Traditional and Novel Vacuum Electron Devices

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***Abstract*—This paper describes some vacuum devices—including conventional and unique multibeam O-type amplifiers and oscillators in the microwave, millimeter wave, and submillimeter wavelength regions of the spectrum, and miniature injection locked M-type amplifiers. Main parameters and operational characteristics are presented. The paper includes a description of synthesis software, which uses "trained" analytical expressions. These codes enable the optimum electrical design and device geometry to be expeditiously determined during the first phase of development.**

***Index Terms*—BWO, klystron, magnatron, multibeam, TWT.**

I. Introduction

In this paper, a brief presentation of the design peculiarities and parameters of several new types of vacuum tubes (single-beam klystrons, traveling-wave tubes (TWTs), and M-type devices) is given. They have an original design and a high level of performance. Among them are multibeam O-type tubes, inductive output tubes (IOTs), high-power broad-band klystrons, miniature klystrons, and millimeter and submillimeter backward-wave oscillators. In multibeam tubes, an ensemble of several parallel electron beams is used. Each beam has a small current and propagates in its own drift channel. As a result, it is possible to overcome the physical restrictions connected with the influence of space charge in a single, large current beam and to obtain serious advantages in build-up of tubes of different types [1]–[3].

In this paper, a brief summary of the synthesis programs of single-beam and multibeam klystrons (MBKs), CC TWTs, and single-beam helix TWTs is given. It is a new and unique software product intended for use in the initial stages of tube design and it has shown good results.

The main design features and parameters of miniature amplifiers based on injection, i.e., locked magnetrons, are also described [4].

The materials included in this paper have been reported at the *International Vacuum Electronic Conference 2000* [5].

II. Multibeam Inductive Output Tubes

The IOT is a hybrid device integrating operation mechanisms and some elements of tetrodes and klystrons.

Appearance of this device in televison (TV) technology became possible due to the efforts of its creators Haeff [6] and, some time later, Preist and Shrader [7].

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From 1995 to 1999, the authors, using experience in multibeam klystron development, created a multibeam IOT [8]. Its principal scheme is similar to the well-known single-beam IOTs. The multibeam structure of IOTs appeared to be attractive for several reasons. One of the most important parameters is the low voltage, similar to TV klystrons, and hence, the possibility of klystron replacement without considerable change of the existing power supply in a TV transmitter.

Higher gain in comparison with a single-beam IOT is an important parameter.

In the process of development, the principal problems of a high-power IOT were solved, including the specific ones connected with the multibeam structure.

The following are two examples. The problem of thermo-mechanical stability of the grid structure has been solved through application of a massive Mo grid holder supporting the grid structure, which contains 18 partial Mo grids corresponding to the number of beams [Fig. 1(a)]. The cathode has a collective heater and 18 spherical emitting spots on the cathode flat surface [Fig. 1(a)]. The diameter of the partial grids and cathodes is 10 mm. Thus, thermal and mechanical stability were achieved, as well as ease of grid fabrication. High-frequency breakdown in the output cavities was excluded by creating a nonresonant connection loop between the active and the passive cavities.

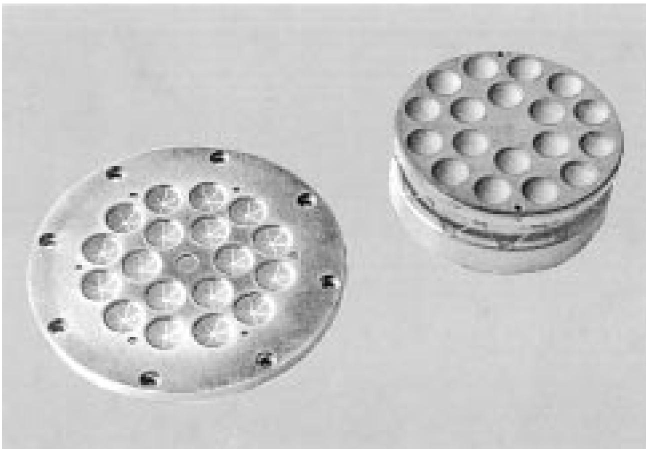
At the present time, two modifications of the multibeam IOT with liquid and air-cooling of the collector for 60 and 30–40 kW applications have been developed. The appearance of the assembled device is shown in Fig. 1(b). Parameters of the devices are given in Table I. The value of the voltage deserves particular attention. It is lower than in single-beam IOTs. The tube has good amplification. According to computer simulations, there is potential for increasing the amplification up to 25–26 dB by increasing the input cavity Q-factor.

III. High-Power Multibeam Klystrons (MBKs)

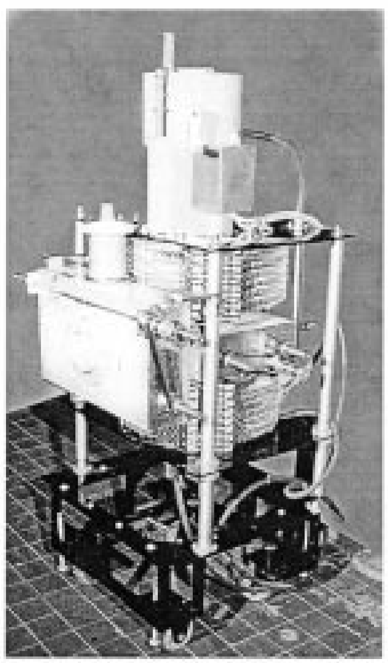
In this section, high-power multibeam klystrons (MBKs) operating in the fundamental oscillation mode of the resonators, as well as the factors limiting power increase and ways of further power increases, are discussed.

Table II gives the main parameters of high-power broad-band MBKs. Fig. 2 schematically presents the cross section of a typical device structure. The high-power MBKs have the following features:

— operation in the fundamental (lowest) mode of resonators;
— compact "packing" of individual channels;
— small beam area convergence in every individual gun (3–5);



a)



b)

Fig. 1. (a) Cathode and grid structure in high-power multibeam IOT. (b) View of the complete assembled device.

— use of a control electrode (grid);
— number of beams 15–36;
— coupled cavity (filter) in the output stage;
— solenoid focussing.

As it is evident from Table II, the output power of the MBK decreases rapidly at short wavelengths. The experimental investigation and estimates performed indicated the following basic factors limiting the power in such MBKs [9], [10]:

— small size of the cavities at short wavelengths;
— limited cathode current density and small convergence of the individual beam in the gun;
— limitation of the overall beam perveance connected with the danger of a virtual cathode appearance in the collector;

TABLE I
BASIC PARAMETERS OF MULTIPLE BEAM IOT

Parameters	Liquid cooled collector	Air cooled collector
1. Frequency range, MHz	470 to 810	470 to 810
2. Maximum output power (vision only), kW	60	40
3.Maximum output power (common amplification), kW	35 vision 3.5 aural	20 vision 2.0 aural
4. Minimum power gain, dB	24	22
5. Beam voltage, kV	26	20
6. Beam current, A	3.9	3.0
7. Grid to cathode bias voltage, Vg	-70 to -100	-70 to –90
8. Heater voltage, Vdc	12.6	12.6
9. Heater current, A	21	21
10. Electromagnet voltage, V	20	20
11. Electromagnet current, A	10	9
12. RF input connector	Type N	Type N
13. RF output	3 1/8 inch 50 Ω coaxial line	3 1/8 inch 50 Ω coaxial line
14.Weight, kg		
- input cavity	26	26
- output cavity system	49.5	49.5
- tube	26.5	40.0
- electromagnet assembly	182.5	182.5
15. Cooling air flow to cavities and cathode terminal, m^3/h	2.8	2.8
16. Cooling water flow required to collector, l /min	38.0	-
17. Cooling air flow to collector, m^3/h	-	1000
18. Inlet air temperature, °C max	-	45.0

— electrical breakdown in the gun;
— high bandwidth requirements.

Quantitative estimations and development experience demonstrated that at long wavelengths, and with typical voltages from 24 to 30 kV, the output power of MBKs of the type considered is limited by the overall beam perveance (usually these are microperveances from 10 to 15).

In the short waveband, the power is limited by electrical breakdown, by the possibility of fulfilling requirements to the bandwidth, and by cathode current density limitations. In particular, in the case of a strict requirement of the field intensity in the gun of 5 kV/mm, the maximum power for short waves (3–5 cm) is limited mainly by this factor (breakdown).

From Table II and the performed calculations, it follows that the pulsed output power of a broad-band MBK at a wavelength of 3 cm is 120 kW. A further increase of MBK power might be realized through the application of resonators working in higher modes. In this case, the effect of the majority of the above limiting factors diminishes significantly. We have constructed MBKs on two types of such resonators operating in the higher modes shown as a schematic cross section in

In both cases, the power of the MBK in the X-band is increased by a factor of 2 to 3 in comparison with the device in the first line of Table II. However, the bandwidth of the MBK with cavities of type 2 in Fig. 3 is not large and is comparable to the bandwidth of the corresponding single-beam klystron. On the whole, MBKs in the higher mode can be considered as a kind of active power combiner.

MBKs at the higher mode possess a small number of multibeam "trunks" or single beams (3 or 6, see Fig. 3).

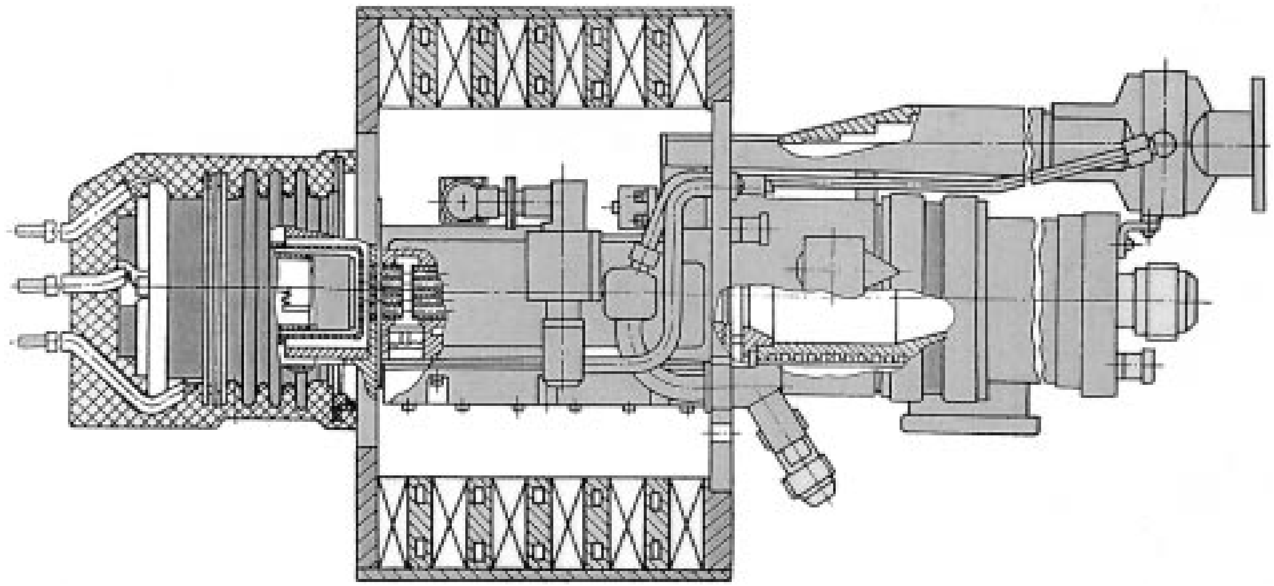


Fig. 2. Drawing of a high-power multibeam klystron installed in its electromagnet. Cathode and collector units and the electromagnet are given in a cross section.

TABLE II
PARAMETERS OF MBKS WITH FUNDAMENTAL MODE RESONATORS

Parameters	KPA – 214-10	KPA - 214-4	KPA - 214-5	KPA - 214-3	KPA - 214-2	KPA - 214-1
λ, cm	3	5,5	5,5	7	10	15
Power supply, kW	400	720	2000	1100	1650	2010
Output pulse power, kW	120	200	600	500	600	800
Output average power, kW	3	11	12	17	12	14
Bandwidth, MHz	200	175	200	200	200	200
Beam voltage, kV	24	24	33	29	31	32
Number of beams	15	24	23	24	36	36

To increase the MBK power to the 75–100 MW range at 3 cm wavelength, the number of beams must be increased to at least 18, thus increasing the number of the operational modes of the resonators.

Under these conditions, rather serious difficulties arise which are connected with the provision of the necessary frequency separation of the oscillation modes, equal amplitudes of the field in the individual gaps, creation of a satisfactory input and output energy, choice of optimal focussing systems, provision of the required bandwidth, etc.

At present, this task is still at the stage of computer simulation.

IV. MINIATURE MULTIBEAM KLYSTRONS (MMBKS) AND MINIATURE INJECTION-LOCKED MAGNETRONS (ILMS)

Miniature airborne and ground transportable radars, as well as multichannel satellite communication and telemetry systems operate, as a rule, in the frequency range of 2–18 GHz.

The output parameters of their transmitters, depending on the system specifications, vary in rather wide limits:

— the output power—from 20 to 1000 W;
— amplification bandwidth—from 20 to 250 MHz;
— gain—from 15 to 45 dB.

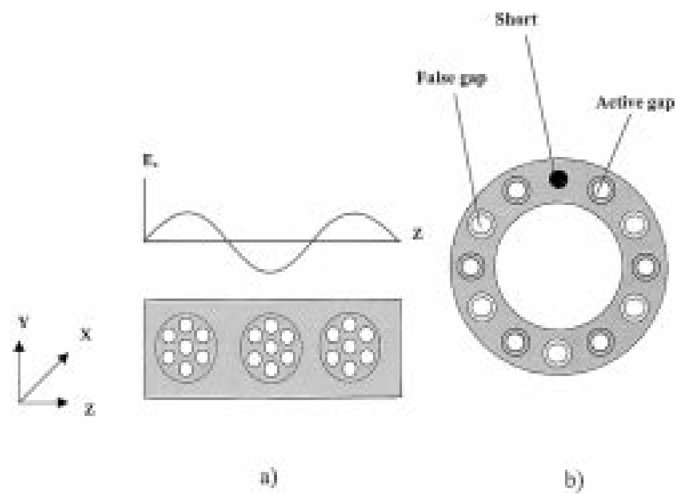


Fig. 3. Simplified cross sections of resonance structures of MBK operating in higher modes: A)—three multibeam in-line positioned "trunks" and the field distribution; B)—six circular positioned beams (active gap); the rest are the false gaps and the short for fixing of the field distribution; the $\pi/2$ operating mode.

High stability of the signal phase and low levels of intermodulation products are necessary in the case of applications for communication purposes.

Common for all systems are the requirements of stable operation under conditions of severe mechanical loads, conduction or air-cooling, and short warm-up times (down to several seconds).

The most severe and urgent requirements are put to the weight and size of the output amplifiers, which must be as small as possible. Miniature MBKs (MMBKs) and injection-locked magnetrons (ILMs) are developed to fit these demands, all of them being packaged with $SmCo_5$ permanent magnets.

A. Miniature Multibeam Klystrons With Cavities in the Fundamental Mode

The structure of MMBKs is common to that of the MBKs described in [2]. The main difference between the MMBK and

TABLE III
MAIN PARAMETERS OF VARIOUS MMBKS

Freq. [GHz]	Pout [W]	Duty Cycle	Δf [MHz]	Gain [dB]	Voltage [kV]	Current [mA]	Weight [kg]	Warm up time*	Cooling
5.8-6.25	100-200	CW	40-50 (-1dB)	40	1.2-1.7	320-420	1.5	3 min.	A
15	50	CW	40 (-1db)	40	1.5	200	2.0	3 min.	C
13-14	500	0.33	60 (-1dB)	40	2.2-2.5	600	1.0	15s	C/A
16-18	400	0.33	40 (-2dB)	45-50	2.3-2.5	600	0.9	15s	C/A
8.5	30-100	0.02	100 (-1.5dB)	40	1.5-2.0	400	1.2	60s	C/A
9-10	400-500	0.02	50 (-1dB)	40	2.5-3.0	500	0.9	60s	C/A
16	500	0.01	185 (-1dB)	40	3-4	1100	1.2	60s	C/W

* - warm up time from a cold state,
C – conduction cooling (at short time operation);
A – air cooling, W – water cooling (prolonged operation)

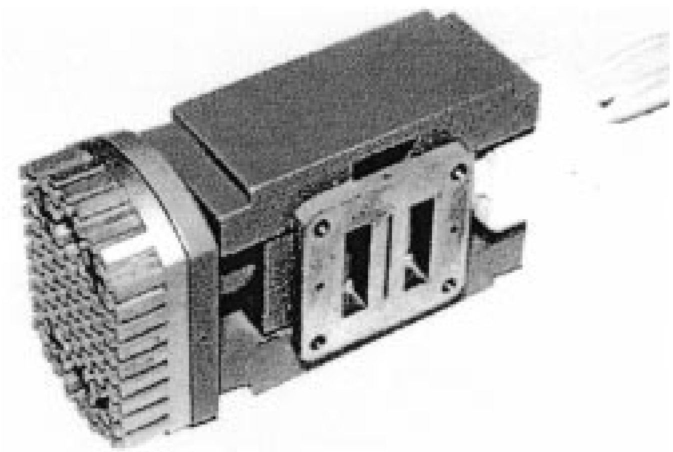


Fig. 4. General view of a packaged MMBK. Operating frequency 15 GHz, output pulsed power 300 W, average output power 100 W, bandwidth up to 100 MHz, cathode voltage 2.5 kV, control pulsed voltage 500 V, and weight 1.2 kg.

other MBK types is determined by their modes of application: all constructive elements of the klystron—the resonance system with frequency adjusting devices, the cathode heater unit, the collector unit, as well as the klystrons as a whole—must be sufficiently rigid to withstand severe mechanical loads up to 20 g and more, and at the same time provide reliable performance under conditions of great environmental temperature changes in the interval from -65 ° to 85 °C. This is achieved by the design of compact thermo-compensated construction. Fig. 4 shows one typical sample of the MMBK. Fig. 3.

Low cathode voltages, which are inherent to MBKs, enable the reduction of the klystron length and magnet interpole gap, thus making possible a significant decrease in the mass and size of the klystron. As a rule, MMBK operating in the X and Ku frequency bands have 5–7 resonators, 18–19 beams, and the same number of partial cathodes impregnated with BaO. The length of the beam channels is 20–30 mm, the diameter of every channel (drift tube) is 0.5–0.7 mm, whereas the diameter of every partial cathode is 0.4–0.6 mm. The typical microperveance of every partial electron beam is 0.2–0.3 which results in an integral microperveance of as much as 3.6–5.4.

The main MMBK parameters are given in Table III. Here, attention must be drawn to the low voltage needed to achieve the rather high output power and small weight of the devices. In some devices, the power/mass coefficient reaches 500 W/kg. The lifetimes of the tubes vary from hundreds of hours up to 10 000 h, depending on the application. MMBKs are successfully applied in a number of important applications including in the transmitter of the communication and telemetry systems in the Russian cosmic orbit station “Mir.”

The trends for further research include: MMBK bandwidth extension up to 2–3%, efficiency increases, and increases of MMBK lifetime for communication systems to over 10 000 h.

B. Miniature Injection-Locked Magnetrons for Communication Systems

Miniature ILMs are a possible alternative to TWTs or klystrons in systems where high efficiency, coherency in a narrow bandwidth, compact size, and long lifetime are required. Due to their efficiency, temperature, and radiation stability, miniature ILMs also have advantages in comparison with transistor amplifiers [4]. To achieve a bandwidth of 1–2% at a gain of 15 dB, the tube must be loaded to the level of $Q_{\rm ext}$ of about 18–36. In such conditions, the full free-running frequency shift of ILMs is large, thus the real locking bandwidth can significantly differ from the theoretical value. The required locking bandwidth must be enough to compensate for the tube frequency drift due to temperature change, voltage instability, output RF-load variation, and the natural frequency shift with life. All frequency shifts increase proportionally to $1/Q_{\rm ext}$, and limit the maximal available gain (MAG) of the ILM. It can be shown [4] that the $\mathrm{MAG} = 4/R^2$, where R is the total frequency factor determined as a sum of normalized frequency shifts caused by any external influences: $R = \sum Q_{\rm ext}|\delta f_i|/f_o$.

The best solution is an integration of a miniature ILM with a high-power microstrip circulator to a single device [Fig. 5(a)]. A special unmatched circulator circuit allows fine frequency tuning and RF-load optimization at the magnetron output.

The modified interdigital resonant system of the ILM [Fig. 5(b)] can be loaded easily to the required external $Q_{\rm ext}$

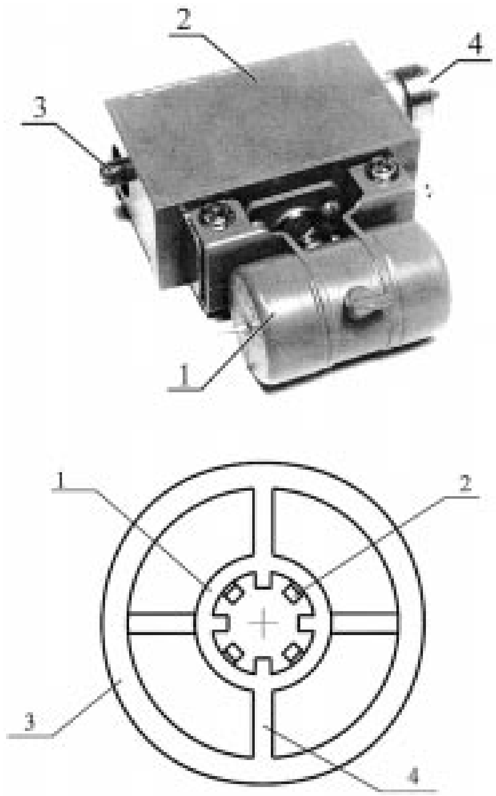


Fig. 5. (a) General view of the miniature ILM packaged with the high-power microstrip circulator; operating frequency 4.5 GHz, power 35 W, efficiency $\geq 50\%$, weight 250 g: 1—magnetron; 2—circulator; 3—RF-input; and 4—RF output. (b) Schematic cross section of the resonator system of miniature magnetron: 1—ring-type strap; 2—interdigital anode vanes; 3—shell; and 4—inductive vanes.

TABLE IV
GENERAL PERFORMANCE OF ILMS

Type	Frequency [GHz]	Output Power [W]	Input Power [W]	Locking Bandwidth [MHz]	Gain [dB]	Efficiency [%]	Weight [g]
MA1	2.5	25	0.75	40	17	51	800
MA2	4.5	35	2.0	60	12.5	52	250
MA3	6.0	25	0.25	30	20	51	250

level. This resonance structure provides an effective mode frequency separation (more than 40%) and an extra low second harmonic level (of less than −60 dB) without any output filter. Miniature ILMs have a sintered nickel powder cathode with a thick oxide coating. Such oxide cathodes provide lifetimes as long as 3000–10 000 h at current densities from 0.10 to 0.25 A/cm^2. Table IV gives the characteristics of some integrated ILMs.

V. MILLIMETER AND SUBMILLIMETER BACKWARD WAVE OSCILLATORS (BWOS)

Today, millimeter and submillimeter waves are more and more actively used in various spheres of science and technology. To master these frequency ranges, broad-band oscillators are indispensable. Backward wave oscillators (BWOs) best suit these purposes.

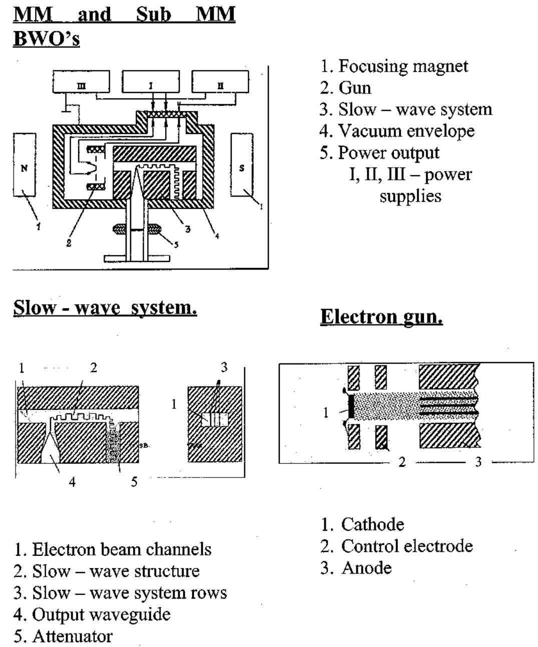


Fig. 6. Scheme of BWOs operating in millimeter and submillimeter wavelength.

A family of electronically tunable BWOs that continuously covers the millimeter and submillimeter ranges has bean created [11].

The schematic structure of these BWOs is shown in Fig. 6. Specific features of these BWOs are as follows:

— multibeam design;
— multirow slow wave structure (SWS) (interdigits or digit comb), manufactured by electro-erosion;
— magnetically restricted $B = (5–6)\ B_{\rm Bril}$ tape electron beams;
— two or three electrode guns without beam compression;
— cathodes:
  a) metal alloy cathode: dimensions from 0.5×0.6 mm^2 to 0.1×0.3 mm^2; warm up time 1 s; cathode current density up to 100 A/cm^2; cathode temperature 1550–1600 °C;
  b) impregnated cathode: dimensions from 0.1×0.3 mm^2 to 0.7×0.3 mm^2; cathode current density up to 300 A/cm^2; cathode temperature 1250–1270 °C;
— permanent focussing magnets made up of $SmCo_5$ or FeNdB are applied to packaged tubes (mm band); unpackaged tubes (submillimeter band) usually use electromagnets;
— extremely small SWS dimensions: pitch of SWS 0.025–0.15 mm; height of digit 0.4–0.5 mm; single row thickness 0.02–0.06 mm; and inter-row distance 0.04–0.16 mm.

The success in creation of such BWOs can be attributed to the following:

— the choice of the multibeam multirow structure, which resulted in low voltages, small weight and size, and a high power;

TABLE V
PARAMETERS OF MILLIMETER AND SUBMILLIMETER BWOs

Packaged BWOs

Parameters	OB – 69	OB - 70	OB – 71	OB – 86	OB – 1
Frequency Range [GHz]	36 …55	52 … 79	78 … 119	118 … 178	177 … 260
Output Power(min) [mW]	15 …40	12 …30	6 … 30	6 … 20	6 …15
Voltage [V]	400…1200	400…1200	500…1500	500…1500	700…1900
Current [mA]	20…25	20…25	20…25	20…25	15…22
Dimensions: Diameter [mm]	76	76	76	76	82
Length [mm]	64	64	64	64	84
Weight [kg]	1	1	1	1	1

Unpackaged BWOs

Parameters	OB-30	OB-32	OB-80	OB-81	OB-82	OB-83	OB-84	OB-85
Frequency Range [GHz]	258… 375	370… 535	530… 714	690… 850	790… 970	900… 1100	1070… 1200	1170… 1400
Output power (min) [mW]	1…10	1…5	1…5	1…5	0.5…5	0.5…3	0.5…2	0.5…2
Voltage [kW]	1…4	1…4.5	1.5…6	1.5…6	1.5…6	1.5…6	1.5…6	1.5…6
Current [mA]	25…40	25…40	30…45	30…45	30…45	30…45	30…45	30…45
Magnetic field [Gs]	7000	9000	10000	10000	11000	11000	11000	11000
Cooling	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid
Weight [g]	300	300	300	300	300	300	300	300

— the choice of interdigital SWS and electro-erosion method of the fabrication, which provided high precision of fabrication for small sizes resulting in the possibility of moving further on into the submillimeter band.

Table V presents parameters of packaged BWOs with permanent magnets (millimeter band) and unpackaged BWOs (submillimeter band). As one can see, the BWOs cover millimeter and submillimeter bands up to a wavelength of 0.2 mm. These are widely used now in various equipment in Russia and other countries (United States, Canada, Germany, France, Japan, etc). They have been applied as voltage tunable signal generators in synthesizers, spectrometers, receivers, medical equipment, and others.

Today, the development of millimeter and submillimeter BWOs are going in the following directions:

— promotion of packaged design into the area of submillimeter waves;
— more extensive application of FeNdB magnets;
— reduction of the consumption power by recuperation of electron beam power in the collector;
— decreasing of beam interception, etc.

VI. CODES FOR TWT AND KLYSTRON SYNTHESIS

The critical solutions concerning the future design of the device are usually adopted in the initial stages of discussion or development. It is very important to have a numerical technique permitting the selection (and synthesis) of a design and the mode of operation of the device instantly taking into account the mutual relations of the basic units of the device and possible restrictions on its design, fabrication technology, and operation. In multibeam devices a choice of an optimum design is significantly more complicated owing to the appearance of an additional degree of freedom—the number of beams, which essentially increments the quantity of possible versions and accessible compromises.

The codes for synthesis of single-beam and MBKs (SYNTEZ) and CC TWT (SYNTWT), and single-beam helix TWT (EXPRES), were developed in the early 1980s and successfully exploited in development [12].

In the restricted space of this paper it is impossible to describe explicitly the mathematical details used in the codes of synthesis. The software uses analytical relations, which interlink the input (design, material, regime) and the output (power, frequency, bandwidth, gain, etc.) parameters by a chain of the functional dependencies. For example, in the code EXPRES, the

TABLE VI
EXPERIMENTAL AND CALCULATED PARAMETERS OF SINGLE BEAM BROADBAND KLYSTRONS

Parameters	Experiment		Computation		
	Device 1[11]	Device 2 [12]		Device 1	Device 2
Frequency, GHz	8	3	Input Data (Requirements)	8	3
Output Power, kW	8.9	255		8.9	255
Perveance, 10^{-6} I/V$^{3/2}$	1.25	2.0	Restrictions	1.25	2.0
Channel Diameter, mm	2.4	9.4		2.4	9.4
Voltage, kV	13	40	Calculated parameters	12.96	40.05
Bandwidth, %	2	9.2		2.1	9.6
Efficiency, %	37	39.8		37.2	39.7
Characteristic impedance ρ of active output resonator, Ohm	150	160		153	154

relation (1) has been used for calculation of the electronic efficiency of the helix TWT. It is similar to the expression, which was published earlier [13]

$$\eta_e = \frac{2\mathbf{C}(1+\mathbf{b})[1+0.1\mathbf{q}+1.25(0.1\mathbf{q})^2]^{-1}}{1+2\mathbf{C}}. \qquad (1)$$

Here b, C, and $q = 4QC$ are the Pierce parameters which depend on the electrical specifications and the geometric parameters of a device. The parameters of the helix (phase velocity, interaction impedance) are calculated using the relations from [14].

The analytical models of the basic units of klystrons and TWTs (containing only algebra and the elementary functions) created at the development of the synthesis codes have considerable significance by themselves, and they are still useful in the analysis. The solution of a synthesis problem requires the inversion of functional relations, i.e., the expression of the input quantities (used in the analysis of the tube) through the output ones. Inverting the relations and organizing of the synthesis procedure has required the solution of a system of nonlinear equations.

In particular, in the code EXPRES the system of three nonlinear equations, $C = C(b, C, \eta)$, $\eta = \eta(b, C, \eta)$, and $b = b(b, C, \eta)$, was solved by iterations, which converge quickly. As a result, the Pierce parameters b, C, d and q, efficiency of the device, beam current, and also a set of geometrical parameters (lengths of the TWT sections), radius of the beam, current density of the beam, amplitude of a magnetic field, dimensions, and weight of a PPM have been found. Finally the calculation of an optimum expression for different numbers of collector stages is implemented [15], [16].

The resulting codes make it possible to determine (synthesize) optimum geometrical parameters and electrical modes of operation for the device based upon the specification of its parameters (output power, frequency, bandwidth, gain, etc.) and a set of design constraints, e.g., restriction on a minimum permissible diameter of the channel. The set of possible designs is produced at the output of the code, the final selection being made by the user.

The synthesis codes cannot replace the conventional analysis programs. The purpose of the synthesis is, first of all, a fast estimation of a hypothetical device having specified parameters and elaboration of the initial design for subsequent rigorous calculations.

TABLE VII
EXPERIMENTAL AND CALCULATED PARAMETERS OF MULTIBEAM CC TWT

Parameters		Computation	Experiment
Frequency, GHz	Input data (Requirement)	10	10
Bandwidth, %		6	6
Power, kW		5	5
Gain, dB		13	-
Number of beams		18	18
Voltage, kV	Calculated And Experimental Parameters	8.3	8.4
Total current, A		2.56	2.70
Total perv. μ		3.39	3.50
Efficiency, %		23.5	22.0
Gain, dB		13	11.5

In some cases, the final design of the device is more complicated, but nevertheless the obtaining of a simple initial approach is very useful.

In Table VI, the results of the code SYNTEZ are compared with experimental data for the example of two single-beam klystrons described in [17] and [18]. The comparison was carried out as follows. With the help of SYNTEZ a design (geometrical dimensions of cavities, etc.) and electrical mode of operation of a klystron (voltage, current), providing the maximum of klystron bandwidth at the maximum efficiency, were determined. The values of an output power and wavelength were taken from experiment [17], [18]. The synthesis of these klystrons was conducted with the following constraints:

1) microperveance of the beam does not exceed that of the experimental specimen.
2) the diameter of the drift tube channel is not less than in the experimental specimen.

As it follows from Table VI, the results of the calculation are in good agreement with experimental data.

In Table VII, the synthesis results of multibeam one-section transparent ("see-through") CC TWTs under the program SYNTWT are given.

Parameters of an actual tube fabricated on the basis of these calculations are also given here. From Table VII it is evident that the real measured parameters of multibeam CC TWT have only small differences from the parameters calculated by the synthesis program used on the initial stage of designing of this tube. Today, this tube is one of the multibeam CC TWTs in mass production.

The synthesis programs of TWTs and klystrons, briefly described, have successfully been used in developments for many years.

VII. Conclusion

In this paper, several trends and developments of microwave tubes were described. Some of the devices described are new classes of microwave tubes and their principles of operation were described. Also, technical details of the tubes were described: features of construction, methods of manufacturing, materials, etc. Parameters of the devices and areas of their application were represented. Finally, a plan for further development was pointed out.

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