ISSN 0027-1349, Moscow University Physics Bulletin, 2010, Vol. 65, No. 6, pp. 487–492. © Allerton Press, Inc., 2010.
Original Russian Text © D.N. Echin, Y.A. Trofimov, K.A. Zaitsev, N.A. Sukhareva, V.M. Pikunov, 2010, published in Vestnik Moskovskogo Universiteta. Fizika, 2010, No. 6, pp. 58–62.

Research Activities on a Double-Gap Output Section of a Multiple-Beam Klystron

D. N. Echin, Y. A. Trofimov, K. A. Zaitsev, N. A. Sukhareva, and V. M. Pikunov

Department of Photonics and Microwave Physics, Faculty of Physics, Moscow State University, Moscow, 119991 Russia
e-mail: suhareva@phys.msu.ru, vmpikunov@mail.ru

Received April 5, 2010

Abstract—In this article the double-gap output section of a multiple-beam klystron is studied using modern measurement equipment and computer simulation methods. Well-known techniques of cold two-terminal measurements are adapted to equipment capabilities. A comparison between the measured characteristic and computer simulation results is discussed.

Keywords: multiple-beam klystron (MBK), output structure, cold measurements, 3D simulation.

DOI: 10.3103/S0027134910060111

INTRODUCTION

Multi-beam klystron amplifiers are widely used as powerful sources of microwave radiation [1]. One component in most constructions is the output system, which defines the quality, power, and operating frequency band of the device.

Figure 1 shows a model of the considered output system of a multi-beam klystron amplifier fabricated in the laboratory of Powerful UHF radiation sources of the Department of photonics and microwave physics in the Faculty of Physics of Moscow State University. The model is made of yellow metal. The output resonator, 1, consists of two partial resonators that form interaction gaps of electromagnetic fields with electron beam. They are penetrated by 19 beamlets: 1 is in the center and the other 18 are located along two concentric circles with the radii R_i, R_e.

The partial resonators are connected with each other by four coupling slots, 4; one of these is connected to the coupling iris, 2. The connection diaphragm is a rectangular aperture $c \times d$ in cross section. A segment of a rectangular waveguide $a \times b$ with wideband coaxial-waveguide transition (CWT), 3, was used as the output waveguide.

The electrodynamic characteristics of similar output system (with two connection slots) were thoroughly studied previously in [2] using the CST Microwave Studio (MS) software complex by Computer Simulation Technology [3].

A new generation of measuring systems and numerical simulation programs of an industrial level are widely used for studying microwave devices. Such devices [4] and programs [3] are used by the Department of photonics and microwave physics for performing scientific research and for providing educational process (preparation of diploma works by students).

During measurements of the coefficient of reflection from double-gap output system of the 19-beam system of the klystron amplifier we used a ZVB20 electric circuit vector analyzer by Rohde & Schwartz [4]. In order to perform numerical simulations, we used the CST MS software complex [3].

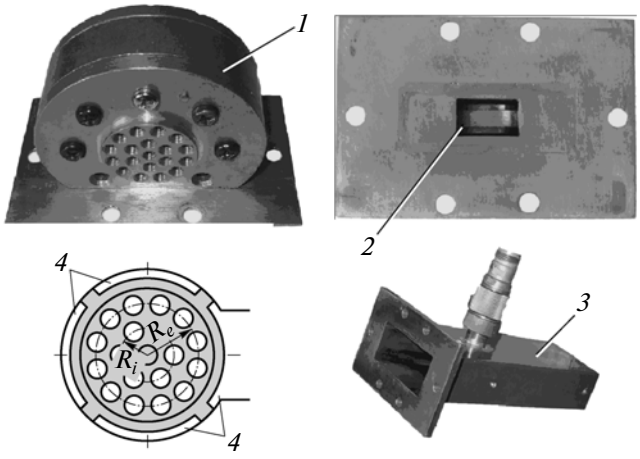

Fig. 1. The model of double-gap output system of a 19-beam klystron amplifier. 1, output resonator, 2, connection diaphragm, 3, segment of output waveguide with CWT, 4, sections of connection cracks between partial resonators.

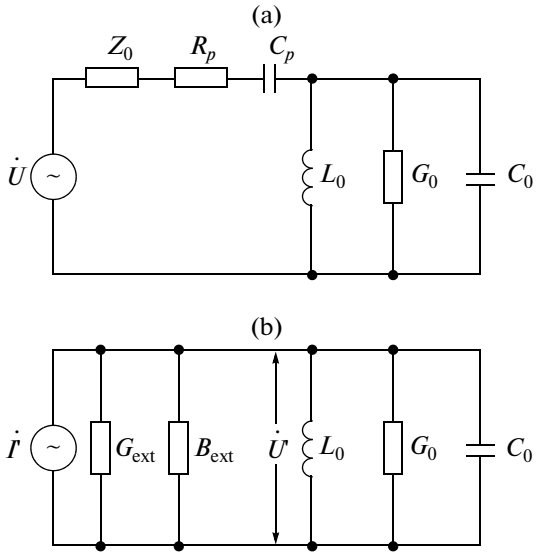

Fig. 2. a), the equivalent measuring scheme for the resonator parameters using a probe, b), the scheme of a resonator-connected system with a current source.

1. THE TWO-TERMINAL METHOD FOR DEFINING THE QUALITY AND RESONANT FREQUENCIES OF CLOSED OUTPUT RESONATOR

The two-terminal method [5, 6] is widely used for measuring the characteristics of microwave resonators, input and output systems created on their basis, and other resonant systems. The corresponding mode for this method is the single-port reflectometer mode for the ZVB20 vector circuit analyzer. This method is used for measuring amplitude–frequency characteristics (APC) $\Gamma(\omega) = |\dot{\Gamma}|$ and phase-frequency characteristics (PFC) $\Psi(\omega) = \arg(\dot{\Gamma})$ of the complex coefficient of reflection $\dot{\Gamma}(\omega)$ from the system under consideration, $\omega = 2\pi f$ – the angular frequency. The obtained frequency characteristics $\Gamma(\omega)$, $\Psi(\omega)$ can be used for defining the dependence of the steady wave coefficient (SWC) on the frequency, the total resistance of the resonator system $Z(\omega)$, etc.

When measuring the quality and resonant frequencies of open and closed microwave resonators we used a corresponding probe or CWT connected to the ZVB20 measuring device [3] via a coaxial cable with a wave resistance of 50 Ohm. The minimum of the reflection coefficient amplitude $\min\Gamma(\omega)$ is reached at the resonant frequency $\omega = \omega_r$. This is used when measuring resonant frequencies during the processing of experimental dependencies $\Gamma(\omega)$.

There are a number of methods that use the two-terminal scheme for determining the quality of closed loaded resonators; these differ from each other in the selection of the measurement points, their position on the frequency axis, the frequency characteristic, the reflection coefficient amplitude, the steady wave coefficient (SWC), power, etc. For instance, let us consider the quality measuring method for three frequency points [6]. For a distinct definition of measurement errors it is convenient to use the least squares method (LSM), based on the linear nature of changes of the reactive resistance of the resonator close to the resonant frequency [7]. We will use exactly this method for defining resonant frequencies ω_r, loaded quality Q_L, connection coefficients β, estimation of casual measurement error, and the qualities of a closed resonator and the output system. It is necessary to note that this method [7] does not allow the estimation of systematic errors of the measurement method itself, which can have significant values; the corresponding estimations for closed resonator will be considered below.

For practical application of the two-terminal methods for obtaining qualities and resonant frequencies [5–7] it is necessary to know the connection value $\beta = P_{ext}/P_0$ of the measuring system with the resonator under consideration, P_{ext}, which is the power of active losses in the source circuit, and P_0, which is the power of thermal losses in the resonator walls. This quantity can be found experimentally (for example, from the SWC value at the resonant frequency) if we know the connection type, which can be defined on the basis of the behavior of the PFC of the reflection coefficient. There are three types [5, 6], which are characterized by their connection coefficient values: (1) Strong connection (greater than the critical one) $\beta > 1$. Increasing of the frequency changes the phase from $+180°$ to $-180°$ passing through zero at the resonant frequency ω_r. (2) Critical connection $\beta = 1$. The phase Ψ has a jump from $+90°$ to $-90°$ at the resonant frequency ω_r. (3) Weak connection (less than the critical) $\beta < 1$. When the frequency increases, the phase Ψ becomes less than $+180°$ and then it increases again, passing through $+180°$ at the resonance (reverse phase behavior). This classification is derived from the analysis of circle diagrams by Smith [5].

Let us consider the estimation of the method of measuring closed resonant systems with the use of a probe. We will assume that when the resonator is excited by the probe it is placed in parallel with the power lines of the electric field, and we will use the parallel equivalent resonator scheme shown in Fig. 2a. Here, L_0, C_0, R_0, $G_0 = 1/R_0$ are the equivalent parameters of the resonator under consideration, viz., inductivity, capacity, resistance, and conductivity of thermal losses; (C_p, R_p) are the connection parameters (capacity and resistance) for the probe. For estimating the error of the two-terminal method using a probe we will introduce an equivalent current source $\dot{I}$ instead of the voltage source $\dot{U}$, which represents the electric circuit vector analyzer (ZVB20), and transform the introduced measurement scheme into a parallel resonator-connected system (Fig. 2b). The expressions for

the active and reactive parts of the conductivity are denoted as:

$$G_{\text{ext}}^{(p)} = (Z_0 + R_p)/[(Z_0 + R_p)^2 + 1/(\omega C_p)^2],$$
$$B_{\text{ext}}^{(p)} = \omega C_p/[(Z_0 + R_p)^2(\omega C_p)^2 + 1]. \quad (1)$$

It can be seen in Fig 2b that the ratio of active power losses in the circuit and power losses in the resonator walls at the resonator frequency ω_r is

$$\beta = \frac{G_{\text{ext}}|U'|^2}{G_0|U'|^2} = \frac{Q_0(\beta)}{Q_{\text{ext}}(\beta)} = \frac{G_{\text{ext}}(\omega_r)}{G_0}$$
$$= R_0(Z_0 + R_p)/[(Z_0 + R_p)^2 + 1/(\omega_r C_p)^2]. \quad (2)$$

The presence of reactive conductivity $iB_{\text{ext}}^{(p)}$ in the transformed equivalent schemes leads to changing the reactive conductivity of the resonator, which can be interpreted as increasing the equivalent capacity:

$$\Delta C_0^{(p)} = B_{\text{ext}}^{(p)}/\omega_0 > 0, \quad \frac{\Delta C_0^{(p)}}{C_0} \approx \sqrt{\frac{\beta}{Q_0(0)}}\sqrt{\frac{\rho}{Z_0}}. \quad (3)$$

The last expression implies that the resonant frequency decreases during the loading of the probe. The following error estimations for the method when measuring the resonant frequency ω_r can be obtained:

$$\omega_r^{(p)}(\beta) \approx \omega_0\left(1 - \frac{1}{2}\frac{\tilde{\Delta C}_0^{(p)}}{\tilde{C}_0}\right), \quad (4)$$

where $\omega_0 = 1/\sqrt{L_0 C_0}$.

The disadvantage of formula (4) lies in the fact that the definition of the relative error (3) contains the wave resistance of the resonator, which is defined ambiguously for resonator systems; this may lead to significant error.

Since the theoretical calculations of the self quality have low accuracy [6]; estimation of the measurement errors of the self quality $Q_0(0)$ must be based on the measurement results. The presented analysis in (1), (2) implies that upon decreasing the connection capacity $C_p \longrightarrow 0$ the quantities $B_{\text{ext}}^{(p)}$, β approach zero. At $\beta \neq 0$ the measured resonant frequency $\omega_r(\beta)$ and self quality of the connected system $Q_0(\beta)$, which consists of the measuring system and the resonator under consideration, differ from the resonant frequency $\omega_0 = \omega_r(0)$ and the self quality $Q_0(0)$ of the closed resonator. Let us consider the expression that results from the definition of loaded $Q_L(\beta)$, self $Q_0(\beta)$ and external $Q_{\text{ext}}(\beta)$ qualities of the resonator:

$$Q_0(\beta) - Q_L(\beta) = \beta Q_L(\beta) > 0. \quad (5)$$

The loaded $Q_L(0)$ and self $Q_0(0)$ qualities of the closed resonator must be equal for the connection coefficient $\beta = 0$. In this way (5) also reflects the error measure in definition of the quality for $\beta \neq 0$. This also points to a method for measuring the self quality of the resonator using the two-terminal method with a probe. The most precise measurement of the quality is obtained with the smallest possible connection coefficient β. Let us introduce the relative error of the two-terminal method:

$$\frac{\Delta Q}{Q} = \frac{Q_0(\beta) - Q_L(\beta)}{Q_0(\beta) + Q_L(\beta)} = \frac{\beta}{2 + \beta}.$$

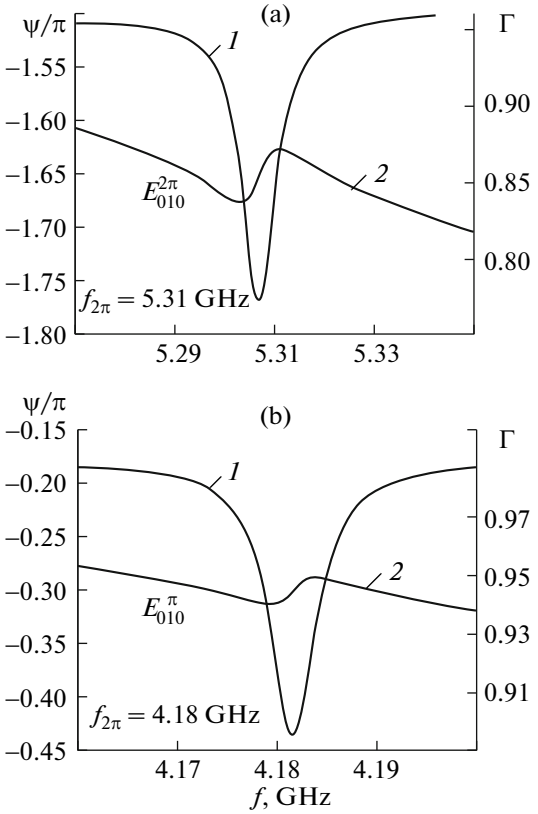

Fig. 3. The amplitudes (1) and phases (2) of the reflection coefficient for the operating (inphase) (a) and parasitic (antiphase) (b) modes of a closed output double-gap resonator during excitation by a probe placed in the central run channel.

The average values for the self $\bar{Q}_0(\beta)$ and loaded $\bar{Q}_L(\beta)$ qualities of the resonator and their systematic method errors ΔQ_0 and ΔQ_L are denoted as

$$\bar{Q}_0(\beta) = Q_0(\beta)(1 - \Delta Q/Q) = 2\frac{Q_0(\beta)Q_L(\beta)}{Q_0(\beta) + Q_L(\beta)}$$
$$= Q_L(\beta)\frac{2 + 2\beta}{2 + \beta} = \langle Q\rangle, \quad \Delta Q_0 = Q_0(\beta)*\frac{\Delta Q}{Q}, \quad (6)$$

$$\bar{Q}_L(\beta) = Q_L(\beta)(1 + \Delta Q/Q) = 2\frac{Q_0(\beta)Q_L(\beta)}{Q_0(\beta) + Q_L(\beta)}$$
$$= Q_L(\beta)\frac{2 + 2\beta}{2 + \beta} = \langle Q\rangle, \quad \Delta Q_L = -Q_L(\beta)*\frac{\Delta Q}{Q}. \quad (7)$$

Figure 3 shows the dependencies of the reflection coefficient module $|\dot{\Gamma}(f)|$ and the phase $\Psi(f)$ of the

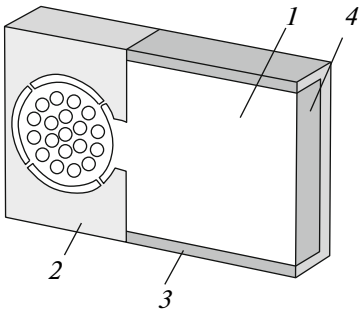

Fig. 4. The section of three-dimensional model of open output system of multiple-beam klystron, built in CST MS environment: *1*, internal volume of the output system, ε_0, μ_0. *2*, walls of the output resonator made of the material σ_r, ε_r, μ_r, *3*, waveguide walls made of the material σ_w, ε_w, μ_w. *4*, waveguide port.

frequency during excitation of the closed output resonator when loading the probe in the central run channel obtained with the ZVB20. In this case the connection diaphragm (Fig. 4) was closed by a metal plate.

We will consider only the 2π-type (operating type) and π-type (parasitic type) of the oscillation mode E_{010}. The behavior of the PFC reflection coefficient (Fig. 3) implies that the measurements were performed in a weak connection mode. The results of the measurement of the resonant frequency, qualities, connection coefficients (index *T*), and the error estimation method and the measurements are presented in Table 1. Only systematic errors of the measurement method according to formulas (4), (6), and (7) are shown. It is necessary to note that for estimating the method error for the frequency f_0^T by the formula (4) we used the wave resistance of $\bar{\rho} = 59$, obtained by averaging the wave resistances for the central, internal, and peripheral run channels. These quantities were calculated similarly [2] and were 75, 64, 37 Ohms, respectively. The relative error of the measurement method [7] for the qualities and resonant frequencies was ≈±1%.

As well, numerical simulations of the multiple-beam double-gap resonator using the module for solving problems of self values of CST MS were performed. The simulation results (index *M*) for the resonant frequency f_0^M are shown in the second column in Table 1. One of the possible ways to estimate the simulation error is the error value for a circular cylindrical resonator without losses, for which a precise analytical solution can be found. It is necessary to note that the dependence of the resonant frequencies on losses in the walls can be neglected with a certain accuracy level for the considered quality values. In this case, the relative simulation error for the frequency is about 0–5% for different sizes of grid cells. At the same time, the geometry of the output system under consideration is more complicated; it contains run channels of a very small diameter and it has edges where electromagnetic waves should be considered differently. Therefore, the estimation described above can be several times greater.

Using the CST MS we performed numerical research on the effective partial conductivity σ_{eff} by direct current for the walls of a closed resonator. This was defined by choosing σ_{eff} during the comparison of the calculated self quality of the resonator with the measurement data for the self quality $\langle Q \rangle = 696$ for the operating mode and it was equal to $\sigma_{\text{eff}} = 7 \times 10^5$ $\text{Ohm}^{-1}\ \text{m}^{-1}$. It is necessary to note that σ_{eff} is defined not only by the wall conductivity, but by the processing quality of the internal surface of the resonator as well; it also depends on the resonator frequency.

2. RESEARCH ON THE OPEN OUTPUT SYSTEM OF A MULTIPLE-BEAM KLYSTRON

In an open output system the output resonator 1 is connected with the output waveguide by the resonant coupling iris (Fig. 1 (*2*)); the output system is excited by the wide-band CWT Fig. 1 (*3*) connected to the measuring complex via a coaxial cable. In this case, obtaining preliminary error estimations for the measuring method is quite difficult. We will consider only the arbitrary measurement errors provided by the least squares method [7]. The model of a 19-beam output system of a klystron amplifier was obtained using CST MS software (Fig. 4). The material wall parameters were defined on the basis of the σ_{eff} obtained above. The wall thickness was significantly greater than that of the skin effect for the selected material walls and the frequencies of the modes under consideration. Excitation of the output system was performed using a waveguide port, which is a numerical analogue of a microwave generator loaded by a rectangular waveguide with the cross section $S_{a \times b}$. The scattering matrix of the single-port system is S_{11}, which is equiv-

Table 1. Comparison of the studied oscillation types of a closed output resonator obtained during simulation and experimental studies

Type	f_0^T, GHz	f_0^M, GHz	$\langle Q \rangle$	Q_0^T	Q_L^T	β^T
π	4.18 (1 + 0.004)	4.10	696	715 – 19	678 + 18	0.055
2π	5.31 (1 + 0.008)	5.28	552	587 – 35	521 + 31	0.13

Table 2. Comparison of the parameters of the operating mode of an open output system, obtained during simulation and experimental studies

Type	f_0^T, GHz	f_0^M, GHz	Q_0^T	Q_0^M	Q_L^T	Q_L^M	β^T	β^M	$(\Delta f/f)^T$, %	$(\Delta f/f)^M$, %
2π	5.24 ± 0.25	5.21 ± 0.03	464 ± 12	435 ± 11	240 ± 16	224 ± 14	0.93	0.94	0.43	0.44

Table 3. The parameters of the studied modes during displacement of the connection diaphragm

Type	δ, mm	f_0^M, GHz	Q_0^M	Q_L^M	β	$(\Delta f/f)^M$, %
π	1.67	4.15 ± 0.02	185 ± 5	183 ± 5	0.011	0.55
2π	1.67	5.21 ± 0.02	365 ± 10	183 ± 5	0.98	0.55

alent to the complex reflection coefficient $\dot{\Gamma}$. In this case, it was built using the method of a non-stationary impulse, realized using the CST MS.

The model of the double-gap output system of a 19-beam klystron was experimentally studied. Figure 5 shows the amplitudes and phases of the reflection coefficients of a multiple-beam output system for the operating 2π mode E_{010}. Figure 5a corresponds to the measurement data and Fig. 5b to the simulation results. The behavior of the phase-frequency characteristics of the reflection coefficient $\dot{\Gamma}$ corresponds to a mode that is close to critical. The results of processing of the experimental data (index *T*), as well as the simulation data (index *M*), are shown in Table 2. The qualities and resonant frequencies obtained with simulation were defined using the least squares method [7], as is done during the processing of experimental data. It is necessary to underline that the fabricated model of the output system has an extremely small operating frequency band. It can be broadened using waveguide filtering systems.

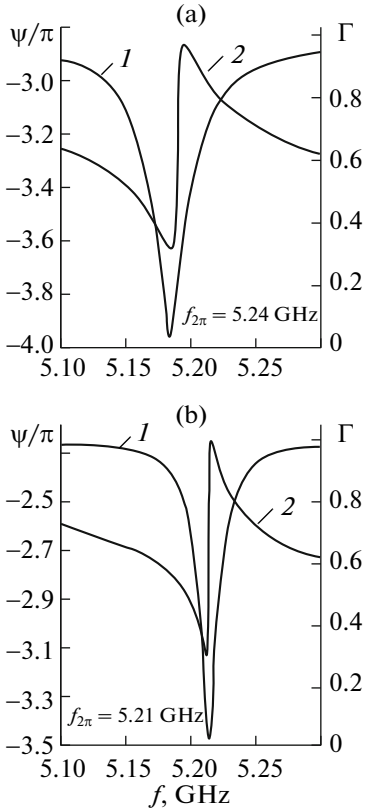

Fig. 5. The amplitudes (1) and phases (2) of reflection coefficients $\dot{\Gamma}$ of a multiple-beam output system for the operating mode, obtained during excitation of the model via CWT (a); obtained during simulation using single-port system (b).

It is necessary to note that the parasitic mode turns out to be closed and is not registered in the output waveguide at the initial position of the connection diaphragm. Due to its high quality, the presence of a closed mode may lead to breakage in the output resonator. During numerical studies on the influence of the position of the output diaphragm on the parameters of the parasitic mode, the module of the reflection coefficient Γ displaced the connection window to the right with respect to the center of the resonator. At the same time both operating and parasitic modes were registered. Displacement of the diaphragm allows a decrease in the self quality of the parasitic mode from $Q_0 = 696$ (Table 1) to $Q_0 = 185$ at $\delta = 1.67$ mm (Table 3). This research has an important practical meaning for designing such devices.

CONCLUSIONS

The well-known two-terminal method for measuring resonant frequencies, qualities, and wave resistances was adopted to the possibilities of the ZBV20 circuit vector analyzer from Rohde & Schwarz.

Comparison of the experimentally obtained parameters with the results of numerical simulation was performed for the double-gap output system of a multiple-beam klystron using the CST MS software package from Computer Simulation Technology. The measured and simulated values of the resonant frequencies for a closed resonator are in good agreement

within the limits of measurement and simulation errors.

It was shown that the operating frequency band of the output system in the output waveguide equals 0.5% without using an agreeing filtering system.

Using numerical simulation it was found that the displacement of the coupling iris allows one to significantly decrease the self quality of the $E_{010}^{(\pi)}$ parasitic mode.

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