

Microminiaturization of Multichannel Multifrequency Radiographs

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Due to the COVID-19 epidemic, the challenge of introducing methods for investigating patients reducing or eliminating the probability of infection of medical staff is currently relevant. This article provides an analytical review of new technological approaches to organizing the work of medical personnel in carrying out auscultation of patients with COVID-19. The development and approval of such technologies is shown to have started around the world. The ubiquitous and large-scale introduction of these methods into medical practice therefore seems expedient.

Introduction

Radiometers or radiographs, which detect microwave radiation from biological tissues, are built mainly using modifications or improvements of the Dicke system proposed in 1946 [1] or a direct amplification receiver system [2]. Barrett was the first to propose the use of microwave radiation from biological tissues for medical diagnostics, particularly for detecting breast cancer [3].

Microwave radiometers are currently used for the diagnosis and monitoring the treatment of breast diseases [4, 5], investigations of the carotid arteries to detect inflammatory atherosclerotic plaques and patients at high risk of stroke [6], to measure brain temperature [7, 8], including in the treatment of stroke and traumatic brain injury [9], for monitoring brain temperature during hypothermia [10], for the diagnosis of inflammatory joint diseases [11], for the diagnosis of vesicoureteric reflux in children [12], to assess the functional activity of brown fat [13], for diagnosis and treatment monitoring of spinal pain [14, 15],

and for diagnosis and treatment monitoring in patients with COVID-19-related lung diseases [16]. Unfortunately, stationary microwave radiometers cannot be used in people taking part in active behavior. However, this direction has been in significant demand in recent years and articles have been published on the development of miniature wearable devices which can be positioned on the human body for dynamic monitoring of internal temperature [17–21]. In particular, Popovic addressed the potential creation of wearable wireless radiometers [19] and noted that miniaturization using monolithic integration is possible.

As regards the physiological characteristics of the distribution of temperature in the human body, differences between organ temperatures, such as the heart and skin, vary by up to $\pm 2^\circ\text{C}$ during the circadian cycle for a presumptively healthy person [22]. Impairments to the circadian rhythm can lead to seasonal affective disorders [23], diabetes [24], and heart diseases [25]. Cosmonauts, sportsmen, firefighters, soldiers, and sailors working in difficult conditions and undergoing active training can be subject to the actions of unfavorable environmental conditions, leading to overheating, hyperthermia, and heat shock, generating the need to monitor internal body temperature [4, 26, 27].

Other technologies for measuring internal temperature are generally invasive and inconvenient, can be uncomfortable, and produce large measurement errors, of up to 6°C [28, 29], or have high costs. However, existing radiometers have a number of drawbacks: lack of sensi-

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tivity and accuracy in temperature measurements, low interference resistance, significant weight, and large dimensions. Attempts to solve these problems have been reported in [17, 19] by developing a compact version of a radiometer based on the Dicke scheme [30, 31].

Data reported in [19] indicate that monolithic integration is possible, using GaAs monolithic integrated circuits (MIC). All the components can be integrated into a single small chip. Manufactured microcircuits are small in size and can be installed and connected to a flexible substrate with a sensor. It should be noted that this approach does not use a chip, i.e., an MIC, but a hybrid integrated circuit (HIC) with a quasi-monolithic design. Increases in the efficiency of microwave thermometers (MT) in medical practice require creation of miniature multichannel multifrequency radiographs to provide information on internal temperatures over time at multiple points at different depths simultaneously. This will provide for a transition to dynamic MT for internal tissues and organs and assessment of tissue status as influenced by various loads and functional tests.

Development of Microwave Radiometry Methods

Development of the method is linked with advances in means of detecting radiation from warm bodies in the microwave range, and, particularly, with the work of Dicke, which was driven by the needs of radio astronomy. Improvements in the component base supported creation of significantly smaller microwave radiometers, such that they could be launched on satellites and flown in aircraft. This provided the opportunity to develop remote studies of planet earth. Further miniaturization of radiometers allowed them to be used on board autonomous aerial vehicles and terrestrial vehicles. Agricultural tasks were solved using multifrequency polarimeter radiometric systems for remote mapping systems [32]. Specialized radiometric systems were developed at the same time for detecting underground leaks in terrestrial dams and assessing risk situations [33]. Results demonstrating successful use of a radiometer based on complementary metal oxide semiconductor structures for detecting fire were presented in [19].

Experience accumulated by the authors of the present article in addressing these tasks provided the basis for developing a microwave radiometric system for medical use to address the early diagnosis of malignant tumors and other diseases associated with internal areas of hyperthermia [34]. Work presented in [35] described a device based on a UHF monolithic integrated circuit which is available commercially. Article [36] presented information on the

first commercial single-channel radiometer developed under the leadership of S. G. Vesnin, one of the authors of this article. Report [37] presented a miniature version of the radiometer. The parameters of the miniature microwave radiometer characterizing measurement accuracy are no worse than those of stationary devices, while size and weight are hundreds of times lower. The dimensions of the miniature radiometer are $23 \times 31 \times 15$ mm and its weight is 50 g, while a stationary device weighs 4.5 kg and has dimensions of $450 \times 500 \times 210$ mm. Averaging of signals over 4 s gave a standard deviation δ of the device of 0.052°C .

The device provides high accuracy even in the presence of strong reflections from the antenna. In particular, when there are reflections at the input ($R^2 = 0.25$), the measurement error of the radio brightness temperature was 0.2K. That is, if 25% of the power is reflected from the antenna and does not reach the radiometer, the noise signal power measurement error changes by 0.07%. The weak influence of antenna mismatch on measurement results is due to the fact that the radiometer uses a scheme – patented in several countries – for because a miniature balanced null radiometer with a sliding reflection compensation arrangement for reflections from the antenna [38].

Figure 1 shows the layout of the microwave part of the radiometer.

As in a traditional radiometer built using the Dicke scheme, the present SPDT switch arrangement connects either the antenna or a standard noise source to the receiver. The reference noise source was a miniature UHF load on a Peltier element. Changes in the current passing through the Peltier element alter the temperature of the UHF load. As the noise temperature for the matched load coincides with the thermodynamic temperature, the task of measuring the noise temperature reduces to measurement of the temperature of the matched load, which can be done using a platinum resistor mounted on the UHF load board. Thus, the device uses two temperature sensors. One sensor measures the temperature of the UHF load located in the thermoelectric module. The second sensor measures the temperature of the UHF module of the radiometer. A circulator load is also mounted on the Peltier element, which allows the temperature of the noise signal passing from the circulator to the antenna to be increased. The source of the reference noise signal has dimensions of 2×2 mm (item 6 in Fig. 1).

With negative feedback, the voltage on the output of the synchronous detector approaches zero and the temperature of the matched load approaches the temperature of the antenna. Thus, the task of finding the temperature of the noise signal reduces to minimizing the load on the output of the synchronous detector and measuring the

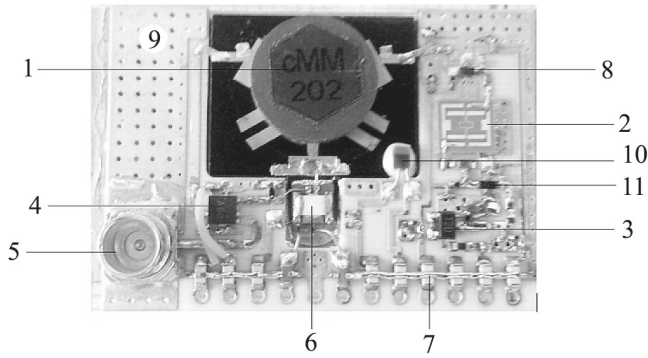


Fig. 1. Microwave radiometer module: 1) circulator; 2) bandpass filter (BPF); 3) detector; 4) SPDT switch; 5) microwave connector; 6) thermoelectric module; 7) low-pass filter; 8, 11) low noise amplifier; 9) radiometer board; 10) temperature sensor.

temperature of the matched load using a standard temperature sensor.

The UHF module was produced using printed circuit board technologies using monolithic integrated microcircuits. In particular, a two-stage low-noise amplifier was used, based on the use of VMMK-3803 monolithic microcircuits (Avago Technologies, USA). A four-resonator filter with a bandpass with attenuation poles at the frequency extremes using four parallel resonator stages was developed as a bandpass filter (BPF). The filter was built on a support of size $4 \times 4 \times 0.5$ mm with high dielectric permeability ($\epsilon = 100$). The reference voltage generator, synchronous detector, selective amplifier, limiter, and delay line were implemented on an AN231E04-QFN-44 chip from Anadigm Inc (USA). This microcircuit works with an analog signal, but provides for adjustment of the gain of the selective amplifier and the values of the time

constant and other parameters in digital format using a personal computer. The block diagram of the device can be altered during both set-up and operation. The signal from the temperature sensor is fed to an eight-channel analog-to-digital converter implemented on an AD7194BCPZ chip from Analog Devices (USA). Microchip PIC18F46J50.I/PT from Microchip Technology Inc. (USA) is used as a microcontroller.

The use of MIC to create the receiver modules of a radiograph reduces the noise coefficient of the receiver path, reduces the signal power loss from the antennas to the amplifier, and reduces the size and weight of the device, thus ensuring optimal device characteristics [35, 39, 40].

The heart of the multichannel radiograph is a highly sensitive radiometric receiver, and the applicator antennas are connected to its inputs. Five-channel radiometric receivers operating in the 40- and 20-cm bands were developed as HIC devices with partial use of MIC. Figure 2 shows the appearance of the five-channel radiometric receiver.

A frequency of 830 MHz with a bandwidth of 100 MHz was selected as the central operating frequency of the 40-cm F_1 radiometric receiver and a frequency of 1420 MHz with a bandwidth of 200 MHz was selected as the central frequency for the 20-cm F_2 receiver. The radiometric receiver is a direct amplification receiver, in which the input signals from five applicator antennas are switched, signals received by the antenna in the working frequency band are amplified and filtered, and detection, filtering and amplification to a predetermined level are carried out. The input switch of the input channels is implemented on an HMC252QS24 microcircuit from Hittite Microwave Corporation (USA) on an Arlon AD-1000 dielectric board from Arlon Materials for Electronics (USA) with low dielectric loss ($\tan\delta = 0.0023$). The low-noise

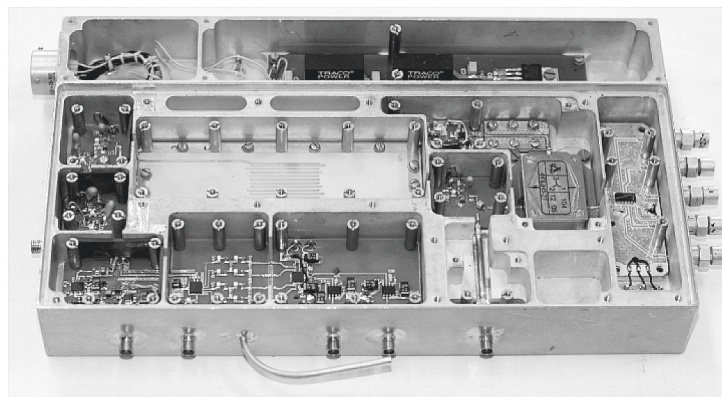


Fig. 2. External view of five-channel radiometric receiver implemented in HIC with partial use of MIC.

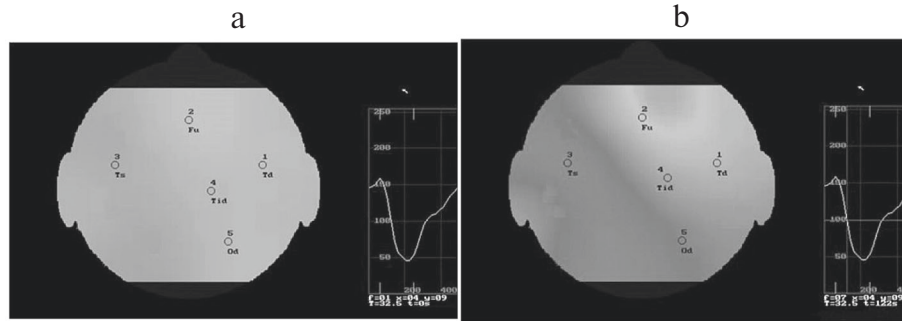


Fig. 3. Results of an experimental study of the human head at frequencies F_1 (a) and F_2 (b).

amplifiers are based on MGA-62563 chips from Agilent (Hewlett-Packard, USA). A microwave bandpass noise filter is installed after the first low-noise amplifier, which essentially eliminates the effects of losses in the filter on receiver sensitivity. An AD8362 chip from Analog Devices (USA) was used as a detector, operating in the range from 50 Hz to 3.8 GHz, with highly stable characteristics over a wide temperature range. The output amplifier of the module is based on AD8000 and AD8002 differential amplifiers from Analog Devices (USA), with a wide bandwidth and high common-mode rejection ratio.

Figure 3 shows the results of measurements of the thermal field of the human head at frequencies F_1 and F_2 obtained using the 5-channel dual-frequency radiograph shown in Fig. 2. The ability to make simultaneous measurements of internal temperatures at different points of the body significantly expands the range of diseases which can be detected, while measurement using multiple frequency ranges allows more accurate localization of the pathological process in depth. This provides information on the characteristics of the temperature distribution in depth by building layered images or three-dimensional temperature fields.

The MT method can be used where other methods are difficult or impossible: in space, the Arctic, forensic medicine, sports, as wearable devices, including in personalized medicine. Astronauts, athletes, firefighters, military personnel, and sailors working in difficult conditions and on active training can have abnormal temperatures, leading to hypothermia, hyperthermia and heat stroke, necessitating monitoring of internal temperatures.

Conclusions

This report presents a study on the combination of multiple channels and multiple frequencies in a radiomet-

ric device. The use of MIC with small interference-resistant broadband antennas will in the future allow creation of less cumbersome radiometer circuits that can find wider commercial applications.

When used as supplementary devices, MT can increase the informativeness of investigation protocols in combination with X-ray and ultrasound diagnostics for detecting diseases at an early stage of development. It should be noted that MT investigations are cheaper than magnetic resonance imaging. Particularly valuable is the fact that MT can be used to diagnose early inflammatory processes that can progress into more serious diseases.

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