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ELECTRONICS AND RADIO ENGINEERING

A Broadband Microwave Calorimeter of Large Cross Section

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Abstract—A flat calorimeter of large cross-sectional area (1200 cm^2) designed to measure 3–60-GHz single-pulse microwave energy ranging from 0.025 to 500 J is described. Ethanol is used as the essential material of the calorimeter, and the quantity measured is the increment in its volume that results from heating by the absorbed microwave energy. The calorimeter is installed outside a vacuum volume to measure the total energy of a microwave pulse. The absorption coefficient is 0.88 ± 0.09 in the 4.5–53.5-GHz frequency band. The calorimeter can be used as an attenuator of large cross section with an attenuation coefficient of 10–30 dB.

The recently developed, pulsed microwave oscillators employing high-current relativistic electron beams are the most powerful sources of pulsed radiation. Typically, they operate in the single-pulse mode at frequencies varying from 1 to 50 GHz (depending on the oscillator type) with pulse duration ranging from 10 to 100 ns, radiation power from 10 MW to 2 GW, and pulse energy from 10^{-1} to 10^2 J. Usually, the radiation is transmitted into free space through a horn and a dielectric port with a large cross-sectional area (10^2–10^3 cm^2) to preclude microwave breakdown. The use of the conventional instrumentation for measuring the parameters of a microwave pulse requires substantial attenuation of the signal to be performed in the diagnostic circuitry (by ≥ 30 dB). Couplers of large cross-sectional area that are commonly employed for this purpose are highly sensitive to the radiation mode and spectrum. A coupler of this type is difficult to calibrate, even when a narrowband oscillator with fixed output mode is used. In the case of a broadband oscillator complex mode composition, coupler calibration is impracticable, and the oscillator power can be evaluated only within an order of magnitude. More accurate and reliable power measurement can be performed by means of a microwave calorimeter.

In total-power calorimeters specifically designed for high-power oscillators, microwave radiation is absorbed by a cylinder, a cone, or a pyramid made of an appropriate material. To preclude breakdown, the absorber is installed in an oversized waveguide. The quantity measured is the increment in the absorber temperature caused by microwave energy absorption. Because of nonuniform heating, the temperature is measured at several points of the absorber. Prior to evaluation of the total energy absorbed, the system must be calibrated with respect to microwave energy and frequency. The output signals of calorimeters depend on the radiation frequency and mode, even though to a lesser degree than do coupler output signals. Moreover, to preclude microwave breakdown and reduce heat loss by the sensors, calorimeters of this type are kept under vacuum, which makes their coupling with the oscillator somewhat difficult.

In this paper, we describe a calorimeter designed to measure the total energy of a microwave pulse radiated into free space by the horn of a high-power microwave oscillator. The calorimeter is characterized by low sensitivity to the radiation mode and spectrum in the 4.5–53.5-GHz band. The error of microwave energy measurement is determined by the frequency dependence of the absorption coefficient ($K_a = 0.88 \pm 0.09$) and the instrumental error (0.025 J) of the measurement of energy absorbed.

The calorimeter (see Fig. 1) is a cylindrical container 1 cm in height with 1-cm-thick disk-shaped organic-glass walls *1* approximately 40 cm in diameter, filled with commercial ethanol *2*. Dielectric spacers *3* are inserted between the disks to enhance structural rigidity. The quantity measured is the increment in the liquid volume that results from the thermal expansion caused by microwave energy absorption. The calorimeter is installed in free space to intercept the total horn output. If the absorbed energy W scales linearly with the temperature increment ΔT, and ΔT does so with the volume increment ΔV, it is clear that ΔV is independent of the initial liquid volume V and the distribution of energy W over the liquid volume. Therefore, a calorimeter can be designed to have large area and thickness, i.e., large absorption coefficient.

This calorimeter can be called absolute in terms of the microwave energy absorbed because the relationship between W and ΔV depends only on the properties of the liquid.

Let us analyze the design requirements that are imposed on the materials used for building a flat calorimeter. We assume that a plane electromagnetic wave

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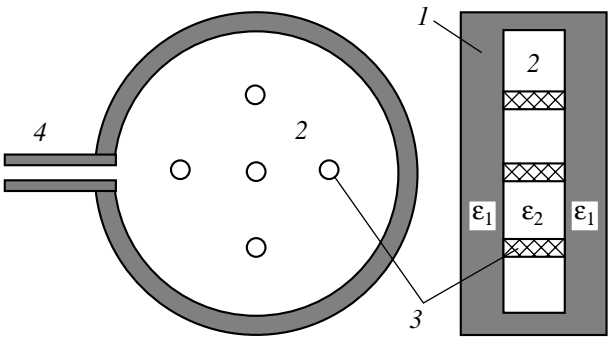

Fig. 1. Schematic of the calorimeter: (*1*) calorimeter walls; (*2*) essential material; (*3*) spacers; (*4*) measurement tube.

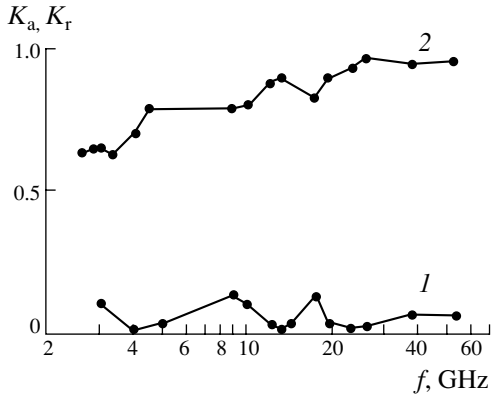

Fig. 2. Frequency response of the calorimeter: (*1*) reflection coefficient K_r; (*2*) absorption coefficient K_a.

travels in the direction perpendicular to a three-layer planar medium (see Fig. 1). An optimum performance is attained when the absorption coefficients K_a of the middle (liquid) layer and walls have, respectively, the highest and lowest possible values, whereas the total reflection coefficient K_r is kept at a minimum value. If ε_1', ε_1'' and ε_2', ε_2'' denote, respectively, the real and imaginary parts of the permittivities of the solid and liquid, then an optimum calorimeter must satisfy the following conditions: $\varepsilon_2' \approx \varepsilon_1'$, $\varepsilon_2'' \approx \varepsilon_2'$, $\varepsilon_1'' \ll \varepsilon_2''$. In addition, the total reflection coefficient can be lowered by minimizing the value of ε_1'.

We did not know the precise values of ε' and ε" in the 3–60-GHz band for the organic glass and ethanol that we used. For this reason, to find the absorption coefficient K_a, we measured the transmission and reflection coefficients, K_{tr} and K_r, for a quasi-plane wave transmitted by a horn in the direction perpendicular to the calorimeter surface. In these measurements, we used low-power, tunable microwave oscillators and thermistor-based power meters. Figure 2 shows the measured reflection coefficient K_r and the absorption coefficient calculated as $K_a = 1 - K_{tr} - K_r$ for the 3–53.5 GHz band. We see that $0.8 \le K_a \le 0.97$ in the 4.5–53.5 GHz band, and K_r and K_a are nonmonotonic functions of frequency. This behavior indicates that $\varepsilon_2' \neq \varepsilon_1'$, and the radiation is reflected by both faces of the front wall of the calorimeter. The minima exhibited by K_r at $f \approx 4$, 13, and 25 GHz imply that reflection by the outer face is similar to reflection by the inner face. This can occur when $\varepsilon_2' - \varepsilon_1' \approx \varepsilon_1'$ or $\varepsilon_2' \approx 2\varepsilon_1'$. The fact that the maximum value reached by K_r somewhat decreases with increasing frequency indicates that both ε_1' and ε_2' are decreasing functions of frequency. According to the fragmentary data on the properties of organic glass and ethanol in the literature, $\varepsilon_1' = 2.3$–2.6, $\varepsilon_1'' = 2.2 \times 10^{-2}$–$1.1 \times 10^{-1}$, ε_2' varies from 6 to 2.5 as the frequency is varied from 3 to 20 GHz, and $\varepsilon_2'' \approx \varepsilon_2'$. These data are consistent with our measurements and estimates.

The key quantity to be measured was the increment in the liquid volume. The measurement was performed by means of a glass tube 2 mm in diameter, which was connected to the calorimeter (see Fig. 3). An increment in the liquid volume resulted in an increment in the length of the liquid column in the tube. The length of the liquid column was derived from the resistance R_2 of the liquid that was in contact with two wires stretched inside the tube. This resistance was measured by means of a bridge circuit. To prevent the liquid in the measurement tube from overheating, we used a pulsed power supply with a pulse duration of 1 ms, amplitude $U_0 = 20$ V, and repetition frequency of 10 Hz. A signal proportional to $R_2 - R_1$ was read out by means of an oscilloscope. It is clear that $R_2 \sim 1/L$, where L is the length of the liquid column in the tube. If L_0 is the column length when the bridge is balanced ($R_2 = R_1$), then the sensitivity of the wire is $\Delta U/\Delta L = U_0/2L_0$, i.e., the sensitivity increases with decreasing L_0. For example, if the initial length is $L_0 = 10$ mm, and $U_0 = 20$ V, the sensitivity is $\Delta U/\Delta L = 1$ V/mm, and the corresponding energy sensitivity of the calorimeter is $\Delta U/\Delta Q = 92.3(U_0/L_0) = 185$ mV/J.

The lowest measurable energy was 0.025 J; this quantity was determined by the scatter (≈ 10 mV) of the wire signal. The nature of the scatter remains unclear; it may be attributed to both the electrical interference and the instability of the liquid volume or calorimeter housing. The highest measurable energy was $Q_{max} \approx 500$ J, which corresponded to the maximum liquid-column length $L = 100$ mm.

High sensitivity of the calorimeter cannot be attained without stabilizing the liquid volume or the initial position of the air–liquid boundary in the tube. This requirement is fulfilled by means of adjustable continuous local

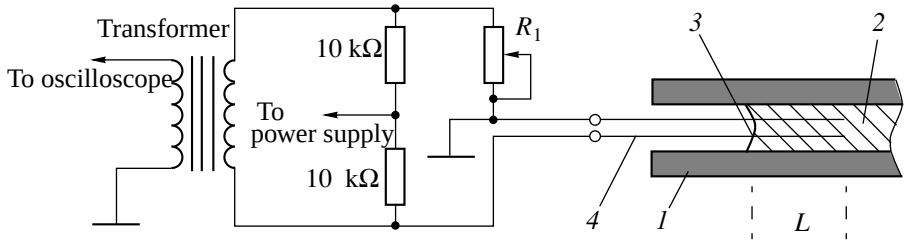

Fig. 3. Schematic of the system for measurement of increment in the liquid volume: (*1*) measurement tube; (*2*) liquid; (*3*) air–liquid boundary; (*4*) wires.

heating of the liquid, preheated to a temperature higher than the ambient temperature. By varying the heating power, the rate of increase in the liquid volume can be either increased or decreased. The optimum heating power corresponds to zero rate. The rate of volume variation instantly responds to a change in the heating power because temperature relaxation across the volume is not required. The liquid was heated by a 10-Ω stainless-steel heating element introduced into the liquid volume.

The measurement was performed as follows. The bridge output signal was read out by an oscilloscope, and the operator manually adjusted the heating power to minimize both the signal amplitude and its drift rate. The microwave oscillator was fired at the operator's command, and the operator measured the new signal amplitude after the signal had settled down. The quantity measured was the difference between the signal amplitudes before and 2–3 s after the firing. The calorimeter was calibrated by using a similar procedure, in which the microwave pulse was simulated by capacitor discharge through the heating element.

The sensitivity of the calorimeter is directly related to the stability of the air–liquid boundary in the measurement tube. The stability of the boundary depends on the stability of the liquid volume and the calorimeter housing, as well as on the exposure of the calorimeter to mechanical disturbance. Thermal insulation of the calorimeter is the best remedy for the instability of liquid volume and calorimeter housing. For example, foam thermal insulation with a layer ~1 cm thick can be used to keep the drift rate of the wire signal within 10^{-3} V/s when the heater current is varied with a 1% step. Since the response time of a calorimetric system subjected to instant heating is about one second, the zero drift does not exceed 1 mV during a measurement cycle and can be taken into account in the calorimetry of low-energy pulses. Since the liquid cooling time is much longer than one minute, it does not affect the measurement accuracy.

To eliminate any mechanical disturbance of the calorimeter by the microwave oscillator, the calorimeter was suspended by ropes fastened to the ceiling without any direct mechanical contact with other equipment. The mechanically induced drift of the air–liquid boundary was thereby made much weaker than its thermal drift in a well heat-insulated calorimeter.

The heater is also used to calibrate the calorimeter with respect to energy. This is done by discharging a capacitor of capacitance $C \approx 300$ μF through the heating element. The energy released in the heating element is varied by changing the voltage applied to the capacitor. The capacitor discharge time is approximately 3 ms, and the heater–liquid energy-exchange time is about 1 s. The discharge can be used to calibrate the diagnostic circuitry as a whole.

A key requirement imposed on the calorimeter is that its internal volume prior to the action of a microwave pulse must be equal to its volume 2–3 s after the pulse is absorbed. For example, when 0.1 J is absorbed, the liquid volume increases by ~0.06 mm^3. For this change in the volume of liquid in the measurement tube to be detected, the calorimeter walls must not be displaced by more than 2×10^{-6} mm. It is clear that this degree of stability of the calorimeter housing cannot be maintained during repeated operation. However, rapid return of the walls (in ~1 s) to the position that they occupied before the pulsed heating of the liquid can be ensured by additionally fixing the walls with five spacers (see Fig. 1). We noted above that the sensitivity of the calorimeter was limited by the scatter (~10 mV) of the wire signal. If the scatter is caused by the jitter of the calorimeter housing, the corresponding wall displacement is 10^{-6} mm. The fact that the scatter of the signal obtained in series consisting of tens of calibration pulses was found to be ~ 10 mV proves that the calorimeter housing settled down with some residual jitter (which corresponds to the lowest measurable energy of 0.025 J). In particular, the signal magnitude was 185 ± 5 mV for L_0 = 10 mm and the heating pulse energy equal to 1 J, which is consistent with its calculated value. Slow variation of the internal volume of the calorimeter, such as that caused by variation of the wall temperature, is offset as the air–liquid boundary is stabilized in the measurement tube. Basically, the stabilization of the boundary implies stabilization of the difference in volume between the liquid and the container.

The strongest effect on the internal volume of the calorimeter is produced by the change in hydrostatic pressure caused by displacement of the air–liquid boundary in the measurement tube. In the calorimeter

described here, this effect is completely eliminated because the measurement tube is set in horizontal position, and the hydrostatic pressure acting on the calorimeter walls does not vary when the air–liquid boundary is displaced. A change in the angular position of the measurement tube leads to a change in the effect of the hydrostatic pressure on the calorimeter volume and, therefore, in the sensitivity of the calorimeter. In particular, the highest sensitivity corresponds to the horizontal position of the measurement tube; when the tube is in vertical position, the sensitivity is lower by a factor of tens.

The calorimeter was used to measure the energy of microwave pulses produced by a broadband relativistic plasma microwave oscillator currently being developed at the Institute of General Physics, Russian Academy of Sciences [3]. By means of this calorimeter, the energy of broadband microwave pulses ~ 50 ns in duration with power ranging from 5 to 300 MW was measured within a 20% error in the 6–30 GHz band. These measurements could not be performed by the conventional methods because of the insufficient stability of the mode and frequency composition of the pulses.

This device was also used to measure the energy of 25-MW, 20-ns, 38-GHz pulses produced by a relativistic cyclotron-resonance maser [4] and 50-MW, 150-ns, 10-GHz pulses produced by a relativistic carcinotron [5]. The results of these calorimetric measurements were within 20% of those of earlier measurements employing calibrated attenuators and detectors.

One advantage of the flat calorimeter is that it can be used as an attenuator of large cross-sectional area without affecting the mode composition of radiation transmitted by a horn of large cross section. Therefore, conventional low-power microwave measurement instrumentation can be used in the near field when placed immediately behind the calorimeter.

The same device can be used in almost any modern experiment with high-power, pulsed microwave generation. However, the calorimeter can be readily modified and adjusted to various experimental conditions by changing its shape and dimensions while retaining its basic advantages, i.e., the measurement of the increment in liquid volume and the broadband operation. In particular, the calorimeter can be modified for use in a waveguide both under vacuum and at atmospheric pressure. If the ε' and ε'' for the solid and liquid dielectrics are carefully measured, the electrodynamic characteristics of the calorimeter can be calculated with high accuracy.

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