UDC 621.3

Expansion of measurement capabilities of the bolometric sensor of the terahertz wave power based on an inexpensive and stable measuring system

M. Wojciechowski [1], K. Hovorova [1], P. Zagrajek [2]

[1] *Central Office of Measures, Elektoralna Str., 2, 00-139, Warsaw, Poland*
marcin.wojciechowski@gum.gov.pl; kateryna.hovorova@gum.gov.pl
[2] *Military University of Technology, gen. Sylwestra Kaliskiego Str., 2, 00-908, Warsaw, Poland*
przemyslaw.zagrajek@wat.edu.pl

Abstract

The paper discusses the results of a joint work of the Central Office of Measures in the Republic of Poland and the Military University of Technology in Warsaw within the framework of the project "Measurement Consistency in Electromagnetic Power Measurements in the Sub-THz Band". The main problems in the study of electromagnetic radiation power in the terahertz range using a bolometric detector are considered. The design and parameters of the measuring system based on the use of a resistive bolometric detector, own signal amplifier, and measuring converter, which were designed and implemented at the Central Office of Measures in the Republic of Poland, are described. The results of metrological traceability to the SI units are presented. This paper is dedicated to expanding measurement capabilities of the bolometric detector based on a highly stable and inexpensive measuring system in the terahertz range. As a result of the joint work, a measuring system characterized by high parameter stability and a gain of more than 20 000 V/V was developed and tested.

Keywords: terahertz range; measuring system; bolometric detector; signal amplifier; electromagnetic radiation power.

Received: 13.05.2024 Edited: 31.05.2024 Approved for publication: 04.06.2024

Introduction

Based on the announcement of November 2, 2021, the Minister of Education and Science of the Republic of Poland has initiated a program called "Polish Metrology".

The program provides support for the implementation of projects aimed at increasing the level of research capabilities of metrological institutions, strengthening intellectual capital, increasing the competitiveness of the Polish economy in strategic areas for the country, developing modern technologies, stimulating the development of metrology, in particular in the fields of healthcare, environment, energy and advanced measurement methods, as well as the development of digital technologies.

The Central Office of Measures in the Republic of Poland and the Military University of Technology in Warsaw participated in the above program with a project entitled "Measurement Consistency in Electromagnetic Power Measurements in the Sub-THz Range" in Section 3 "Development of the Concept of a Terahertz Radiation Sensor based on a Bolometric Detector".

A bolometer is a sensitive thermometer, which electrical resistance varies with temperature, and which is used for detecting and measuring feeble thermal radiation and is especially adapted to the study of infrared spectra [1].

The main component of the bolometer is a thin plate painted black to increase the absorption coefficient of radiation. Due to its small thickness, the plate heats up quickly being exposed to the radiation and its resistance increases. To measure small deviations in the resistance of the plate, the latter is included in a measuring bridge that is balanced in the absence of illumination.

A semiconductor bolometer consists of two thermistors. One of the thermistors is active, directly exposed to irradiation. The second is a compensation thermistor. It is shielded from external radiation and is designed to compensate for changes in the ambient temperature. Both thermistors are placed in a common sealed housing.

The bolometer is sensitive to the entire spectrum of radiation. However, it is mainly used in astronomy to record radiation with submillimeter wavelengths (intermediate between ultra-high-frequency radiation and infrared). For this range, the bolometer is the most sensitive sensor. The source of thermal radiation can be the light of stars or the Sun, which has passed through the spectrometer and decomposed into thousands of spectral lines, each of which has a very low energy.

The main problem with measurements using bolometric detectors, especially in wide ranges (e.g., terahertz), is the significantly small output signals. The joint work of the Central Office of Measures in the Republic of Poland and the Military University of Technology in Warsaw within the framework of the project entitled "Measurement Consistency in Electromagnetic Power Measurements in the Sub-THz Band" is dedicated to solving this problem.

Analysis of recent research and publications

A bolometric detector is an instrument for broadband measurement of electromagnetic radiation power, usually equipped with a pair of temperature transducers, where one transducer compensates for the effects of ambient temperature and in the other, the electromagnetic radiation energy is absorbed and converted into heat, which changes the temperature of the transducer. The temperature difference between the transducers measured over a period of time is a measure of radiation power.

It was invented by American astronomer Samuel Langley in 1878 [2]. At that time, the two temperature transducers were the legs of the Wheatstone Bridge. At that time, amplifying components such as transistor or operational amplifier were not yet known, not even tube amplifiers invented in 1906, and yet the inventor, using a precise galvanometer on the diagonal of the bridge, received a sufficient signal to detect a cow passing on the objective axis line from a distance of about 0.5 km [3].

The development of electronics has made it possible to amplify the measurement signal, but both tube and transistor amplifiers generated electrical noise that significantly reduced the measurement accuracy. Mass production of operational amplifiers with minimized temperature drift of parameters and elimination of flicker noise has only recently begun, having opened new prospects for designing precision measuring instruments.

Currently, measuring transducers for use in the terahertz range are manufactured using nanotechnology [4–6]. Due to financial limitations of the project, it was not possible to develop a measuring transducer using this technology. In this project, compared to the above-mentioned work, it was decided to expand the frequency measurement range from 100 GHz to several hundred THz, possibly dividing it into two sub-bands depending on the waveguides used. It was decided to use transducers made using SMD and THT technologies with a conversion factor in the range of several mW/K, which, with a one percent measurement resolution and four percent transducer sensitivity, makes it necessary to measure a voltage difference of 5 μV (R_T = 10 kΩ, I_R = 100 μA, P_r = 1 mW).

Description of the construction of the measuring system for the bolometric detector of electromagnetic radiation

In this task, it was decided to manufacture two bolometer heads. The first one is with waveguides made of insulating materials, operating in the frequency range up to 1 THz, and the second one is with metal waveguides, operating with a WM-250(WR1.0)DH cone antenna manufactured by VDI to measure the power of electromagnetic radiation sources above 1 THz. The scheme of a bolometer head with metal waveguides is shown in Fig. 1.

The following terahertz radiation sources are available that operate on this principle:

- multiplication of gigahertz signals up to about 1 THz with a power of about 1 mW,

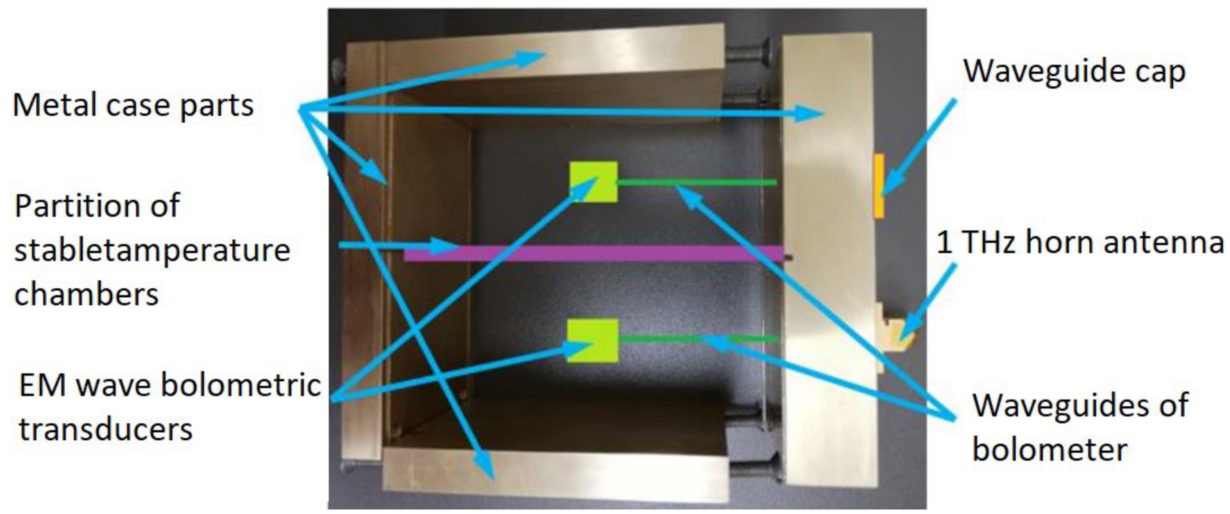

Fig. 1. Scheme of a bolometer head with all components

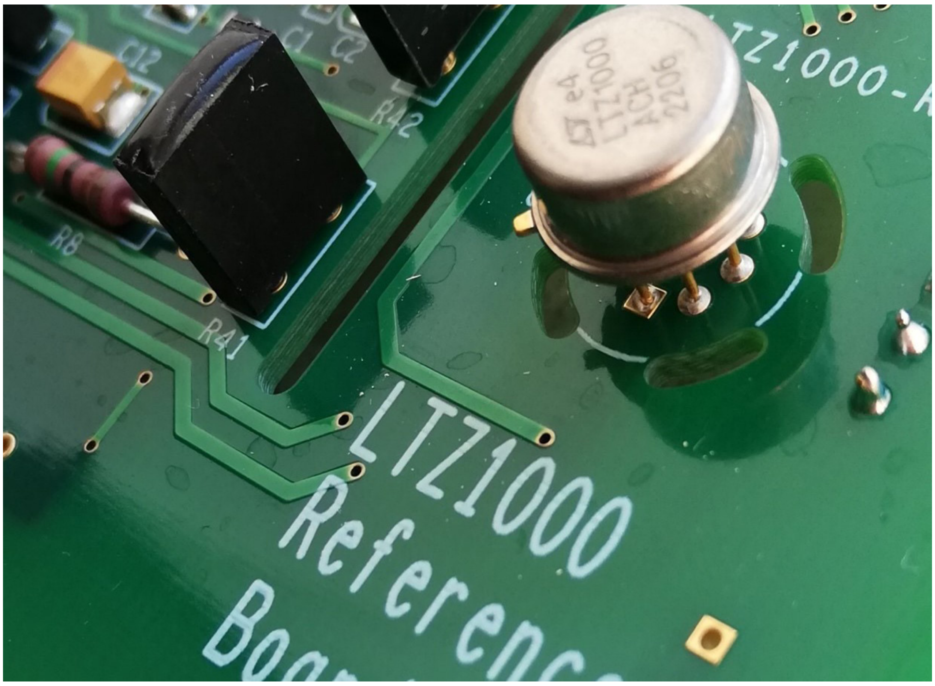

Fig. 2. Exterior view of the LTZ1000 integrated circuit [7]

• quenching of laser fluxes up to several terahertz with a power of several μW.

Due to the low signal power of terahertz generators, it was decided to make the measuring system of the bolometric electromagnetic radiation detector with optimal amplification of the measuring signal based on modern commercially available integrated circuits.

The measuring system of the bolometric electromagnetic radiation detector consists of five components:

1) A DC reference voltage source.
2) Two identical voltage/current converters.
3) Differential amplifier.
4) Output amplifier.
5) Power supply.

Description of the DC voltage reference source

Each measuring instrument shall be traceable to a reference. This can be an internal or external reference. The measuring system under consideration uses an internal voltage reference.

The internal voltage reference in the measuring system of the bolometer detector is based on the LTZ1000 integrated circuit, which is shown in Fig. 2.

The LTZ1000 is a high-precision, ultra-stable Zener voltage reference originally developed by Carl Nelson for Linear Technology (now Analog Devices) [8, 9].

This chip has four components in its case: two control transistors, a heating element, and a high-stability Zener diode with a voltage of ~7 V.

The diode has the following parameters: temperature drift – 0.05 ppm/K, noise – 1.2 $\mu V_{p\text{-}p}$ and long-term stability – 2 μV/√kh. The circuit for the temperature stabilization and raising the reference voltage to 10 V is based on two dual ADA4077 operational amplifiers (maximum 0.25 μV/K, 6.9 nV/√Hz, type 0.5 μV/10kh) [10]. The main characteristics of the ADA4077 operational amplifier are shown in Fig. 3.

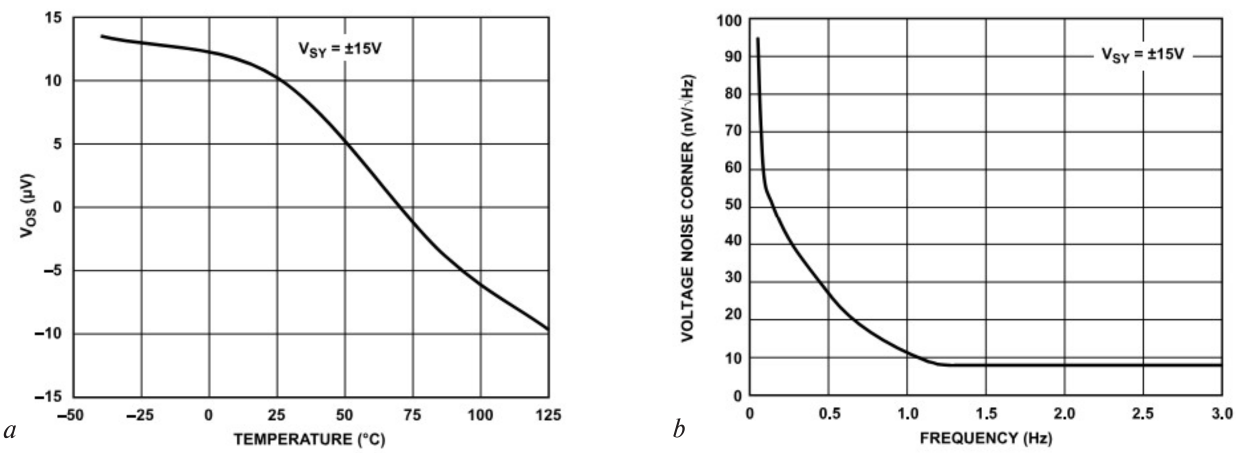

Fig. 3. Dependence graphs of the operational amplifier ADA4077 [10]: *a* – offset voltage (V_{OS}) vs temperature, *b* – voltage noise corner vs frequency

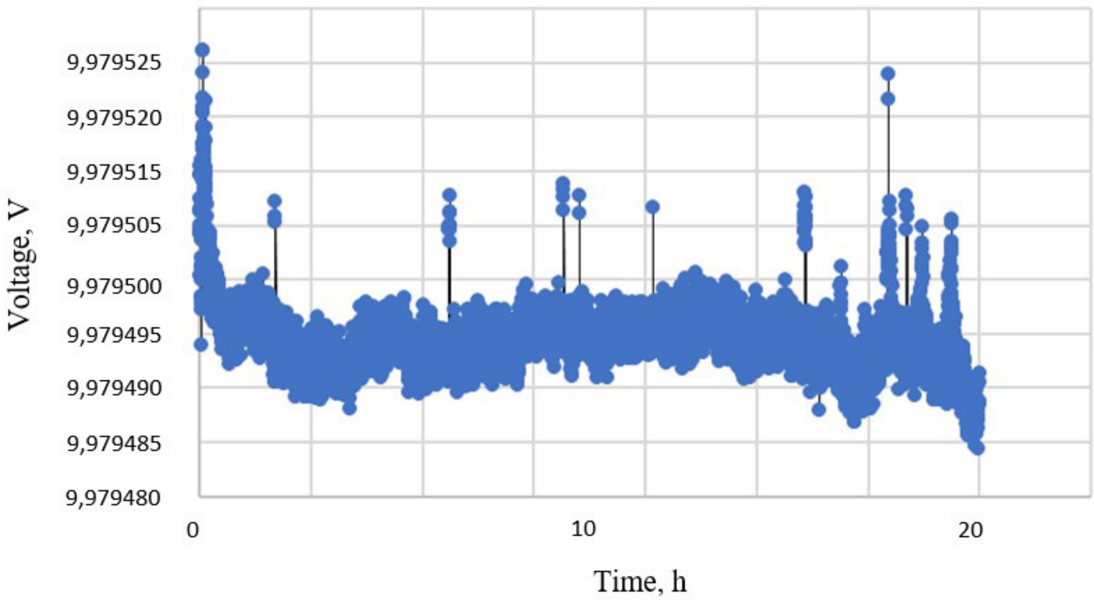

Fig. 4. Illustration of seven thousand results of measuring the reference voltage of the measurement system for the bolometric detector, performed every 10 seconds

When the component is powered by a +/– 15.00 V symmetrical power supply and a Keithley Type 2000 digital multimeter is used, the source reference voltage is 9.97951 V with a stable display of six significant digits. The change in the reference voltage over time is shown in Fig. 4 (the installation was not in a shielded enclosure).

Description of voltage to current converters

The two identical voltage converters that convert reference voltages into current to power resistive temperature sensors were manufactured using 100 kΩ precision resistors with a tolerance of 0.01% and a temperature coefficient of 2 ppm/K, as well as extremely accurate, low noise, low temperature drift of the MAX44251 type. The main feature of this type of operational amplifiers is the use of autocorrelation zeroing technology, which provides continuous measurement and compensation of input offset, time and temperature drift, and the influence of 1/f noise [10].

The current of ~100 μA from the current sources thus created flows through two temperature transducers, one of which emits the power of the measured electromagnetic wave. The temperature difference between the two transducers is fed back to the operational amplifiers and produces a voltage signal at their output, which is then transmitted to a differential amplifier.

Description of the differential amplifier and output amplifier

So far, the design of amplifiers with such high resolution has been based on methods developed for measuring electrical noise [11]. Today, thanks to new technologies for manufacturing integrated operational amplifiers (Low Noise Zero-Drift), they can be used in the first stage of an amplifier. In this project, the differential amplifier is constructed from three MAX44251 operational amplifiers described above and precision resistors with a tolerance of 0.01% and a temperature coefficient of 2 ppm/K.

There are two stages in the amplifier: the first with a 21 V/V gain and the second with a 10 V/V gain. The output of the differential amplifier is the output to the outside of the case via a BNC connector and fed to the next final stage of the amplifier.

The last amplification stage, the final output amplifier, is based on the ADA4523-1 operational amplifier with the following parameters: noise voltage spectral density of 4.2 nV/√Hz at 1 kHz and its peak-to-peak value of 88 nV_{P-P} (from 0.1 Hz to 10 Hz), with is TCVOS = 10 nV/K (maximum) [10]. The gain of this stage is 101 V/V, and the output signal is fed to the second BNC connector.

Description of the power supply

To power the measuring system, three options were implemented: from two stationary laboratory regulated symmetrical power supplies; from the Eco-Line 20C 7.4 V 2.4 Ah lithium-polymer battery; from an internal battery – for less accurate measurements with voltage converters. The latter power supply option consists of a 230 V/24 V DC power supply, two 24 V DC to +/– 12 V and +/– 15 V symmetrical voltage converters, voltage ripple suppression filters, and positive and negative voltage stabilizer chips.

Results

A model of a measuring transducer for use in the terahertz range with a previously described measuring

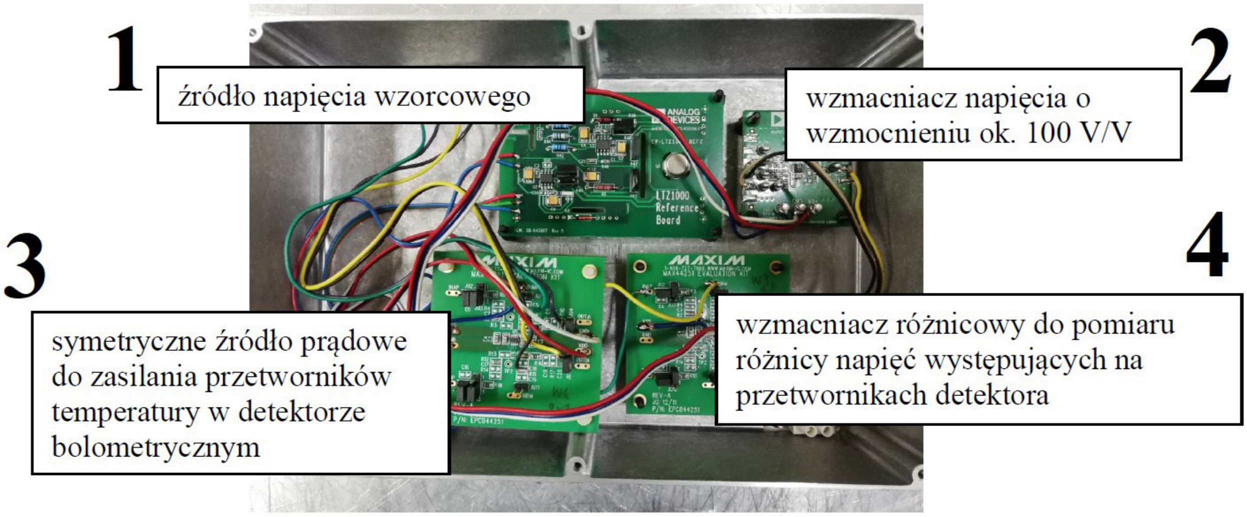

Fig. 5. Arrangement of electronic components of the measurement system for the bolometric detector in the housing where: 1 – reference voltage source; 2 – voltage amplifier with a gain of ~100 V/V; 3 – symmetrical current source to power the temperature transducers in the bolometer detector; 4 – difference amplifier for measuring the voltage difference occurring on the detector transducers

circuit for use with a resistive bolometric detector for measuring the power of electromagnetic radiation in the terahertz range was manufactured based on prototype printed circuit boards of the integrated circuit manufacturers listed in the above description. The components used in the device made it possible to ensure high stability of the voltage source, current sources, and amplification circuits.

The differential signal gain of the entire measuring system is 21210 V/V. To minimize noise, the bandwidth of the amplification unit was limited to 2 Hz (3 dB). This limits the output noise of the instrument to a value of 1.2 mVn(RSM), and allows for a stable reading of three to four significant digits, depending on the head used, with the digital multimeter mentioned above.

Fig. 5 shows a photograph of the arrangement of electronic components of the model of a measuring system of the bolometric electromagnetic radiation detector made as a result of joint work of the Central Office of Measures in the Republic of Poland and the Military University of Technology in Warsaw within the framework of the project "Measurement Consistency in Electromagnetic Power Measurements in the Sub-THz Band".

Conclusions

The work resulted in the development and testing of a measuring system characterized by high parameter stability and a gain of more than 20 000 V/V.

The main problem with measurements using bolometric detectors in wider ranges is the significantly small output difference signals. A popular solution to this problem is the use of high-speed and highly stable signal amplifiers and measuring transducers for the terahertz range based on nanotechnology, which are very expensive. The paper describes the design and parameters of a measuring system for studying the power of electromagnetic radiation in the terahertz range based on the use of a resistive thermistor bolometric detector, own made signal amplifier and a measuring converter based on inexpensive publicly available elements that were implemented at the Central Office of Measures in the Republic of Poland.

Acknowledgement

This work was financed by the Polish state budget under the program of the Minister of Education and Science "Polska Metrologia project" no. PM/SP/0042/2021/1, financing amount PLN 744128, total project cost is PLN 744128.

Розширення вимірювальних можливостей болометричного давача потужності терагерцових хвиль на основі недорогої та стабільної вимірювальної системи

М. Войцеховскі[1], К. Говорова[1], П. Заграєк[2]

[1] *Центральна служба мір та ваг, вул. Електоральна, 2, 00-139, Варшава, Республіка Польща*
marcin.wojciechowski@gum.gov.pl; kateryna.hovorova@gum.gov.pl
[2] *Військова технічна академія, вул. генерала Сильвестра Каліскєго, 2, 00-908, Варшава, Республіка Польща*
przemyslaw.zagrajek@wat.edu.pl

Анотація

У статті розглядаються результати спільної праці Центральної служби мір та ваг у Республіці Польща та Військової технічної академії у Варшаві в рамках проєкту "Узгодженість вимірювань при вимірюваннях електромагнітної потужності в суб-ТГц діапазоні". Наведений проєкт реалізовується на основі програми Міністра освіти та науки Республіки Польща "Польська метрологія". Розглянуто основні проблеми при дослідженнях потужності електромагнітного випромінювання терагерцового діапазону за допомогою болометричного детектора. Описано конструкцію та параметри вимірювальної системи для дослідження потужності електромагнітного випромінювання терагерцового діапазону, що базується на високостабільних вимірювальних перетворювачах. Наведену в статті систему розроблено на основі використання резистивного болометричного детектора, власної продукції підсилювача сигналу та вимірювального перетворювача, що були спроєктовані та реалізовані в Центральній службі мір та ваг у Республіці Польща. Наведено результати метрологічної простежуваності до одиниць SI. Основною проблемою при вимірюваннях із використанням болометричних детекторів у ширших діапазонах є значно малі вихідні сигнали різниці. Цю проблему можна розв'язати за допомогою вискоточних та високостабільних підсилювачів сигналу й вимірювальних перетворювачів. Але наразі вимірювальні перетворювачі для застосування в терагерцовому діапазоні виготовляються з використанням нанотехнологій, що є дуже дорогими. Роботу присвячено розширенню вимірювальних можливостей болометричного детектора на основі високостабільної та недорогої вимірювальної системи в терагерцовому діапазоні. У результаті спільної праці було розроблено й протестовано вимірювальну систему, що характеризується високою стабільністю параметрів і коефіцієнтом підсилення понад 20 000 В/В.

Ключові слова: терагерцовий діапазон; вимірювальна система; болометричний детектор; підсилювач сигналу; потужність електромагнітного випромінювання.

References

1. Available at: https://www.merriam-webster.com/dictionary/bolometers
2. Available at: https://collection.sciencemuseumgroup.org.uk/objects/co2578/langleys-bolometer-1880-1890-bolometer-measuring-device-radiant-energy
3. Langley S.P. The Bolometer and Radiant Energy. *Proceedings of the American Academy of Arts and Sciences*, vol. 16 (May, 1880 – Jun., 1881), pp. 342–358. doi: 10.2307/25138616
4. Erickson N. A fast and sensitive submillimeter waveguide power meter. *Proc. 10th Int. Symp. Space Terahertz Technology*, 1999, pp. 501–507.
5. Erickson N. A fast, very sensitive calorimetric power meter for millimeter to submillimeter wavelengths. *Proc. 13th Int. Symp. Space Terahertz Technology*, 2002, pp. 301–307.
6. Anbinderis T., Anbinderis P., Usoris A.-V., Bagdonaite P. et al. Waveguide-based calorimeter for terahertz frequency range. *Electronics Letters*, 2007, vol. 43, issue 14, pp. 759–760. doi: 10.1049/el:20071299
7. Available at: https://commons.wikimedia.org/wiki/File:Keysight_34470A_Multimeter_Teardown.jpg#/media/File:Keysight_34470A_Multimeter_Teardown.jpg
8. Available at: https://www.analog.com/media/en/technical-documentation/data-sheets/LTZ1000.pdf
9. Available at: https://www.electronicdesign.com/technologies/analog/article/21805566/an-interview-with-analog-guru-carl-nelson
10. Available at: https://www.analog.com/en/product-category/fully-differential-amplifiers.html
11. Achtenberg K., Mikołajczyk J., Bielecki Z. FET input voltage amplifier for low frequency noise measurements. *Metrology and Measurement Systems*, 2020, vol. 27, no. 3, pp. 531–540. doi: 10.24425/mms.2020.132785