted that most radiographs have considerable size, even in a single-channel version. The main disadvantage of the above devices is that they do not have sufficient noise immunity and can only be used in special shielded rooms (capsules), which complicates their practical application.

The results of measurements of radiothermal radiation of the brain in the range of 3.2 ± 0.45 GHz are presented in [31]. A multichannel phased array radiometer is used. A printed conformal antenna with a radiator having an L-shaped cutout is used as a lattice element. According to the authors this system has limitations related to accuracy and temperature resolution compared to other technologies. The proposed antenna system requires additional research to determine its potential value in clinical practice.

This radiothermometer is also currently used only for scientific purposes and does not have a permit for using.

Creation possibility of the single-frequency radiothermometer constructed according to the R. H. Dicke scheme which is inexpensive, small-sized, stable, highly sensitive device and consists of available microwave components is investigated in work [32].

Results of research in the field of creation of multi-channel and multi-frequency radiometers are presented in [30, 31, 33-38]. Registration of information is carried out by a multi-channel radiometer with antennas tuned to different frequencies, or a single-channel multi-frequency radiometer. These devices allow to receive information about the temperature of internal tissues simultaneously in several points of the patient's body in accordance with the number of receiving antennas and to build dynamic temperature distributions. The microwave radiothermometer intended for diagnostics of diseases of mammary glands is presented in [39]. This device is single-channel as well as radiothermometer presented in [40]. Measurements are simultaneously made in five frequency bands, which makes it possible to determine the temperature in depth. This radiothermometer are used a broadband antenna operating in the frequency range of 1-4 GHz. All functional parts of the device are located in one sensor.

Information on the development of a 20-channel radiothermometer for visualization of thermal changes in the brain is presented in [30]. This device has 20 receiving channels and 20 antennas. The operating range is 780 MHz or 1.5 GHz with a 200 MHz band. A balanced dyke 20-channel microwave radiometer is used for receiving its own radiation. It works on a scheme with a pilot signal of known power to measure the reflection coefficient, which allows taking into account the antenna misalignment with different tissues. An antenna module with a U-shaped dipole applicator is used as an antenna. The device allows simultaneously to receive information from several points and to build "radiothermal maps" of an organism.

Five-frequencies dyke radiothermometer (1.2, 1.65, 2.3, 3.0 and 3.6 GHz with a band of 400 MHz in each) is used to register the internal radiation of the brain by authors in [34-36]. A rectangular waveguide that measures the temperature of biological tissue through an aqueous bolus is used as a receiving antenna. The device allows to receive information from different depths of the brain and restore the temperature profile. The temperature resolutions received for each receiver are 0.183, 0.273, 0.148, 0.108 and 0.118 °C for 1.2, 1.65, 2.3, 3.0 and 3.6 GHz receivers, respectively [36]. However, if the conductivity of the brain is estimated incorrectly at 10%, it will lead to an error of 0.3-0.4 °C according to [36]. The result of this work is encouraging for the implementation of radiometric measurements of the temperature profile in the child's head. The measurement accuracy, which is the difference between the calculated temperature using a radiothermometer and the temperature measured by a thermocouple at a depth of 5 cm, was about 2 °C according to [35]. The result is not satisfactory for clinical use, the accuracy should be better than 1 °C. A 2-frequency balanced dike radiothermometer (1.2 GHz and 3.0 Hz) was created for a similar medical problem in [37]. Multi-channel 2-frequency radiometer is presented in [38]. The results of the development of basic units and an experimental sample of a multichannel radiometric system for non-invasive diagnosis of the functional state of the brain are presented.

A number of features combine all of the above development: the ability to assess the nature of temperature changes in depth stationary using, large size, the need to use a shielded room. The main disadvantage of these devices is that they do not have noise immunity and can only be used in special shielded rooms, which complicates their practical application. Most radiometers are used only for scientific purposes and not have permission to use.

An additional advantage of multi-channel radiometer could be to ensure the functioning of their antennas in several frequency ranges, realizing the possibility of measuring radio brightness temperatures at different depths and allowing to significantly increase the resolution of the radiothermic mapping system. The measurement of the radio brightness temperatures of biological objects is performed using a modulation radiometric receivers. The modulator is located in the input of them. It is by the control signal from the

synchronizer switches to the antenna or the equivalent input UHF with frequency modulation F_M after amplification of the modulated signal, which is corresponded to the brightness temperature of a biological object. The amplitude envelope of the input signal, which is integrated with a time constant, is allocated by using a synchronous detector. The transfer of the information signal to the modulation frequency and its amplification by low frequency amplifier can significantly weaken the influence of flicker noise.

A modulation radiometer can be represented as a set of two full – power radiometric receivers, one of which measures the antenna temperature and the other the equivalent temperature, and a subtractor whose output, after averaging over time τ , produces a signal proportional to the temperature difference between the antenna and the equivalent. The linearity of subtraction and averaging operations implies the possibility of their permutation. Then it is averaged at the output of each of the radiometers by minor, in accordance with the duty cycle, the number of independent countdown.

Using of several antennas and multichannel radiometric receivers operating in the microwave range allows to make dynamic researches of deep (up to 4 cm) brain temperatures with a measurement accuracy of about $0.1\text{ }^{\circ}\text{C}$ and computer processing with the presentation of the results in the form of temperature maps and dynamic graphs.

The described scientific and technological barriers restrain to the full development of radiometry, because the designs created by using of traditional technology of antenna manufacturing, hybrid integrated circuits, methods of forming are bulky, uncomfortable for medical workers, do not provide the required parameters, and therefore did not find wide application. It is necessary to use new technologies, namely monolithic integrated circuit technology, providing a breakthrough in this area.

Developers of electronic equipment are imposed strict requirements for modules with cost restrictions in the framework of modern trends in technological development. Complex task to radically improve the parameters and characteristics of GIC and MIC of various classes and applications: to improve power density, efficiency, stability, reliability, functionality had been set to the developers. This predetermined the transition from traditional microwave materials (Si, GaAs) to new wide-band materials: AlGaIn/GaN heterostructures; InAlAs/InGaAs/InP, hybrid heterostructures of JET/HBT type on GaAs substrates, SiC epitaxial structures on SiC substrates, etc.; design optimization of transistors, diodes and other active elements based on these new materials; development of appropriate basic industrial technologies that provide high reproducibility of GIC and MIC parameters in production and high stability of these parameters during operation of products [30].

Planar antennas with minimal topological dimensions are created due to the high dielectric constant of such materials as GaAs, GaN and solid solutions based on them. This feature of these materials allows to create receiving and transmitting paths in the form of monolithic integrated circuits, providing on the one hand, reducing the noise coefficient of the receiving path, on the other-reducing the loss of signal power from the antennas to the amplifier. In addition, the using of MIC with built-in antennas can solve actual questions related to weight and size parameters. It should be noted that using of MIC as a component base can significantly increase the variability of circuit solutions, which will allow to provide optimal characteristics of the developed device. Structural scheme of dual-channel radiothermography is shown in Fig. 3. It is obvious that with increasing frequencies and channels, the scheme must be modified, because it is necessary to determine the optimal number of channels and frequencies, and to do work to reduce the number of elements.

Considering the listed advantages, using of microwave component base on MIC is topical solution to enable to create the multi-channel multi-frequency microwave radiothermograph based on MIC with integrated antennas for finding the 3D distribution and dynamics of brightness temperature in the depths of the human body.

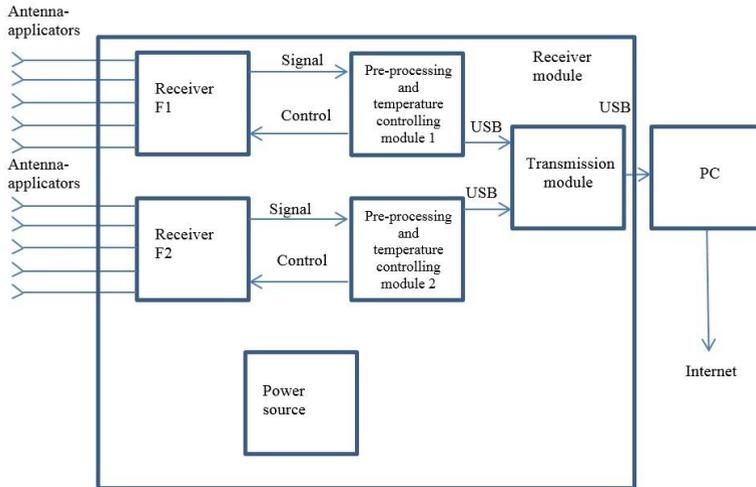


Fig. 3. Structural scheme of dual-channel radiothermography.

3 Conclusion

Thus, the development of compact multi-channel multi-frequency microwave radiothermography on fundamentally new principles of the structure and using of monolithic integrated circuits technology will allow to identify and localize pathology of organs and tissues based on finding the 3D distribution and dynamics of brightness temperature in the depths of the human body.

The development of the device based on new principles of the structure construction and using of monolithic integrated circuits technology will enable medical professionals to develop new methods and medical techniques, as well as the integration of microwave radiograph with other medical diagnostic methods, which is especially important in the early stages of diseases.

Research was supported by a grant of the Russian Science Foundation (project No. 19-19-00349).

References

1. A. Jemal, E. Ward, C. Johnson, et al., Annual Report to the Nation on the Status of Cancer, 1975–2014, Featuring Survival, *J. Natl. Cancer Inst.*, 109(9) (2017)
2. Y. Erdi., Limits of Tumor Detectability in Nuclear Medicine and PET, *Mol. Imaging Radionucl. Ther.*, 21(1), pp. 23–28 (2012)
3. S. Vesnin et al., Modern microwave thermometry for breast cancer, *J. Mol. Imag. Dynamic*, v. 7, No 136, p. 10 (2017)
4. M. Sedankin, S. Agasieva et al., Mathematical Simulation of Heat Transfer Processes in a Breast with a Malignant Tumor, *Biomedical Engineering*, v. 52, No 3, pp. 190-194 (2018)
5. M. Gautherie, C. Gros., Breast thermography and cancer risk prediction, *Cancer*, V. 45, pp. 51–56 (1980)
6. T. Yahara, et al., Relationship between microvessel density and thermographic hot areas in breast cancer, *Surgery Today*, v. 33, pp. 243–248 (2003)
7. D. Chebokсарov et al., Diagnostic opportunities of noninvasive brain thermomonitoring, *Anesteziologiya i reanimatologiya*, v. 60, No. 1, pp. 66-69 (2015)

8. A. Gudkov, V. Leushin, A. Korolev, V. Plyutshev et al., Element Base for Radio Passive Device, Proceedings of the Russian-Bavarian Conference on Biomedical Engineering, pp. 154–155 (2012)
9. A. Gudkov, V. Leushin, A. Korolev, V. Plyutshev et al., Electronic module of multichannel microwave tract for radiothermometry systems // *Jelektromagnitnye volny i jelektronnye sistemy*, No 1, pp. 27–34 (2014)
10. V. Anzimirov, A. Gudkov, V. Leushin, D. Tsyganov, Modern possibilities and perspectives of neuro heat vision // *Biomedicinskaja radiojelektronika*, No 3, pp. 49–54 (2010)
11. K. Toutouzas et al., Noninvasive detection of increased carotid artery temperature in patients with coronary artery disease predicts major cardiovascular events at one year: Results from a prospective multicenter study, *Atherosclerosis*, v. **262**, pp. 25-30 (2017)
12. M. Drakopoulou et al., The role of microwave radiometry in carotid artery disease. Diagnostic and clinical prospective, *Current opinion in pharmacology*, v. **39**, pp. 99-104 (2018)
13. E. Zampeli et al., Detection of subclinical synovial inflammation by microwave radiometry, *PLOS ONE*, v. 8(5), e64606 (2013)
14. J. Crandall et al., Measurement of Brown Adipose Tissue Activity Using Microwave Radiometry and 18F-FDG PET/CT, *Journal of Nuclear Medicine*, v. **59**, No 8, pp. 1243-1248 (2018)
15. A. Tarakanov, V. Efremov, Perspectives of microwave radiometry application at dorsopathy in hospital department of the emergency medical care, *Emergency medical care*, No 1, pp. 64-68 (2016)
16. A. Kaprin, S. Agasieva et al., Microwave Radiometry in the Diagnosis of Various Urological Diseases, *Biomedical Engineering*, Vol. **53**. Issue 2, pp. 87–91 (2019)
17. B. Snow et al. Non-invasive vesicoureteral reflux detection: Heating risk studies for a new device, *Journal of pediatric urology*, v. 7. No 6, pp. 624-630 (2011)
18. Y. Ivanov et al., Use of microwave radiometry to monitor thermal denaturation of albumin, *Frontiers in physiology*, v. **9**, p. 956 (2018)
19. Y. Ivanov et al., Monitoring of microwave emission of HRP system during the enzyme functioning // *Biochemistry and biophysics reports*, v. **7**. P. 20-25 (2016)
20. A. Gudkov et al., Prospects for application of radio-frequency identification technology with passive tags in invasive biosensor systems, *Biomedical Engineering*, v. **49**, No. 2, pp.98-101 (2015)
21. V. Emtsev., The relationship between the reliability of transistors with 2D AlGaIn/GaN channel and organization type of nanomaterial, *Technical Physics Letters*, v. **42**. No. 7, pp.701-703 (2016)
22. V. Feigin et al., Global and regional burden of stroke during 1990—2010: findings from the Global Burden of Disease Study 2010, *Lancet*, v. 383, No. 9913, pp. 245-255 (2014)
23. L. Winter et al., Magnetic resonance thermometry: methodology, pitfalls and practical solutions, *J. Hyperthermia*, No 32(1), pp.63–75 (2016)
24. D. Gensler et al., MR safety: fast T1 thermometry of the RF-induced heating of medical devices, *Magnetic Resonance in Medicine*, V. **68**, pp.1593–1599 (2012)
25. O. Craciunescu et al., Accuracy of real time noninvasive temperature measurements using magnetic resonance thermal imaging in patients treated for high grade extremity soft tissue sarcoma, *Med Phys.*, V. **36 (11)**, pp.4848-4858 (2009)
26. L. Lüdemann et al., Non-invasive magnetic resonance thermography during regional hyperthermia, *Int. J. Hyperthermia*, v. **26 (3)**, pp. 273–282 (2010)
27. E. Siores et al., First in vivo application of microwave radiometry in human carotids, *Journal of the American College of Cardiology*, v. **59**. No 18, pp.1645–1653 (2012)

28. L. Mustata, O. Baltag, Applications of microwave radiometry in diagnostic suspicion of mammary pathology, *IFMBEProceedings*, v. **22**, pp. 825–828 (2008)
29. Yu. Gulyaev, A. Gudkov, V. Leushin, S. Vesnin, M. Sedankin, I. Sidorov et al., Devices for the diagnosis of pathological changes in the human body by methods of microwave radiometry // *Nanotehnologii: razrabotka, primenenie - XXI vek*. No 2. pp. 27-46 (2017)
30. S. Agasieva, A. Gudkov, V. Leushin et al., Improving the reliability and quality of GIC and microwave MIC (Book 2, edited by A. Gudkov and V. Popov, Moscow, Avto-test Ltd., 2013)
31. N. Asimakis, I. Karanasiou et al., Non-invasive microwave radiometric system for intracranial applications: a study using the conformal l-notch microstrip patch antenna, *Progress in electromagnetics research-pier*, v. **117**, pp. 83-101 (2011)
32. P. Stauffer et al., Design of small-sized and low-cost front end to medical microwave radiometer. *Prog. Electromagn Res Symp*. pp. 932–936 (2010)
33. B. Stec, A. Dobrowolski, W. Susek, Multifrequency microwave thermograph for biomedical applications, *IEEE transactions on biomedical engineering*, v. **51**, No. 3, pp. 548-550 (2004)
34. J. Hand et al. Monitoring of deep brain temperature in infants using multi-frequency microwave radiometry and thermal modeling, *Physics in Medicine & Biology*, v. **46**, No. 7, pp. 1885–1903 (2001)
35. T. Sugiura et al., Five-band microwave radiometer system for noninvasive brain temperature measurement in newborn babies, Phantom experiment and confidence interval, *Radio Science*, v. **46**. No. 5, pp. 1-7 (2011)
36. T. Sugiura et al., Five-band microwave radiometer system for non-invasive measurement of brain temperature in new-born infants: system calibration and its feasibility, *The 26th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, v. **1**, pp. 2292-2295 (2004)
37. F. Bardati, G. Marrocco, P. Tognolatti, New-born-infant brain temperature measurement by microwave radiometry, *IEEE Antennas and Propagation Society International Symposium (IEEE Cat. No. 02CH37313)*, v. **1**, pp. 811-814 (2002)
38. A. Gudkov, S. Agasieva, V. Leushin et al. Use of multichannel microwave radiometry for functional diagnostics of the brain, *Biomed. Eng*, v. **53**, No. 2, pp. 108-111 (2019)
39. N. Livanos et al. Design and interdisciplinary simulations of a hand-held device for internal-body temperature sensing using microwave radiometry, *IEEE Sensors Journal*, v. **18**, No 6, pp. 2421-2433 (2018)
40. K.Toutouzas et al. Microwave radiometry: a new non-invasive method for the detection of vulnerable plaque, *Cardiovascular diagnosis and therapy*, v. **2**, No 4, pp. 290-297 (2012)