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Resistive Sensor for High-Power Microwave Pulse Measurement

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A resistive sensor (RS) devoted to the measurement of a high-power microwave (HPM) pulse is presented. The performance of the RS is based on the electron-heating effect in semiconductors. It can measure HPM pulses directly; it is resistant to large power overloads and demonstrates very good long-term stability. The RS can produce an output signal of the order of a few tens of volts without any amplification circuit, and it can measure nanosecond-duration HPM pulses. Different types of the RS developed, manufactured, and tested in our laboratory are presented. They are the cross-waveguide RS for an intermediate pulse power level, the waveguide-type RS with diaphragm for HPM pulse measurements, the coaxial-type RS for the measurement of microwave pulses in a wide frequency range, and the RS for a millimeter-wave region.

KEYWORDS: Electron heating, High-power microwave pulse measurement, n-Si, Sensors

1. Introduction

High-power microwave (HPM) pulse generators are being intensively studied in laboratories as well as being manufactured by industry. Owing to the increasing growth in the use of HPM sources, their potential threat to electronic equipment should be taken into account. On the other hand, intentional attacks on the electronic infrastructure using an HPM source as a directed energy weapon might be expected, and possible disturbances with fatal consequences for civil and military systems should be considered. Both these trends demand that tests of electronic equipment be performed at higher pulse power levels. This in turn brings forward new requirements for sources and sensors that are used in tests.

Traditionally, calibrated diodes are employed to measure the power of microwave pulses, but they can handle only a very low power level. Therefore, before being measured with the diode the HPM pulse has to be strongly attenuated. An additional attenuation results in a decrease in measurement accuracy. Moreover, problems may arise when measuring a small dc signal from the diode due to the presence of stray pickup and electromagnetic interference, which are typical of the environment of HPM sources. Novel electro-optic measurement techniques[10] can be applied efficiently in the HPM environment, but the external sensitive equipment (such as lasers, polarizers, and other optics) restricts application areas.

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An alternative HPM pulse measurement device, a resistive sensor (RS),[3] helps to overcome these difficulties. The performance of the RS is based on the electron-heating effect in semiconductors. A sensing element (SE) of the RS is placed in the transmission line. The electric field of the HPM pulse heats electrons in the SE; its resistance increases, and by measuring this resistance change, the HPM pulse power is determined. Such a compact and rigid sensor can measure HPM pulses directly, can produce a high output signal, is overload resistant, and demonstrates very good long-term stability. In this paper, different types of RS are presented. The paper is organized as follows. In the second section the principle of performance of the RS and its sensitivity are described. The actual design of the RS for the rectangular waveguide is presented in the third section. The coaxial RS is described in the fourth section.

2. Resistive Sensor

The investigation of semiconductors subjected to a strong electric field began more that 50 years ago when Ryder and Shockley[7] found that for large electric fields, the current deviates from the dependence predicted by Ohm's law. It was understood that in a strong electric field, electrons gain additional energy from the electric field and a new steady state is established with mean electron energy greater than that of the equilibrium one. As a rule, heated electrons are more frequently scattered by lattice imperfections (phonons), and the resistance of the semiconductor usually increases. It was realized that the resistance change in a strong electric field could be used for pulsed-microwave-signal measurement. By placing a semiconductor sample in the transmission line and measuring the resistance change occurring when the electric field of the microwave pulse heats electrons in the sample, the microwave pulse power in the transmission line can be determined.

2.1. Sensing element and output signal

Because the resistance change of the semiconductor is a basis for a RS's operation, for HPM pulse measurement we actually use a resistor made from n-type Si. The SE is a bar- or plate-shaped piece of Si with ohmic contacts. Impurity diffusion followed by metal evaporation is used to form contacts. A typical sample length is 0.1–10 mm. Depending on the particular application, various ingots of silicon with different specific resistances are used.

To measure the resistance change in the microwave electric field, the SE should be connected to a dc circuit. Therefore, the output signal from the RS being measured using a high-input resistance-measuring unit can be expressed in the following way:

$$U_S = U_0 \frac{\Delta R}{R}, \tag{1}$$

where U_0 is a dc voltage drop on the SE and $\Delta R/R$ is a relative resistance change in the SE, obtained by averaging the instantaneous current over the period of the microwave electric field. In a low power limit, the strength of an average microwave electric field in the SE is sufficiently small. Therefore, its resistance change can be expanded in a power series of the electric field and only the first nonvanishing term can be taken into account,[3] thus yielding

$$\frac{\Delta R}{R} = \beta^*(f)\langle E\rangle^2, \tag{2}$$

Table 1. Typical values of phenomenological parameters characterizing current voltage characteristics of n-Si at room temperature for different specific resistance ρ materials

ρ, Ω·cm	β_0^*, cm^2/V^2	k_n^*	τ_ε, s
5	9.0×10^{-8}	3.0	2.9×10^{-12}
20	9.3×10^{-8}	3.4	
200	10.1×10^{-8}	4.3	

where $\beta^*(f)$ is frequency dependent, so-called, an effective warm-electron coefficient defining a deviation of the current-voltage characteristic from Ohm's law, and $\langle E \rangle$ is an average amplitude of the electric field in the SE. The region where equation (2) expression is valid is called a warm-electron region. In general, the effective warm-electron coefficient is frequency dependent and this dependence accounts for the influence of electron-heating inertia on the resistance change in the microwave electric field:

$$\frac{\beta^*(f)}{\beta_0^*} = \frac{1}{3}\left[1 + \frac{2}{1 + (2\pi f \tau_\varepsilon)^2}\right], \tag{3}$$

where β_0^* is a value of the effective warm-electron coefficient in a low-frequency region and τ_ε is a phenomenological energy relaxation time. Typical values of β_0^* and τ_ε for n-Si at room temperature are collected in Table 1. From Eq. (3) one can find that at 12 GHz the decrease of β^* due to heating inertia is roughly 3%. Therefore, the influence of heating inertia on β^*can be neglected up to and including X band.

Experimental investigations have revealed that the warm-electron approximation holds well up to the electric field strength around 1 kV/cm, at which $\Delta R/R$ is of the order of 10%. At a higher electric field, there is a considerable deviation of the relative resistance change from the dependence predicted by expression (2). It was found that over a wider range of the electric field strength, the resistance change is described by the following empirical relation, with two adjustable parameters:

$$\frac{\Delta R}{R} = \frac{\sqrt{1 + 4k_n^* \beta^* \langle E \rangle^2} - 1}{2k_n^*}, \tag{4}$$

where k_n^* describes the deviation of $\Delta R/R$ from quadratic dependence predicted by Eq. (2). Typical values of k_n^* for n-type Si at room temperature are presented in Table 1.

2.2. Sensitivity

Let us consider the sensitivity of the RS in the linear region where the output signal of the RS is proportional to the pulse power P propagating in the transmission line. Because the resistance change of the SE is the quantity indicating pulse power level, it is convenient to define the sensitivity ζ of the RS as

$$\zeta = \frac{\Delta R/R}{P}. \tag{5}$$

Definition (5) is not unique. Often sensitivity is defined as a signal-to-power ratio. Taking into account that the signal amplitude depends not only on the dc voltage drop on the SE but on the input resistance of the measurement unit used for the output signal measurement, the proposed definition of the sensitivity is likely more acceptable. Inserting Eqs. (2) and (3) into Eq. (5), one can get the following expression:

$$\zeta = \frac{\beta_0^*}{3}\left[1 + \frac{2}{1+(2\pi f \tau_\varepsilon)^2}\right]\frac{\langle E\rangle^2}{P}, \tag{6}$$

describing the sensitivity of the RS in the linear region. The average electric field is the only unknown quantity in Eq. (6). Thus determining it, the sensitivity of the RS in the linear region can be calculated. For the calculation of the average electric field in the SE and optimization of the frequency response of the RS, we used the finite different time domain (FDTD) method.[8]

As already mentioned, when measuring power increases, the relative resistance change deviates from the linear dependence [Eq. (5)]. It was well established that $\Delta R/R$ dependence on the pulse power in a wide range of P can be approximated as the second-order polynomial in the following way[3]:

$$P = A\frac{\Delta R}{R} + B\left(\frac{\Delta R}{R}\right)^2, \tag{7}$$

where coefficients A and B are determined by fitting the experimentally measured dependence of $\Delta R/R$ on P with Eq. (7). Comparing Eq. (7) with Eq. (5), one can see that $\zeta = A^{-1}$. Expression (7) can be used as an analytical description of the calibration curve of the RS. When the coefficients A and B for the particular RS are determined, inserting Eq. (1) into Eq. (7), one obtains an expression binding the pulse power P with the measured signal U_s. Making use of such an analytical expression allows us to improve the measurement accuracy when the amplitude of the measured signal falls outside the linear region of the RS.

2.3. DC pulse supply

Considering expression (1), one can see that the output signal linearly grows with the dc voltage drop on the SE. The increase in the dc voltage applied to the SE is limited by sensor heating that worsens the sensor's characteristics. Instead, a pulsed-current source is used. It produces a roughly 120-μs dc pulse. The amplitude of the current is adjusted to get the desirable voltage drop on the SE. After 100 μs when the current pulse starts, the HPM pulse source is triggered. Therefore, the output signal appears as a short video pulse on the pad of the feeding pulse. A differencing circuit cuts the pad, and the useful signal is measured by an oscilloscope. The pulsed-current source provides a significant increase in the output signal from the RS without any amplification circuit.

3. RS in Rectangular Waveguide

Rectangular waveguides are widely used as transmission lines for HPM applications. Therefore, we have focused our attention on the measurement of pulsed power in rectangular waveguides.

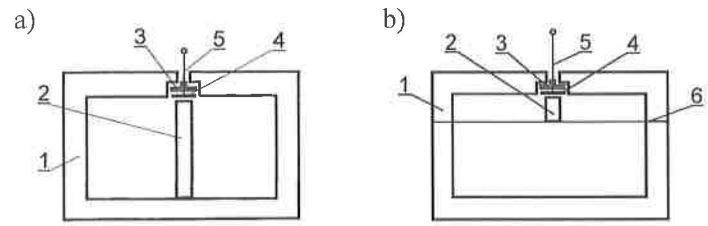

Fig. 1. Schematic views of cross-waveguide-type RS (a) and diaphragm-type RS (b): 1, waveguide; 2, SE; 3 and 4, insulating and metallic washers; 5, output; and 6, diaphragm.

3.1. Cross-waveguide-type RS

A cross-waveguide-type RS is made as a section of a standard waveguide where the SE is mounted. A schematic view of the RS is shown in Fig. 1a. The SE of the RS is placed in the center of the waveguide. It is a bar-shaped piece of semiconductor with ohmic contacts on its ends. The specific resistance of the semiconductor used as the SE is in the range 20–200 Ω·cm. The length of the SE corresponds to the dimension of the narrow wall of the waveguide. The grounded end of the SE is directly connected to the waveguide. The other end of the SE is isolated and connected to the measurement circuit and current source. The RS described above has been mainly used for the measurement of intermediate levels of pulse power (~1 kW) at X band (waveguide size 23×10 mm^2).

Considering the thermal characteristics of the cross-waveguide-type RS, it was shown that some average heating of the SE occurs when it is fed by a sequence of microwave pulses. Electron and lattice heating inertia differ by many orders. Therefore, two kinds of measurements can be performed independently: the measurement of the pulse signal that appears due to electron heating and the measurement of the increase in the average resistance caused by the heating of the SE. The measured pulse signal is proportional to the pulse power, whereas the increase in resistance is proportional to the average power absorbed in the SE. This means that the cross-waveguide sensor can serve as a pulse power meter and bolometer simultaneously. Making use of this feature, the RS can be independently calibrated, replacing the microwave electric field in the sensor by a dc electric field the strength of which can be measured with high accuracy.

The readings of two sensors calibrated in such a way were compared with the readings of the Russian (former Soviet Union) pulse power standard. The measurements were performed for 18 years, starting in 1982. During this long-term experiment, some change in the sensitivity within ±4% was observed. Bearing in mind that the main error of the standard was ±4%, it becomes clear that the tested sensors demonstrate very good long-term stability.

3.2. Diaphragm-type RS

Improving thermal characteristics of the sensor and widening its possible applications for HPM pulse measurements, the diaphragm-type RS shown in Fig. 1b was developed. It is seen that in this case the SE is placed in the center of the waveguide between a thin metal foil and the wide wall of the waveguide. The length of the SE roughly corresponds to 1/10th of the waveguide's narrow wall.

The diaphragm-type RS has at least two advantages over the cross-waveguide-type RS. First, by decreasing the length, the thermal characteristics of the SE are improved. Second,

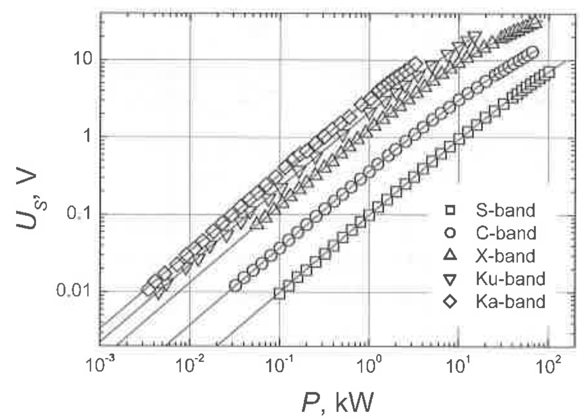

Fig. 2. Output signal dependences on microwave power for the RS designed for short HPM pulse measurement at different frequency bands. Points denote experimentally measured values using a dc pulse supply producing a 50-V dc drop on the SE, and solid lines correspond to the polynomial approximation [Eq. (7)].

because the SE occupies only a part of the waveguide window, a smaller reflection from it can be expected even though a lower-specific-resistance semiconductor is used for the manufacturing of the SE.

Diaphragm-type RSs have been manufactured and tested beginning from L up to Ka band. They are used in Russian, Swedish, U.S., and other laboratories dealing with HPM pulses. The RS found application for the measurement of HPM pulse power density in free space. A RS connected to a horn antenna from one side and to a matched load from the other comprises a unit that is able to measure pulse power density up to a few megawatts per square meter.[1] The measurements were carried out in an anechoic chamber driven by the Microwave Test Facility at SAAB Military Aircraft, Sweden.

The diaphragm-type RS has been upgraded for the measurement of nanosecond-duration HPM pulses. RSs from S to Ka band have been manufactured, calibrated, and tested. The output signal dependencies on pulse power are shown in Fig. 2. It is seen that using dc pulse feeding, output signals up to 30 V are obtained. It should be pointed out that the RS has been calibrated up to pulse power levels available in the laboratory. RS can likely be used at higher pulse power levels, ultimately limited by air breakdown in the waveguide.

We estimated a response time of the RS using the time domain reflectometry method. The sensor is fed by a dc pulse with a subnanosecond rise time, and by measuring the duration of the transient formed by the initial and reflected pulse, the response time of the RS was estimated. Measurement results for the different-band RS are collected in Table 2. As one can see from the third column of the table, where the ratio of the response time to the average period of the oscillations in the waveguide's frequency band is presented, the manufactured RS can measure microwave pulses with durations on the order of a few tens of periods of microwave oscillations. It was confirmed by tests of the X-band RS using short HPM pulses generated by a backward wave oscillator driven by the SINUS-6 electron beam accelerator at the University of New Mexico.[2]

The main drawback of the waveguide-type RS for short HPM pulse measurement is a large variation of the sensitivity [Eq. (5)] in a waveguide's frequency band. It was determined

Table 2. Measured time responses for the different-band RS

Band	τ, ns	τ/T
S	2.5	8
C	2	10
X	0.5	5
Ka	0.4	7
Ku	0.2	7

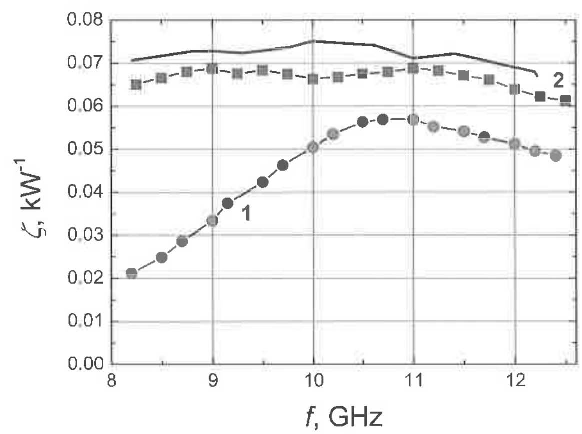

Fig. 3. Dependencies of the sensitivity on frequency for the initial (1) and optimized (2) X-band diaphragm-type RS. Points show measurement results, and the solid line shows the theoretical prediction.

that the sensitivity of the X-band RS changes in the frequency band by more than a factor of two (Fig. 3). The same frequency response is likely to be characteristic of the RS in other frequency bands as well. Bearing in mind this drawback of the waveguide-type RS, we performed investigations of factors influencing frequency response.

Making use of the FDTD method,[8] the peculiarities of the interaction of the semiconductor sample inserted under a thin metal diaphragm in the waveguide were investigated. It was shown that the average electric field strength in the SE is influenced by a resonance phenomenon.[6] The resonance occurs when the effective length of the diaphragm for the wave propagating under it becomes a whole number of half-waves. Varying the electrophysical parameters of the diaphragm-type RS (diaphragm length, dimensions, and specific resistance of the SE) and taking into account that the resistance of the RS should be less than or equal to 50 Ω, the optimal set of parameters providing the smallest possible sensitivity variation in the waveguide's frequency band was determined. A maximum-to-minimum-sensitivity ratio of 1.09 was found for the optimal set of parameters.

Theoretical predictions were proven experimentally. Experimentally measured frequency responses of the initial and optimized RS are shown in Fig. 3. It is seen that the optimized

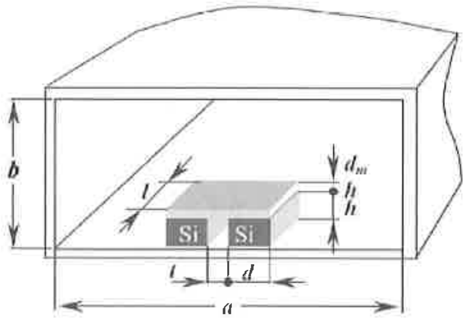

Fig. 4. Schematic view of the RS for millimeter-wave band.

RS is characterized by a smooth dependence of the sensitivity on frequency. Experimentally measured sensitivity variation is roughly ±6% in the waveguide's frequency range. That is sufficiently close to the theoretically predicted value of 1.09. The absolute value of the measured sensitivity coincides well with the calculated one. A small difference between them can be attributed to size tolerances between the actual device and modeled prototype, to small mechanical displacements when installing the SE under the diaphragm, and to measurement errors.

3.3. RS for millimeter wave

High-power microwave pulse generation techniques progressed rapidly toward higher frequencies in recent years.[9] This imposes new requirements for sensors that can be used for the measurement of HPM pulses in the millimeter-wave region. One of the possible solutions is the RS. Unfortunately, the most successful concept of the diaphragm-type RS could not be directly downscaled to the millimeter-wave region due to the small dimensions of the waveguide. For the measurement of high-power millimeter-wave pulses in the frequency range 78–118 GHz (W band, waveguide window 2.54×1.27 mm^2), we propose a new concept of the SE consisting of two separate samples mounted in the center of the wide wall of the waveguide in close proximity to each other, as shown in Fig. 4. Their upper contacts are shorted with a metal foil. The lower contact of one of the sensors is grounded, whereas the other one is isolated. It is used for RS feeding and output signal measurement. To measure pulse power, the RS is connected into a dc circuit with a current source. Thus, SEs are connected in series with respect to the dc circuit but in parallel with respect to the millimeter-wave electric field.

We performed FDTD simulations in order to investigate the interaction of such a semiconductor structure with millimeter waves. It was found that some resonances occur in the SE when increasing its length in a wave propagation direction. Making use of the interplay between half-wavelength resonance in the structure and the conductivity current in it, the increase in the average electric field in the sensor with frequency was compensated by the electric field decrease in the waveguide because of waveguide dispersion and the decrease in the electron-heating effect with frequency [Eq. (3)]. Thus, the RS having nearly independent sensitivity with frequency in a waveguide's frequency band has been proposed. The details of the simulations were published by Kancleris et al.[5]

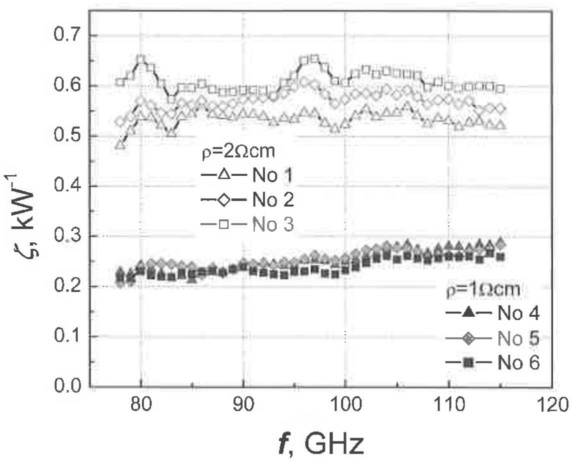

Fig. 5. Experimentally measured dependencies of the sensitivity on frequency for both groups of the RS for millimeter-wave band.

The RS with optimal dimensions of the SE (height $h = 0.1$ mm, width $d = 0.15$ mm, length in the wave propagation direction $l = 0.6$ mm) was manufactured. The surface-mounted device technology of component soldering was applied to fix SEs on polished metal disks, which in turn were mounted into waveguide holders. Thus, finally the RS was manufactured as a section of a W-band waveguide with the SEs inside. Two groups of SEs with optimal dimensions were made from different specific-resistance n-Si wafers, namely, $\rho = 1\ \Omega$ and $-2\ \Omega$ cm with nominal dc resistances of 11 and 22 Ω, respectively. For final tests, three sensors from each group were chosen.

The sensitivity, voltage standing wave ratio (VSWR), and insertion loss dependencies on frequency were measured using a low-power tunable millimeter-wave source, reference wattmeter, and lock-in amplifier. It was found that VSWR is less than 1.25 and insertion loss -0.8 dB for the RS of both groups in the frequency range 78–118 GHz. Results of the measurements of the dependence of sensitivity on frequency are presented in Fig. 5.

It is seen that the sensors of the second group are more sensitive than those of the first one. Such behavior was predicted by our theoretical considerations.[5] Taking into account the finite thickness of the metal foil d_m shorting upper contacts and an air gap t between SEs, a reasonable agreement between measured and calculated values of sensitivity was obtained (refer to Fig. 4). Details of the comparison were published by Kancleris et al.[4] From experimental results it is seen that the measured sensitivity variation within the waveguide frequency range was $\pm15\%$ for the first group and $\pm8\%$ for the second one. This is a very good result because the Agilent sensor W8486A available on the market and devoted to average power measurement demonstrates a $\pm15\%$ sensitivity variation in a 3-mm-wave band.

The dependencies of the output signal on the pulse power were measured up to 2 kW using a magnetron operating at 94 GHz. The duration of millimeter-wave pulses was 300 ns. To get a high output signal, the RS was fed by a pulsed-current source producing a 10-V drop on the SEs. At a maximum pulse power, the output signal was roughly 1.5 V for the RS of the first group and exceeded 2 V for the second one. From the experimental data, the dependence of the relative resistance change of the RS on the pulse power was

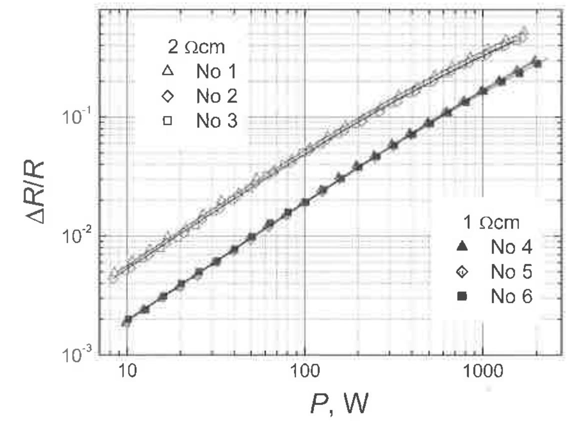

Fig. 6. Dependencies of the relative resistance change on pulse power for both groups of the RS at $f = 94$ GHz. Points show measurement results, and solid lines demonstrate two-term approximations [Eq. (7)].

determined. These results are shown in Fig. 6. It is seen that at a maximum pulse power, the largest value of $\Delta R/R$ was about 30% for the first group of the RS and 50% for the second one. Bearing in mind that at a lower frequency the RS was successfully employed up to a twofold increase in the resistance, one can expect that the present RS could register even higher pulses of millimeter waves.

4. Coaxial-Type RS

The application of the waveguide-type RS is restricted by the bandwidth of certain waveguides. Hence, for the HPM pulse measurement in a wide frequency range a set of sensors has to be used. Therefore, the measurement system becomes complicated and its cost increases. Moreover, at a lower frequency the size and weight of the waveguide section with the RS increase and it becomes inconvenient to use. These reasons pushed us to develop a coaxial-type RS (CRS) that can be used in a wider frequency range.

A schematic block diagram of the CRS is shown in Fig. 7. It is seen that the CRS was designed as a two-terminal device. One of them will be used to connect the sensor to a coaxial line where the measuring microwave pulse is propagating. The other one connects the CRS to the measuring circuit and sensor-feeding unit. The CRS was designed on the

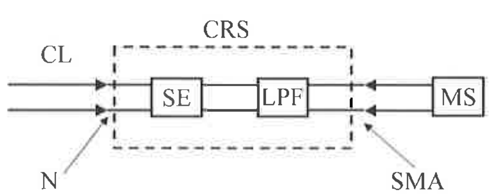

Fig. 7. Schematic block diagram of the CRS: SE, sensing element; LPF, low-pass filter; CL, coaxial line; N, N-type connector; SMA, SMA-type connector; and MS, sensor's feeding and measuring system.

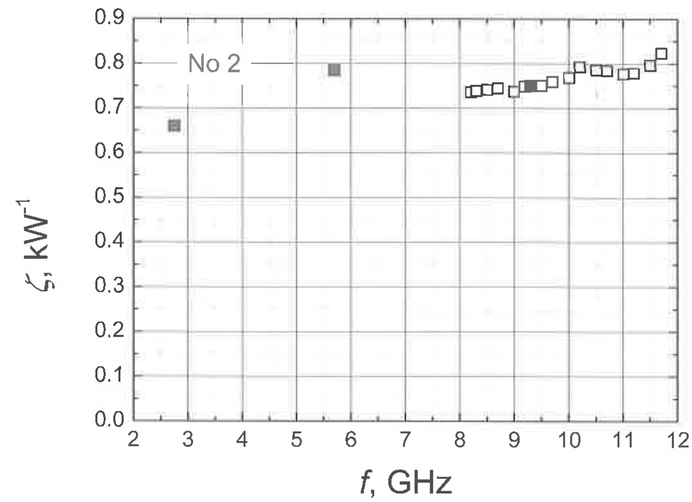

Fig. 8. Dependence of the sensitivity of the CRS on frequency. Solid points demonstrate measurement results using magnetron generators, and open points show measurement results using X-band TWT.

basis of a 50 Ω impedance coaxial line. It actually consists of the SE and a low-pass filter. One contact of the SE is directly connected to the center core of the coaxial line, whereas the other one is connected to the shield. Therefore, the SE serves as a matched load and a pulse power detector simultaneously. To achieve good matching of the CRS with the coaxial line, the resistance of the SE is set to be 50 Ω. Because the dimensions of the SE are chosen to be much smaller than the wavelength of the microwave, the SE might be considered as a lumped element of the circuit. This is why a good matching might be achieved in a wide frequency range. The main purpose of the low-pass filter of the CRS is to prevent the direct propagation of the microwave pulse to the measuring unit. At the same time, the low-pass filter should not spoil the matching of the SE with the coaxial line in a wide frequency band. Finally, the parameters of the low-pass filter influence the response time of the CRS. Therefore, all three factors should be taken into account when choosing the parameters of the low-pass filter.

As the low-pass filter, we employed a five-element Butterworth filter. Filters made from lumped elements and from the sections of a microstrip line and a hybrid filter were tested. In the hybrid filter the first element of the filter, the inductance, was partly replaced by a conductor coated by a layer of ferrite. This improves significantly the performance of the filter in the high-frequency region, providing measurements of the microwave pulses in the frequency range 2–12 GHz. The measured frequency response of the CRS with the hybrid filter is shown in Fig. 8. Solid points in the figure show results obtained at fixed frequencies using magnetron generators, and open points demonstrate results measured using X-band TWT. It is seen that the sensitivity of the CRS is slightly growing with frequency, and from 2.7 to 11.7 GHz, it increases by a factor of 1.25. The measured VSWR was less than 1.6 within the considered frequency range.

The output signal dependence of the CRS on the pulse power measured up to 1 kW at 9.3 GHz is shown in Fig. 9. A dc source producing a 4-V drop on the SE was used. It is seen that the output signal at maximum pulse power exceeds 1.5 V.

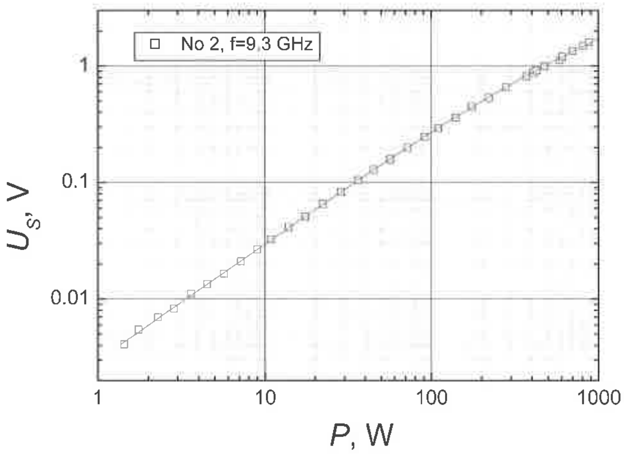

Fig. 9. Dependence of the output signal on pulse power at $f = 9.3$ GHz and $U_0 = 4$ V for the CRS with hybrid filter. Points show experimentally measured results, and the solid line corresponds to the polynomial approximation [Eq. (7)].

5. Conclusions

The RS, based on the electron-heating effect in semiconductors, is one of the most promising devices for HPM applications. The RS can measure 40–60-dB-higher pulse power in comparison with a conventional diode. It can be used in a wide frequency range for which powerful HPM pulse sources are now designed and manufactured. The RS demonstrates very good long-term stability and is resistant to large power overloads. Using the dc pulse supply for the RS feeding, an output signal up to a few tens of volts can be obtained without any amplification circuit. The RS can be made sufficiently fast to measure microwave pulses with a duration of the order of a few tens of periods of microwave oscillations. Making use of the increase in the electric field in the SE with frequency due to a resonance phenomenon, a sufficiently flat frequency response of the RS in the waveguide's frequency band can be engineered, compensating not only the decrease in the electric field due to waveguide dispersion but also the decrease in the electron-heating effect with frequency.

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