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CONFERENCE PROCEEDINGS

VOLUME 2

TELECOMMUNICATIONS RESEARCH INSTITUTE

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S. Rodikov, Y.Bragina, B. Savin, A. Morosov, V. Tsutskov, S. Pustovalov: *Special Research Bureau of MPEI, Moscow, Russia*

SESSION A9 **Aula** **Wednesday, 11^{00}**

ELECTROMAGNETIC MODELLING FOR ADVANCED APPLICATIONS

Session Chairman: Wojciech GWAREK
Warsaw University of Technology, Poland

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Z. Nosal , A. Abramowicz: *Warsaw University of Technology, Poland*

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J.Macháč, J. Zehentner: *Czech Technical University in Prague, Czech Rep.*

A9/3 MULTIMODE ANALYSIS OF WAVEGUIDE DISCONTINUITIES USING THE CONCEPT OF GENERALISED SCATTERING MATRIX AND POWER WAVES
A. Kręczkowski: *Telecommunications Research Institute, Gdańsk, Poland*
M. Mrozowski: *Technical University of Gdańsk, Poland*

A9/4 ADVANCED DESIGN OF RE-ENTRANT BEAM DISTRIBUTED-EMISSION CROSSED-FIELD TUBES
G. Churyumov, T. Frolova, A. Gritsunov, S. Terehin: *Kharkov State University of Radio Electronics, Ukraine*

A9/5 ESTIMATION OF INTERNAL DISTRIBUTION OF TEMPERATURE INSIDE BIOLOGICAL TISSUES BY MEANS OF MULTIFREQUENCY MICROWAVE THERMOGRAPH
B. Stec, A. Dobrowolski: *Military University of Technology, Warsaw, Poland*

ADVANCED DESIGN OF RE-ENTRANT BEAM DISTRIBUTED-EMISSION CROSSED-FIELD TUBES

G. I. Churyumov *, T.I. Frolova # A.V. Gritsunov # S.N. Terehin

Abstract — The computed and measured results for the re-entrant beam, distributed emission, crossed-field tubes are presented. The computer modelling is carried out by a particle-in-cell method (PIC-method) in quasi-periodic, single-mode and non-relativistic approximations. The PIC-method provides an accurate mean to accomplish the computer modelling of the classical continuous-wave magnetron generators including the low-voltage magnetron as well as the millimeter wave magnetron. The 3-D self-consistent mathematical model of the non-traditional magnetron generator (combined magnetron) is considered.

INTRODUCTION

The creation of new more effective microwave tubes (both generators and amplifiers) is an important and currently central problem. The solution of the given problem is of great importance both for further advancement of radar-tracking and communication systems, industrial and household microwave heating as well as for scientific researches in plasma physics, laboratory and medical applications, etc. [1]. The future of the re-entrant beam, distributed emission, crossed-field tubes was shown to be associated with an application of the low-voltage magnetrons, including the pulsed and continuous-wave magnetrons and crossed-field amplifiers to operate in millimeter-wave band. Particular emphasis of the researchers is being placed to the new methods of a frequency tuning and perfection of operation modes (for example, the development of the new re-entrant beam, distributed emission, crossed-field amplifier (CFA), modulated by pulsing only r.f. input signal (self-modulation) [2]). In order to achieve these objectives it is necessary to extend considerably the theoretical and experimental investigation including the computer modeling of an interaction process of an electron beam with a slow electromagnetic wave in the crossed-field tubes. As it has been shown in [3], there are two lines of the investigation of the crossed-field tubes. On the one hand, it connected with the investigation of the existing (classical or traditional) designs of the tubes. On the other hand, of special interest is the investigation of new (non-traditional) crossed-field tubes (generators and crossed-field amplifiers).

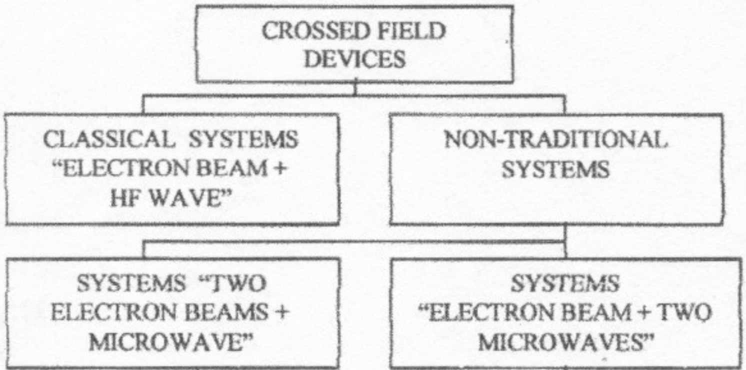

Fig. 1.

This paper deals with the theoretical and experimental researches of the magnetron generators both classical and non-traditional designs. In both cases the mathematical modelling of the electron-wave processes is considered in 2-D and 3-D approximation over all the interaction space (a multi-periodical model [4]) as well as on one-wavelength cell moves with the velocity determined by the delay

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line (a quasi-periodical model [5]). The application of full-scale computer modelling allowed not only to calculate principal parameters of tubes, and to evaluate their limiting values as well as to explain the possible anomalous physical appearances to schedule paths of their elimination. Particular attention has been given to the investigation of the physical processes of an electron-wave interaction in the classical magnetrons for microwave heating (including the low-voltage magnetrons), the classical millimeter wave magnetrons as well as in the magnetrons having a non-traditional design (combined magnetrons).

Fig. 1 shows schematically the classification of the re-entrant beam, distributed emission, crossed-field tubes. The classical crossed-field tubes can be considered as electron - wave systems, in which a re-entrant electronic beam interacts with a (synchronous) slow electromagnetic wave («the re-entrant electron beam + RF wave» systems). As it has been shown in [3], the non-traditional crossed-field tubes are examples of future advanced technologies, which are connected with the creation of the new tubes. These tubes are defined as electron - wave systems, in which a re-entrant electronic beam interacts with two synchronous electromagnetic waves («re-entrant electronic beam + two RF waves» systems), or two re-entrant electronic beams interact with a synchronous electromagnetic wave («two re-entrant electron beams + RF wave» systems).

The particle-in-cell (PIC) method was chosen as the basis for computer modelling of an electron-wave interaction in the crossed-field tubes [6]. To carry out the computer modelling the 2-D and 3-D mathematical models in one-wave approximation are used. Their main equations can be considered as a self-consistent system of integro-differential equations which include the motion equation of an electron beam (or the electron beams for non-traditional tubes), the excitation equation for electromagnetic waves propagating in the interaction space of the tubes, and the Poisson equation for a calculation of the space-charge forces.

<u>*The investigation of the classical crossed-field tubes.*</u> For the investigation there was chosen the typical continuous-wave magnetron with the following parameters: frequency = 2.45 GHz; anode radius = 0.0044 m; cathode radius = 0.00195 m; resonators number = 10; magnetic field = 1700 G. The multi-periodical 2-D model of the magnetron was used. The prime objective of a study of an electron-wave process in given magnetron is to understand the mechanism of development of the physical processes in an interaction space of the tube. The comparison of the results obtained of the computer modelling with experimental data allowed not only to improve the algorithm of the mathematical model as well as to use its for the study of the physical processes in new tubes.

The results of a computer modelling of the electron-wave interaction in the magnetrons of a classical design are presented in Fig. 2.

Fig. 2, a shows the typical distribution of a space charge in the magnetron when the anode voltage equals 3.9 kV. The computed parameters are in a good agreement with experimental data in a wide range of the anode voltage (from 3.7 kV to 4.0 kV). The difference between the indicated parameters does not exceed 5 percent.

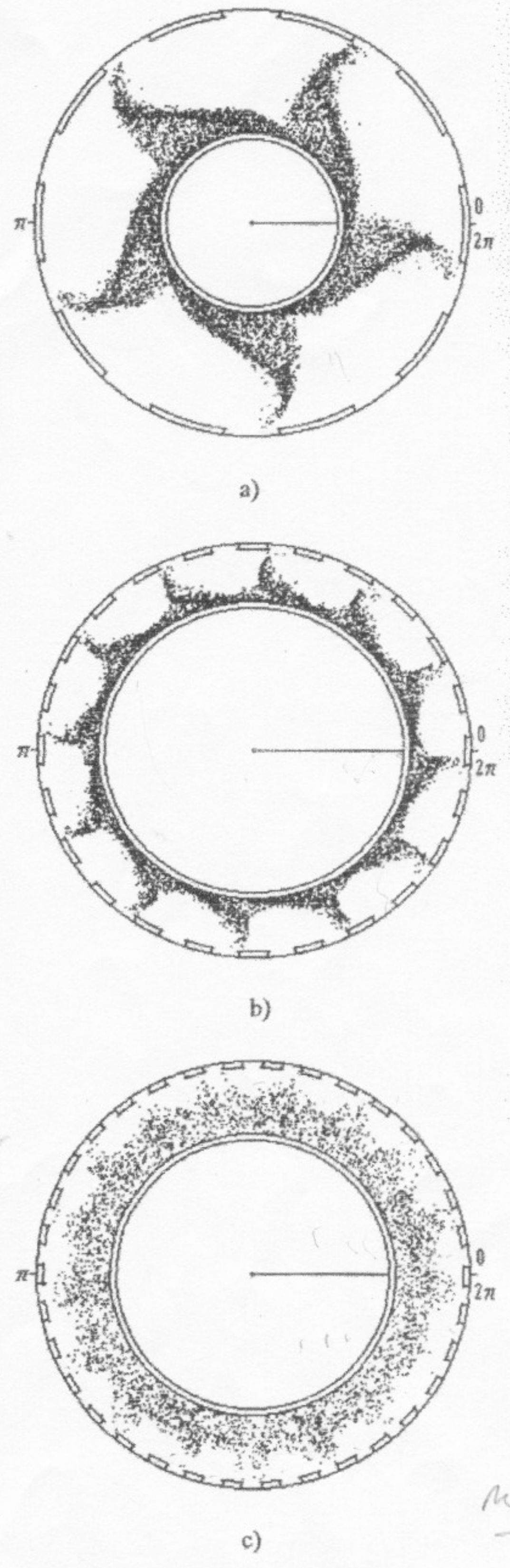

Fig. 2. Space charge distributions in the classical magnetrons

Fig. 2, b. shows the space charge distribution in the low-voltage magnetron, in the case when the anode voltage equals 0.8 kV. For a simulation there was used the magnetron having the following parameters: frequency = 2.45 GHz; anode radius = 0.00425 m; cathode radius = 0.0032 m; resonators number = 24; magnetic field = 1500 G. It has been shown that the magnetron has a output power of over 0.74 kW and an electronic efficiency exceeding 48 percent.

By using the multi-periodical 2-D model, there was carried out the computer modelling of an electron-wave interaction in the millimeter wave magnetron with the following parameters: frequency = 35 GHz; anode radius = 0.0029 m; cathode radius = 0.002 m; resonators number = 34; magnetic field = 5700 G. The results obtained of electron bunching in the interaction space of the given magnetron are presented in Fig. 2, c. The design of the millimeter wave magnetron have been developed. Fig. 3 shows variation of the computed and measured values of the efficiency and output power as functions of an anode current

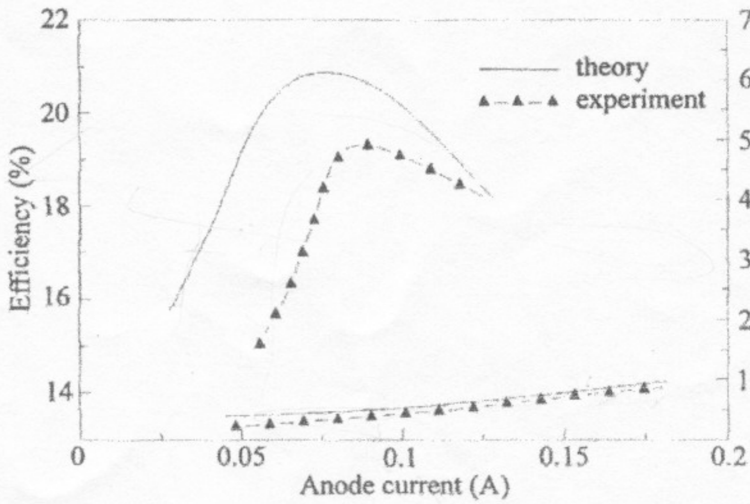

Fig. 3. Computed and measured characteristics of the magnetron

<u>*The investigation of the non-traditional crossed-field tubes.*</u> As an example of the non-traditional crossed- field tube a new design of the magnetron is considered [7,8]. For an investigation of the physical processes in such tube as well as in order to consider all its potentialities the mathematical model of the magnetron have been created. The magnetron is combined device including the two azimuthal-symmetrical electron-wave systems: classical (internal space) and inverted (external space) one's (Fig. 4). By analogy with [7], a like magnetron was named as combined magnetron. Fig. 5. schematically shows the distribution of electrical field corresponding a central part of a sector having the central angle $2\pi/\gamma$, where γ - propagation factor. Taking into account, that internal (1) and external (2) interaction spaces are coupled by means of coupling slots, there is the oscillation π- mode in spaces (1) and (2).

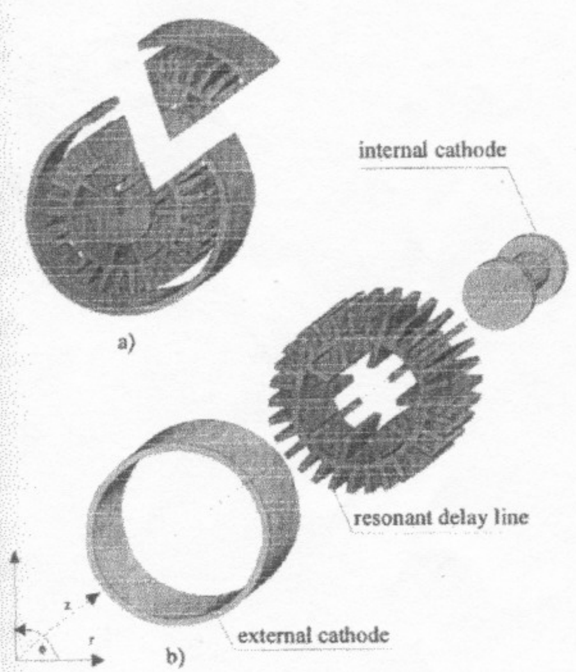

Fig. 4. General view of non-traditional magnetron (a), component his design (b)

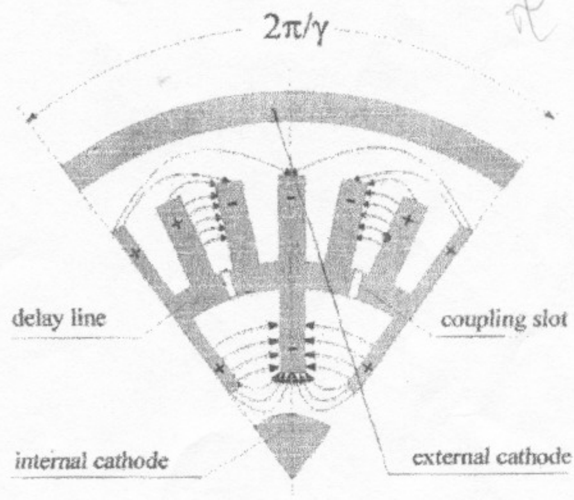

Fig. 5. Schematical distribution of an electrical field on high-frequency period to slot coupling

N = 12
da = 10
τ - 17
M 105

The combined magnetron design consists of internal and external cathodes between which there is the delay line. The electron-wave interaction processes are considered in quasi-periodic, non-relativistic and single-mode (π-mode) approximations.

The computer modelling of an interaction between electronic beams and HF field is carried out by PIC-method. The mathematical model of the combined magnetron represents a self-consistent set of equations including the motion equation (for the electronic beams in the internal (1) and external (2) interaction spaces)

$$\frac{d\vec{V}^{1,2}}{dt} = \eta(\tilde{\vec{E}} + \vec{E}^{1,2} + \vec{E}_0^{1,2} + \left[\vec{V}^{1,2} \times \vec{B}_0^{1,2}\right], \tag{1.1}$$

excitation equations (for an electromagnetic field)

$$-\frac{dC_n}{dt} + j(\omega - \omega_n)C_n = \frac{1}{N_n}\int\limits_V (\vec{J}_{nl} + \vec{J}_{n2})\vec{E}_n e^{jn\omega t} dV, \tag{1.2}$$

and Poisson's equation (for analysis of a space charge)

$$\frac{1}{r}\frac{\partial}{r}\left(r\frac{\partial U^{1,2}}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 U^{1,2}}{\partial \varphi^2} + \frac{\partial^2 U^{1,2}}{\partial z^2} = -\frac{\rho^{1,2}}{\varepsilon_0}. \tag{1.3}$$

$$\tilde{\vec{E}}^{1,2} = -grad\ U^{1,2}. \tag{1.4}$$

The developed program is realized in algorithmical language Fortran-90 and is adapted for Windows 95, 98, and NT.

CONCLUSIONS

The theoretical and experimental researches of the crossed field tubes have shown that their future is connected not only with the application of new technologies and materials but also with application of the new designs of the tubes. Numerical results have been presented for 2.45 GHz magnetrons including the household and low-voltage magnetron as well as for a 35 GHz magnetron. It has been shown that the development of the non-traditional design of the magnetron (combined magnetron) is a one way to advance the solving some problems of the crossed-field tubes.

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