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ELECTRONICS AND RADIO ENGINEERING

A Calorimetric Spectrometer Measuring Single Pulses of Relativistic Microwave Generators

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Abstract—A calorimetric spectrometer measuring individual pulses radiated by wideband relativistic microwave oscillators is described. The calorimetric spectrometer comprises two calorimeters and a set of low-pass filters. In the development of such a spectrometer, the basic feature consists in the high radiation power (~10^8 W) and low pulse energy (~1 J). To prevent the microwave surface discharge, the calorimeters have a rather large area (~0.1 m^2). The calorimeters' sensitivity is 0.05 J. Frequency responses of the filters were measured experimentally and calculated with the help of a three-dimensional version of the KARAT computer code. The experimental spectrum of a wideband relativistic microwave plasma oscillator measured in a frequency range of 5–40 GHz is presented.

At the General Physics Institute of the Russian Academy of Sciences, wideband relativistic microwave plasma oscillators have been designed. The oscillators offer the following features: mean radiation frequency can be varied from 8 to 24 GHz, the frequency bandwidth in different operating modes varies from 5 to 25 GHz, power is ~50 MW, durations of an individual microwave pulse are 20 and 400 ns depending on the duration of the voltage pulse of a high-current relativistic accelerator, and the diameter of the radiating horn window is ≥15 cm [1–3]. In order to prevent possible microwave discharge, the window is made sufficiently large.

The spectrum of a high-power wideband plasma radiation was first studied in paper [4], where a 15-channel spectrometer operating in a frequency range of 6–40 GHz and having a channel bandwidth of 2.3 GHz was used. A power of ~1 W was branched into the spectrum analyzer at a total power of several tens of megawatt. Large attenuation of the signal traveling from the receiving horn to the detector assembly causes a substantial (±50%) error in absolute measurements of the power density spectrum. A similar 5-channel spectrometer operating in a frequency range of 18–40 GHz was used in [5]. In paper [1], a power of ≤1 MW is fed to the 5-channel spectrometer; however, the accuracy of the measured power density spectrum was also rather low, in this case, because of difficulties in the absolute calibration of channels at a high power level.

One should take into account that the analyzed radiating sources have different power density spectra at different points in the cross section of the microwave beam and the measured results depend also on polarization of the receiving antenna. Thus, it is impossible to restore correctly the total power density spectrum of the microwave radiation from the measurements [1, 4, 5]. The spectrum of the total radiation power flux of oscillators of the type described in [1–3] is a fundamental parameter, which is calculated theoretically and is used to judge about possible applications.

In this work, a device is described that measures the energy spectrum of the total microwave radiation flow in absolute units. The radiation spectrum is measured in a frequency range of 5–42 GHz with a frequency resolution of several gigahertz. The energy spectral density is measured with an accuracy of 0.01 J/GHz. In different operation modes, the bandwidth of the radiation spectrum of a relativistic microwave plasma oscillator varies from 5 to 25 GHz and the corresponding typical spectral densities reach 0.2–0.04 J/GHz for a microwave pulse duration of 20 ns and total energy of ~1 J. The relative accuracy of the measured spectrum of the radiated microwave pulse with a duration of 400 ns (the total energy is ~10–20 J) is substantially higher, since, in this case, a typical energy spectral density equals 0.5–1 J/GHz. Independent measurements of the shape of the power density pulse allow us to measure the spectrum of the total power flux in absolute units (MW/GHz).

Figure 1 presents the design of the calorimetric spectrometer. Radiation of the microwave oscillator *3* propagates from the output window *5* and enters the low-pass filter *4*, which is made in the form of a metal plate with thickness L and openings of diameter d. Each opening can be considered as a waveguide, since $L > 2.5d$. Therefore, filter *4* transmits part of the radiated flux with frequencies $f > f_{cut} \approx c/1.7d$, where c is the velocity of light, and f_{cut} is the critical frequency (hereinafter, f_i, i is a number). This part (Q_1) of the microwave pulse energy is measured by the calorimeter *1* [6], whereas the reflected part of the flux (Q_2) is measured by the calorimeter *2*. The diameter of the horn *3* is 15 cm, the diameter of the calorimeter *2* is 36 cm, and the distance between the horn and the filter *4* is chosen such that the radiation reflected from the filter does not propagate into the horn. Thus, sum $Q_1 + Q_2$ equals the total energy of the microwave pulse.

A perfect below-cutoff-waveguide filter has zero transmittance at $f < f_{cut}$ and unity transmittance at $f > f_{cut}$. Comparing energies passed through two filters with different cutoff frequencies f_1 and f_2 in two successive microwave pulses, we obtain the radiation energy in a frequency band of $f_1 - f_2$. Actually, only part of the energy passing through the filter is measured in each pulse. By measuring ratio $Q_1/(Q_1 + Q_2)$ instead of Q_1 in two successive microwave pulses, we remove the error associated with the pulse-to-pulse instability of the total energy. Unfortunately, the frequency response of actual filters differs substantially from that of a perfect filter. This complicates the method used to calculate the spectrum from the measured results.

The frequency response of actual filters was determined from a numerical simulation and from "cold" measurements. Filters of the calorimetric spectrometer are diffraction gratings with different diameters of openings d and periods h (see. Fig. 2), with $h \approx d$. All filters have a diameter of 40 cm, which far exceeds the diameters of openings of any filter, $d_{max} = 3.5$ cm. The grating transmission coefficient K depends on the relationship between λ_{cut} ($\lambda_{cut} \cong 1.7d$) and λ (the wavelength of an external radiation). If $\lambda << \lambda_{cut}$, the transmission coefficient can be calculated geometrically, from the ratio between the total area of the openings and the filter area. When $\lambda > \lambda_{cut}$, the transmission coefficient is close to zero, which corresponds to features of below-cutoff waveguides. When $\lambda \sim \lambda_{cut}$ (the resonance region), the transmission coefficient is frequency-dependent and takes different values up to unity. This effect of total transmission, known as the Malyuzhinets effect [7], is observed for many gratings in the resonance region.

In order to calculate the frequency response of the filters, we used a universal software designed for solving various electromagnetic problems. We used a three-dimensional version of the KARAT code [8, 9], which solves the nonstationary boundary value problem for the Maxwell's equations with the help of a difference scheme with shifted grids [8, 9]. The diameter of the microwave flux in the spectrometer far exceeds the wavelength; therefore, in the numerical model, the plane monochromatic wave is incident along the normal onto the filter plane. The KARAT code is intended for solving the time-domain problem; therefore, we assumed that a microwave pulse, whose duration far exceeds the period of microwave oscillations, is incident on the filter. We determine the portion of the power passed through the filter in the stationary state. For the

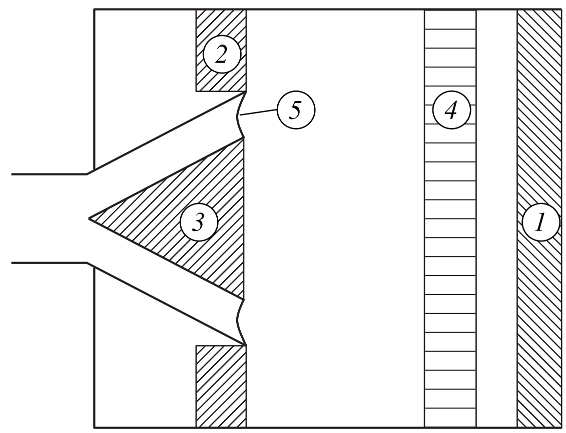

Fig. 1. Design of calorimetric spectrometer: (*1*) calorimeter; (*2*) calorimeter measuring the reflected part of the flux of microwave radiation; (*3*) horn of the microwave oscillator; (*4*) low-pass filter; and (*5*) window.

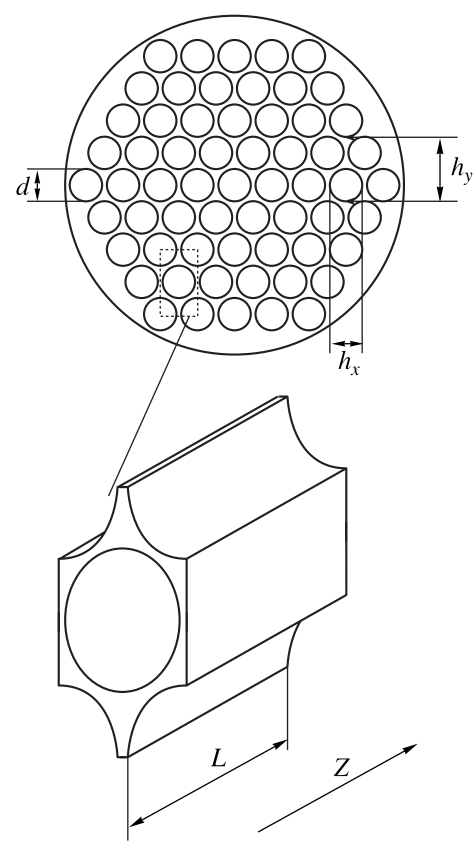

Fig. 2. Grating used as a low-pass filter and the element of an infinite periodic structure, which is used in simulation of the grating.

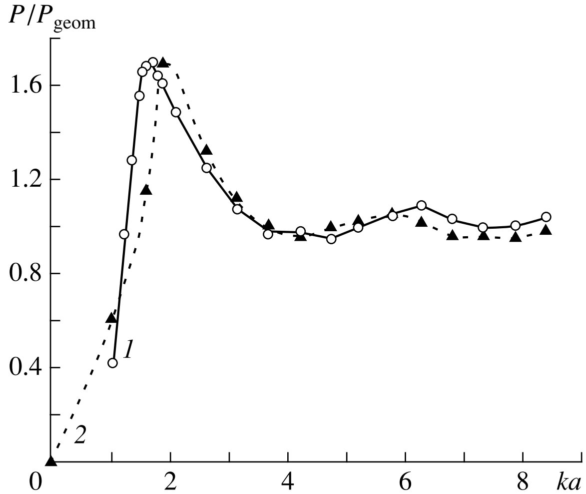

Fig. 3. Comparison of (*1*) the results of numerical simulation obtained for the test problem with (*2*) the exact solution.

test problem, we have chosen the plane wave diffraction by a circular aperture of radius a in a perfectly conducting plane, which has a rigorous analytical solution [10]. Figure 3 presents calculated and analytical functions P/P_{geom} plotted as a function of parameter ka, where $k = 2\pi/\lambda$, P is the actual power passing through the opening, and P_{geom} is the portion of the power flux of the wave incident on a section with area πa^2. The graph demonstrates that the transmittance increases substantially at wavelengths comparable to the opening radius. The correspondence between the calculated and the analytical solution forms the basis for utilizing the KARAT code for calculation of the filters.

In calculations of actual filters with the use of the KARAT code, the finite-dimension filter was replaced with an infinite periodic structure in the *X*–*Y*-plane. Figure 2 presents an element of this structure. A wave packet with a specified envelope is incident along the

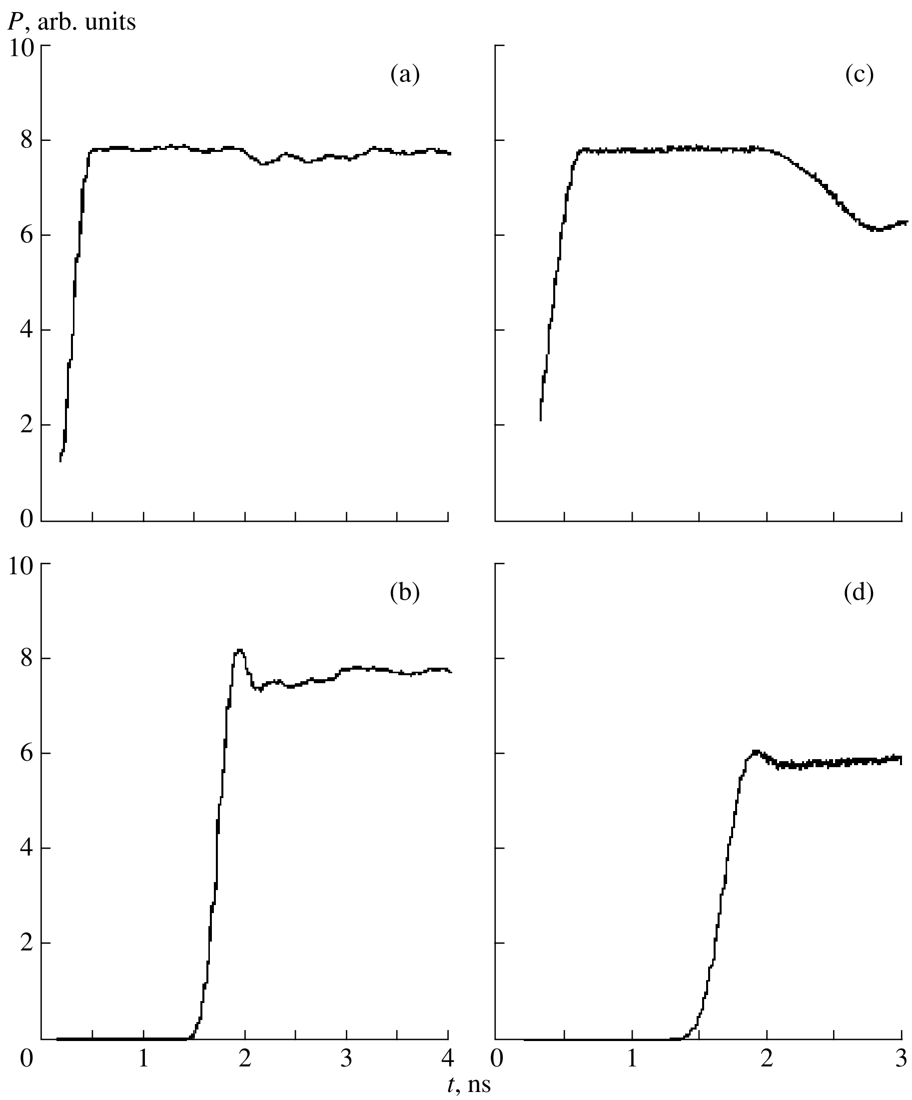

Fig. 4. Time dependence of the energy flux propagating along the *Z*-axis (a and c) before and (b and d) after the grating for different frequencies of the incident wave (f_{cut} = 5.3 GHz): f = (a and b) 8 and (c and d) 12 GHz.

Z-axis on the element. We assumed that the tangent component of the electric filed is zero on the grating surface as on the surface of a perfect conductor, [**En**] = 0. We also used the periodicity (Floquet's) condition related to the fact that the structure transforms to itself when it is shifted along the *X*- and *Y*- axes by its periods h_x and h_y.

Figure 4 presents the results obtained from the numerical simulation of the time variation of the energy flux (the Poynting vector) on the *Z*-axis in two cross sections: before (Figs. 4a, 4c) and after (Figs. 4b, 4d) the grating. One can see from Fig. 4c that the wave flux reaches maximum at $t = 0.3$ ns and, by the time instant $t = 2$ ns, it decreases (nonresonant case) because of reflection from the grating. Figures 4b and 4d depict the flux transmitted by the grating. At time $t = 3$ ns, it reaches a stationary value. Determination of the ratio of the transmitted power to the incident one for different frequencies of the incident wave allows us to obtain frequency characteristics of the transmission coefficients of seven filters in a frequency range of 5–42 GHz. Figure 5 shows such characteristics for two filters: with maximal (Fig. 5a) and minimal (Fig. 5b) opening diameters.

In "cold" measurements, we determined similar characteristics. Measurements were performed at the Gramat Research Center (France) on the bench developed by D.H. Ghodgaonkar, V.V. Varadan, and V.K. Varadan. A lens with 30.5-cm focal length was placed in the radiating horn aperture with a diameter of 30.5 cm. A filter was placed in the focal plane of this lens. The radiation passed through the filter was recorded by a receiving horn antenna. The receiving antenna was located at a distance of 30.5 cm from the filter and was identical to the radiating antenna. The measurements were performed in a frequency range of 5.85–110 GHz. The diameter of the microwave beam, which had the Gaussian distribution in the filter plane, was $\approx 3\lambda$ at a level of 3dB. Unfortunately, the conditions of this model experiment do not fully correspond to propagation of the microwave radiation through the filter in the spectrometer, in which the microwave beam diameter is substantially larger than the wavelength.

We measured transmission coefficients as functions of the incident wave frequency for the same set of filters that was simulated numerically. Figures 5a and 5b present the calculated and measured values of the transmission coefficient versus frequency of the incident wave for two filters. At frequencies close to λ_{cut}, the calculated and experimental values of the transmission coefficient shown in Fig. 5a are close to unity. At $\lambda < \lambda_{cut}$, the calculated transmission coefficients are ~0.8, which coincides with the geometrical transmittance. Small values of the transmission coefficient (~0.6) measured at $\lambda \approx 0.5\lambda_{cut}$ (Fig. 5a) do not agree with the calculated values. This discrepancy may be related to the fact that, in the model experiment, the diameter of the microwave beam compares to the diameter of opening, whereas, in the numerical simulation, the microwave beam diameter was substantially larger than the diameter of openings. The measurement error arising due to the small diameter of the microwave beam is especially large in the high-frequency region, where we observed the most pronounced discrepancy between the calculated and measured data. We consider the correspondence between the calculated and experimental values presented in Fig. 5b as satisfactory. Both methods prove that the filter exhibits perfect transmittance in the resonance region. Measuring the radiation spectra of high-power relativistic microwave oscillators [3, 6], we used values of the transmission coefficient calculated as a function of frequency.

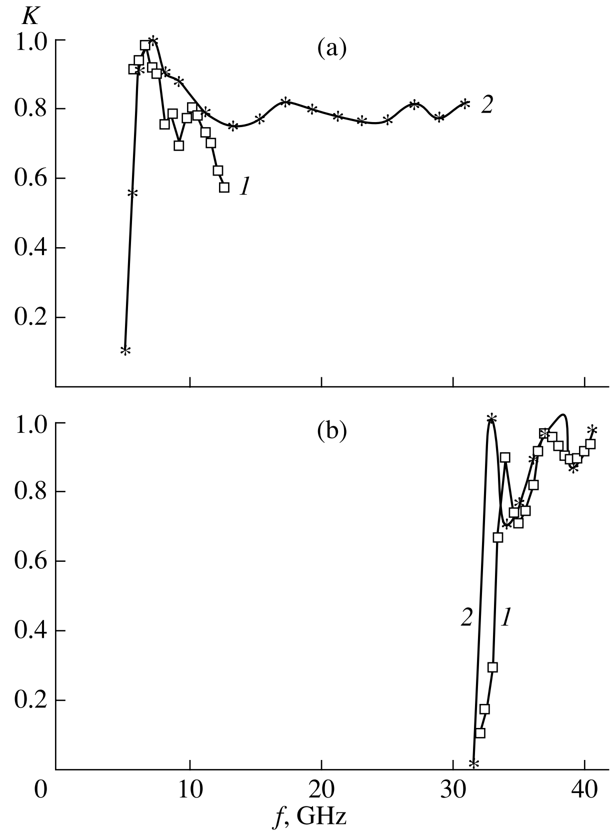

Fig. 5. Comparison of the (*1*) measured and (*2*) theoretical values of the transmission coefficient as a function of frequency of the incident wave for two filters of different geometries: (a) $d = 3.47$ cm, $h_x = 3.62$ cm, $h_y = 6.26$ cm, and $L = 10$ cm and (b) $d = 0.54$ cm, $h_x = 0.59$ cm, $h_y = 1.02$ cm, and $L = 1.5$ cm.

The technique used in spectrum measurements consists in successive (from pulse to pulse) measurements of values Q_1 and $Q_1 + Q_2$ for several filters with different f_{cut}. This technique may be used if, for unaltered parameters of the experiment and for any given filter, the ratio $Q_1/(Q_1 + Q_2)$ remains the same from pulse to pulse. This means that the spectrum is reproduced from pulse to pulse. Information on the spectrum is obtained in the

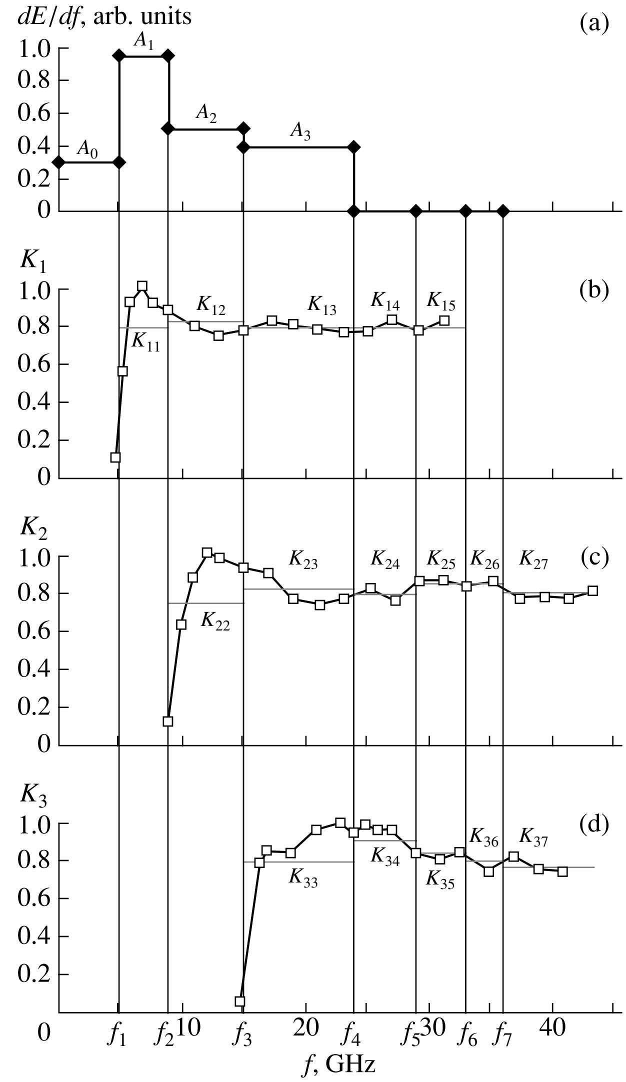

Fig. 6. Illustration to the spectrum measurement technique: (a) signal spectrum in the form of a histogram and (b, c, and d) transmission coefficients K_1, K_2, and K_3 of filters nos. 1, 2, and 3 with cutoff frequencies f_1, f_2, and f_3 as functions of frequency.

form of histograms (Fig. 6a) with amplitudes $A_1, A_2, \ldots, A_n$. Figures 6b–6d present transmission coefficients as functions of frequency: K_1 is the transmission coefficient of filter no. 1 with cutoff frequency f_1, K_2 is the transmission coefficient for cutoff frequency f_2, etc. We call the mean value of the transmission coefficient of filter no. n in a frequency band ranging from f_n to f_k as K_{nk}; then, we can write a system of equation, for example, for three filters:

$$A_0 + A_1 + A_2 + A_3 = W_0 \text{ without filter,}$$

$$K_{11}A_1 + K_{12}A_2 + K_{13}A_3 = W_1 \text{ for filter no. 1,}$$

$$K_{22}A_2 + K_{23}A_3 = W_2 \text{ for filter no. 2, and}$$

$$K_{33}A_3 = W_3 \text{ for filter no. 3,}$$

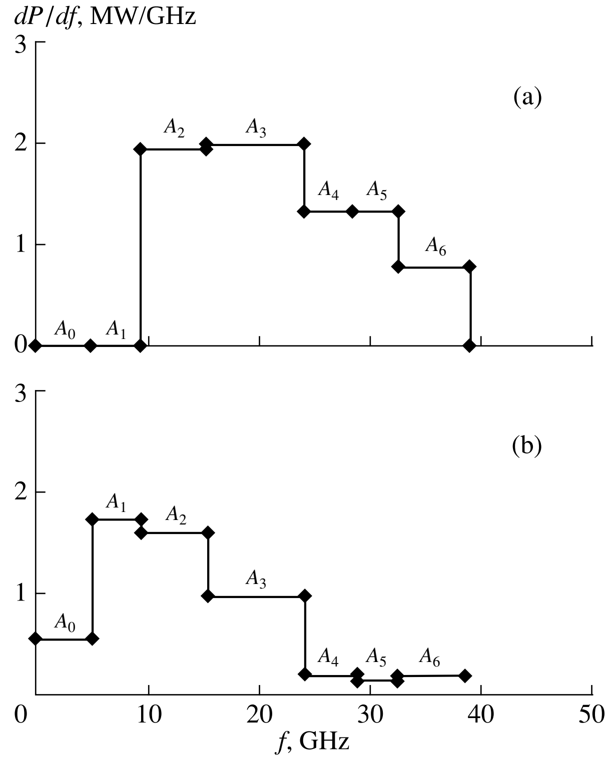

Fig. 7. Example of the spectrum of a wideband relativistic microwave oscillator; the pulse duration is (a) 20 and (b) 400 ns.

where W_0 is the mean value of the total radiation flux obtained from the averaging over all pulses. The mean value of ratio $Q_1/(Q_1 + Q_2)$ measured for filter no. 1 and multiplied by W_0 yields W_1. Similarly, we obtain W_2 for filter no. 2, W_3 for filter no. 3, etc. Usually, W_0 is averaged over ≈50 pulses and ratio $Q_1/(Q_1 + Q_2)$ is averaged over ≈5 pulses. The relative rms deviation of the ratio $Q_1/(Q_1 + Q_2)$ is no more than 0.1. Figure 7a presents an example of the spectrum of a wideband relativistic microwave oscillator [11]. The ordinate is the spectral power density measured in MW/GHz. The power was determined from the measured energy of microwave pulses and their durations, ~20 and 400 ns. The error in the measured spectral power density was 0.5 MW/GHz at a pulse duration of 20 ns; it was determined mainly by the calorimeter's sensitivity. For a pulse duration of 400 ns, the measurement error is determined by the statistics (the relative error is 0.1), and the error associated with the calorimeter's sensitivity (25 kW/GHz) may be neglected (see Fig. 7b) [3].

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REFERENCES

1. Strelkov, P.S., Rukhadze, A.A., and Shkvarunets, A.G., *Fiz. Plazmy*, 1994, vol. 20, no. 7–8, p. 686.
2. Kuzelev, M.V., Loza, O.T., Ponomarev, A.V., *et al.*, *Zh. Eksp. Teor. Fiz.*, 1996, vol. 109, no. 6, p. 2048.
3. Loza, O.T., Strelkov, P.S., and Ivanov, I.E., *IEEE Trans. Plasma Sci.: 7th Special Issue on High Power Microwave Generation*, 1998, vol. 26, no. 3, p. 615.
4. Kato, K.G., Benford, G., and Tzach, D., *Phys. Rev. Lett.*, 1983, vol. 51, no. 20, p. 1587.
5. Ando, R., Masuzaki, M., Morita, H., *et al.*, *J. Phys. Soc. Jap.*, 1996, vol. 65, no. 8, p. 2518.
6. Shkvarunets, A.G., *Prib. Tekh. Eksp.*, 1996, no. 4, p. 72.
7. Shestopalov, V.P., Kirilenko, A.A., Masalov, S.A., and Sirenko, Yu.K., *Difraktsionnye reshetki. Rezonansnoe rasseyanie voln* (Diffraction Gratings. Resonance Wave Scattering), Kiev: Naukova Dumka, 1986, vol. 1.
8. Koteteshvili, P.V., Rybak, P.V., and Tarakanov, V.P, *Preprint of Inst. of General Phys., Russ. Akad. Sci.*, Moscow, 1991, no. 44.
9. Tarakanov, V.P., *User's Manual for Code KARAT*, Springfield, VA, Berkley Research Associates, Inc., 1992.
10. Vainshtein, L.A., *Elektromagnitnye volny* (Electromagnetic Waves), Moscow: Sov. Radio, 1957.
11. Kuzelev, M.V., Loza, O.T., Ponomarev, A.V., *et al.*, *11th Int. Conf. on High Power Particle Beams*, Prague, Czech. Republic, 1996, vol. 1, p. 225.