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Development and Testing of a Device for Regulation and Stabilization of Powerful Millimeter Radiation

M. V. Kamenskiy[a],*, M. A. Koshelev[a], A. A. Orlovsky[a,b], A. S. Sedov[a], S. A. Skorokhodov[c], and A. I. Tsvetkov[a,b]

[a] *Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 603950 Russia*
[b] *Volga State University of Water Transport, Nizhny Novgorod, 603950 Russia*
[c] *Institute of Applied Physics, Russian Academy of Sciences, Young Researcher School, Nizhny Novgorod, 603950 Russia*
**e-mail: mkamenskiy@ipfran.ru*

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Abstract—The results of the development and experimental implementation of a device for controlling the parameters of high-power microwave radiation, the principle of operation of which is based on the controlled rotation of the polarizing plate in a plane perpendicular to the linearly polarized microwave beam propagation axis are presented. Stabilization of the power of a subterahertz gyrotron at a level of several percent in a wide range of tuning of control parameters is experimentally demonstrated. The developed device can be successfully used to solve a number of problems aimed at studying the interaction of high-power microwave radiation with matter.

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INTRODUCTION

Currently, electromagnetic radiation in the terahertz range is increasingly used in various physical, technological, chemical, and biological problems, including diagnostics and studies of interaction with various media [1–3]. Modern gyrotrons are capable of providing a very high (hundreds of watts at frequencies up to 1 THz) output power level, which makes them very attractive devices in this frequency range [4–6]. In this case, some of the problems mentioned above impose additional requirements on the operating modes of gyrotron complexes. In particular, for successful and accurate studies on high-resolution microwave spectroscopy [7], it is necessary to ensure the stabilization of the output power when the control parameters are tuned (the current and accelerating voltage of the electron beam, the magnetic field of the main solenoid and cathode coil, the temperature of the resonator-cooling liquid, etc.) [8]. The main problem is that when these parameters are tuned, both the output frequency and the power of the gyrotron change simultaneously [9]. In this case, it is possible to provide power stabilization, including using a feedback system and appropriate devices. This paper describes an automated device based on a polarizer based on this principle for stabilizing the power of microwave radiation and presents the results of experiments.

DESCRIPTION OF THE EXPERIMENTAL SETUP

The radiation source was an automated gyrotron complex developed and manufactured at the Institute of Applied Physics of the Russian Academy of Sciences (Nizhny Novgorod, Russia) jointly with ZAO NPP GIKOM (Nizhny Novgorod, Russia). At this complex, tests and studies of a number of continuous and pulsed gyrotrons are currently being carried out. The device described was tested on two of them: on a gyrotron operating at the fundamental cyclotron harmonic with a frequency of 0.26 THz and a maximum output power of 1 kW (operating mode TE_{53}) [10] and on a gyrotron operating at the second cyclotron harmonic with a frequency of 0.53 THz with a maximum output power of 240 W (operating mode TE_{65}) [11]. Each of the gyrotrons has its own built-in high-performance quasi-optical converter of the operating mode into a narrow output Gaussian wave beam. In such a design of the gyrotron, the reflected radiation is scattered during the passage of the quasi-optical converter in the opposite direction, which, among other things, prevents the influence of the signal reflected from the polarizer on the gyrotron's operation mode.

ATTENUATOR DESIGN

Since the output radiation of the gyrotron, formed by a quasi-optical converter [12], is linearly polarized,

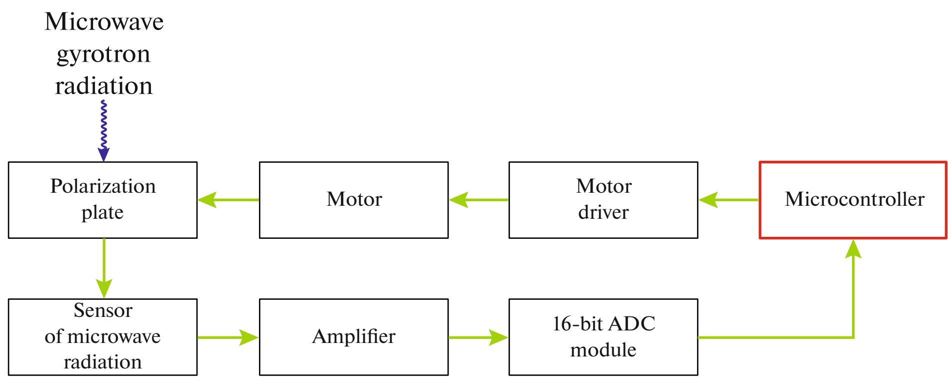

Fig. 1. Functional diagram of device.

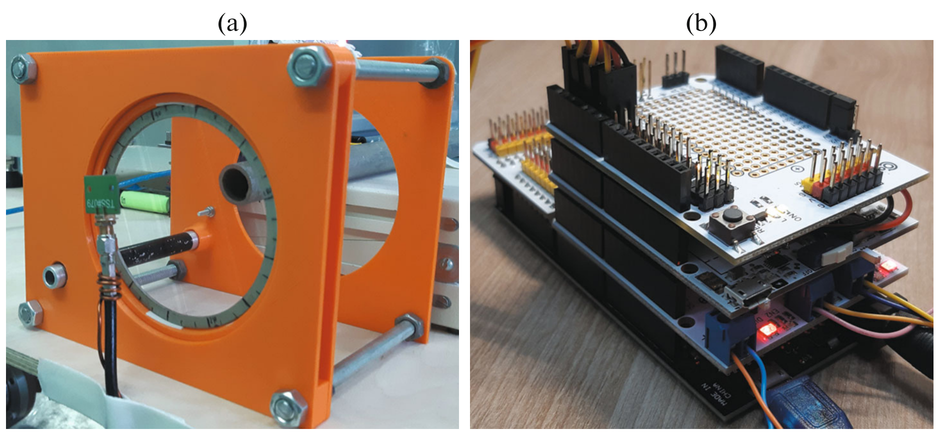

Fig. 2. Photos of the (a) device body and (b) control unit.

a device for controlling and stabilizing the power (attenuator) can be implemented on the basis of a polarizer. The design of the polarizer are stretched at an equal distance, parallel, thin—compared with the wavelengths used—metal wires made of tungsten, which is a refractory material.

Some of the experiments were carried out at a power of the wave incident on the polarizer on the order of several hundred watts with a beam width of 1.5–2 cm in the continuous mode. At this power level, no destruction or deformation of the polarizer elements or a significant increase in its temperature was observed. Also, in preliminary experiments, the radiation power passing through the polarizer was measured as a function of the angle of rotation of the polarizer. The minimum value of this power was within the error of the calorimeter, which indicated the correct operation of the polarizer. The maximum value of the transmitted power also differed from the initial value by an order of magnitude of the measurement error, which made it possible to neglect the radiation absorbed in the polarizer in further estimates. By turning the plate in a plane perpendicular to the beam propagation axis, one can smoothly control the radiation power passing through the polarizer.

The attenuator used in this work for controlling the radiation power consists of several main structural and software elements: a housing with a rotary mechanism and a polarizer, a microwave radiation sensor, and a programmed microprocessor unit. The functional diagram of the device is shown in Fig. 1.

The body of the device (Fig. 2a) is a rectangular parallelepiped 130 × 165 × 140 mm in size, consisting of three plastic panels with large central holes, four metal screw studs, a shaft (metal tube), and two plastic gears fixed between the plastic body panels. The dimensions of the case are primarily determined by the dimensions of the polarizer and the stability of the structure. The stepper motor is fixed on one of the panels of the device.

The operation of the device is as follows. The rotation of the stepper motor shaft drives the main shaft of the device, which rotates the small gear. The rotation of the latter sets in motion a large gear, inside of which is a polarizer. As a result, the tilt angle of the polarizer changes, which makes it possible to control the linearly polarized power of the gyrotron radiation passing through it. The plastic elements of the device (plates and gears) are modeled and manufactured using additive technologies, taking into account the dimensions of the polarizer.

The device was controlled and configured, and also communicated with a computer, using a control unit (Fig. 2b), which contains a board with a microprocessor, a board with a stepper motor driver, and an expansion board for convenient connection of LED indication and other peripherals. The device was powered by a 12 V DC power supply.

The core of the control unit was the Arduino Mega 2560 R3 platform, built on the basis of an eight-bit microcontroller of the AVR family, ATmega2560, operating at a frequency of 16 MHz and having 8 KB of RAM.

IMPLEMENTATION OF THE SOFTWARE PART OF POLARIZER CONTROL

The program developed for this device made it possible to measure the signal level from the microwave radiation sensor, process incoming data based on proportional-integral-derivative (PID) algorithm regulator [13] and issue a control signal to the stepper motor driver to rotate the polarizer in a certain direction. The device also provided manual control of the speed and direction of rotation of the polarizer using a remote control. The program code made it possible to overwrite at any time the value of the signal level, relative to which stabilization would be carried out, and turn on or off the automatic operation mode of the device. All functions of the device could be activated using the remote control and see the status of their work using LED indication.

Microwave radiation that hit the microwave radiation sensor was amplified and entered the input of a 16-bit analog-to-digital converter, where it was processed and sent to the microprocessor unit using the I2C protocol. Received data using programs were smoothed by the "moving average" filter, and then processed using the PID-controller algorithm with feedback. During this process, the mismatch signal or error ($e(t)$) and its differential and integral components were calculated. Then these components were multiplied by experimentally selected coefficients (K_p, K_i, K_d) and summed up. The resulting sum was the value of the control signal ($u(t)$):

$$u(t) = P + I + D = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de}{dt}. \quad (1)$$

The range of control signal values was limited by software.

The total time of one cycle of measurements, calculations, and data processing took approximately 10 ms.

Next, the control signal was sent to the stepper motor driver, which made the required number of steps in the right direction. This directly affected the position of the polarizer; its angle of inclination with respect to the plane of polarization. Turning the polarizer, in turn, made it possible to stabilize the power of the radiation incident on the sensor and calorimeter. One step of the engine was carried out in 50 μs. It should be noted that it is advisable to set the polarizer to an intermediate position with an inclination angle of 45° relative to the plane of polarization. This position allows one to both increase and decrease the transmitted power when you turn the polarizer.

Bringing the polarizer to its original position and limiting the rotation angle (based on the number of steps counter), which does not allow exceeding the specified one, were implemented in software. The program also allowed one to overwrite at any time the value of the specified power level relative to which the adjustment will be carried out.

EXPERIMENT PROCEDURE

The general scheme of the experiment is shown in Fig. 3. The output radiation of the gyrotron fell on the splitter, and its main part (approximately 90%) was transported to the calorimeter, while the calculated power level was several hundred watts. This made it possible to ensure the safety of equipment and personnel during the experiments since the design of the device used in these demonstration experiments was not equipped with a shield or some kind of protective casing.

The rest of the radiation (approximately 10%) passed through the polarizer; part of it hit the calorimeter designed for low power [14] and part of it hit the microwave radiation sensor located nearby. The calorimeter used here was developed at the Institute of Applied Physics, Russian Academy of Sciences, on the basis of two high-precision temperature sensors, a flowmeter designed for an extremely small liquid flow, and a microprocessor unit. The temperature sensors are integrated into a specially shaped plastic case manufactured using photopolymer 3D printing technologies. The architecture of the calorimeter case contributes to the maximum absorption of the gyrotron radiation, which, together with a number of other advantages, makes it possible to achieve high sensitivity and measurement accuracy of low radiation powers.

The data from both calorimeters were transferred to a computer. The radiation received by the sensor located behind the polarizer and included in the feedback loop was converted into a digital signal (straight green lines), which was transmitted to the polarizer position control unit. The control unit data also entered the computer.

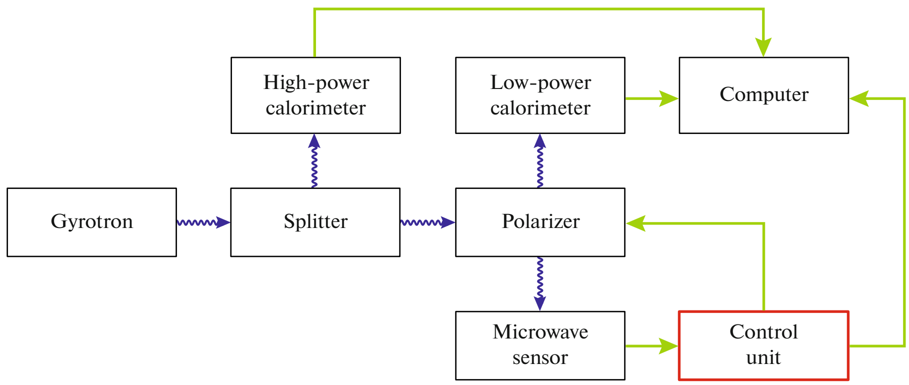

Fig. 3. Scheme of experiment.

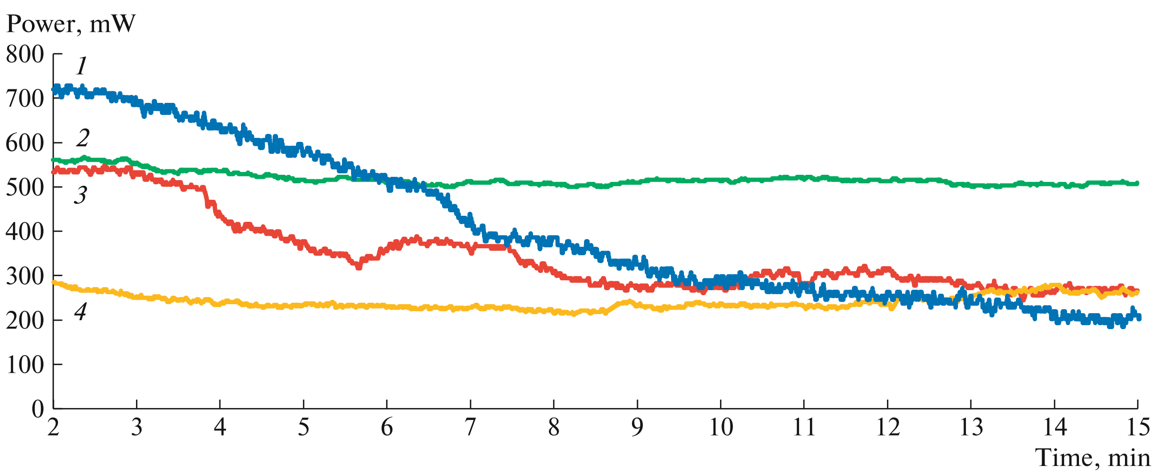

Fig. 4. Graph of power measurement with a calorimeter: *1*—without polarizer; *2*–*4*—with polarizer and included adjustment system.

RESULTS

Figure 4 shows graphs of power measurements by the calorimeter. The average radiation power in the experiments was several hundred milliwatts. Curve *1* shows the results of a control measurement without a polarizer. One can see a fairly smooth change in power with time, which is associated with a smooth change in the temperature of the coolant and, as a result, with a change in the transverse dimensions of the resonator, leading to a change in frequency. Curves *2*–*4* show the plots of power measurements by a calorimeter with a polarizer and the PID control system turned on are shown for various values of the PID controller coefficient and a small change in the position of the calorimeter relative to the trajectory of the wave beam. The best level of stabilization corresponds to the curve *2*; in this mode, the radiation power was stabilized at a level of approximately 9%, which satisfies the requirements of many possible applications

CONCLUSIONS

The developed device for stabilizing the power of microwave radiation based on a polarizer was tested using a subterahertz gyrotron stand. It is demonstrated that the output radiation of the gyrotron is stabilized with an accuracy acceptable for spectroscopic problems. The described device can be effectively used in other tasks that require control of the parameters of high-power microwave radiation.

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