ISSN 1064-2269, Journal of Communications Technology and Electronics, 2011, Vol. 56, No. 4, pp. 475–477. © Pleiades Publishing, Inc., 2011.
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Electron Bunching in the Optimal Operating Regime of a Carcinotrode

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Received September 16, 2010

Abstract—Electron bunching processes in a carcinotrode (backward-wave oscillator with self-modulation of electron emission) operating in the high-efficiency regime determined previously are investigated. The possibility of obtaining an efficiency of about 80% is explained from the physical viewpoint.

DOI: 10.1134/S1064226911040115

INTRODUCTION

The carcinotrode is a backward-wave oscillator (BWO) with the cathode feedback (CFB) circuit, which is used to completely or partially fed the BWO output signal power to the cathode for modulation of electron beam ejected to the slow-wave structure (SWS) [1]. Physical considerations and the results of a theoretical study and simulation of stationary and nonstationary processes in the carcinotrode indicate the possibility of a significant increase in the efficiency (up to 80%) in comparison with the efficiency of a conventional BWO and retention of electronic frequency tuning inherent in the BWO [2–4]. The aim of this study is to analyze transformation of electron trajectories and electron bunching during oscillation excitation for the carcinotrode's operating regime, which has an efficiency of 80% [4].

1. DESCRIPTION OF EMISSION MODULATION

The voltage between the cathode and the grid (first anode) of the carcinotrode's electron gun is the sum of the static voltage and the RF voltage transmitted by the CFB from the SWS output:

$$U = U_0 + U_1 \cos\omega t_0 = U_{\max}(1 - \mu + \mu\cos\omega t_0), \quad (1)$$

where $\mu = U_1/U_{\max}$ is the modulation index with respect to the maximum voltage $U_{\max} = U_0 + U_1$. As it was done in [4], we will consider thermionic cathodes and will use the three-halves power law for emission current J:

$$J = PU^{3/2}, \quad (2)$$

where P is the perveance. As oscillations pass to the steady-state condition, the value of parameter μ increases due to an increase in voltage U_1. At low RF voltage, there is no current cutoff at $\mu \le 0.5$. As μ increases, the current cutoff arises with cutoff angle θ determined as

$$\cos\theta = 1 - 1/\mu \text{ for } \mu > 0.5. \quad (3)$$

At $\mu = 1$, we have $\theta = \pi/2$, which corresponds to the class B operating regime of the cathode–grid diode.

In simulation of the oscillation excitation process in the carcinotrode, the system of equations, the mathematical model, and the GAMS3 program from [4] were used. We consider the dimensionless slowly varying (in time) field $F(0, \tau) = U(0, \tau)/U_{\text{norm}}$ at the SWS output, which determines the field modulating the emission on the cathode, $F_c(\tau) = K_{\text{FB}}F(0, \tau)$, where τ is the dimensionless time, K_{FB} is the transmission gain of the CFB circuit and U_{norm} is the normalization constant. It is convenient to present modulation index μ via $|F(0, \tau)|$:

$$\mu = \frac{|K_{\text{FB}}|\,U(0, \tau)}{U_0 + |K_{\text{FB}}|\,U(0, \tau)} = \frac{GF(0, \tau)}{1 + GF(0, \tau)},$$

where parameter G has the meaning of the feedback parameter and is determined by the ratio between the transmission gain index and the normalized static voltage.

2. ANALYSIS OF ELECTRON TRAJECTORIES AND ELECTRON BUNCHING

To simulate the electron trajectories, dimensionless parameters from [4], namely, dimensionless oscillator length L, amplification parameter ε, feedback parameter G, and feedback phase φ_{FB} were specified in the GAMS3 program. Figures 1–4 show the results demonstrating variations in dimensionless RF field $|F|$ at the BWO output and in the electron trajectories during oscillation excitation for the following variant: $L = 1$, $\varepsilon = 0.1$, $G = 1.3$, and $\varphi_{\text{FB}} = -2.3$. This variant corresponds to the maximum efficiency (82%) of the carcinotrode in the steady-state regime calculated with the

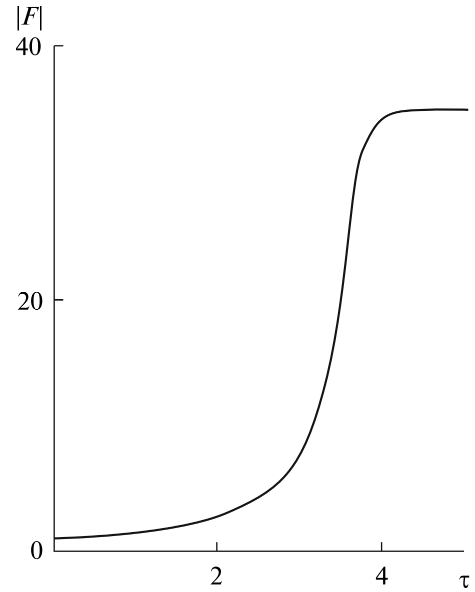

Fig. 1. Variation in the field amplitude at the output of the carcinotrode during oscillation excitation.

use of $F(0, \tau)$ from formula (35) presented in [4]. Note that, in Figs. 2–5, z is the dimensionless coordinate along the oscillator length (normalized by the oscillator length) and u is the electron phase.

As seen from Fig. 1, at the initial stage of the oscillations development at $0 < \tau < 3$, the output field slowly increases, then, at $\tau \approx 3$, it rapidly grows and transfers to the steady state with an efficiency that is maximal for this variant. Such a behavior of the field can be explained by the change in the electron bunching in time, which is presented in Figs. 2–4 for the phase trajectories. At $\tau < 3$, an electron bunch is slowly formed and, at $\tau = 3$, a dense bunch is formed at the oscillator center ($z \approx 0.5$). Then, the bunch shifts toward the starting point of the oscillator, transfers into an intense RF field and becomes denser. As a result, the aforementioned high efficiency is obtained. Figure 5 demonstrates the time variation of modulation index μ with the maximum value $\mu = 0.98$ in the steady-state regime. Thus, the diode formed by the cathode and the grid (first anode) changes to the class B operating regime with a small phase width of the bunch (Fig. 6), which explains the obtained high efficiency.

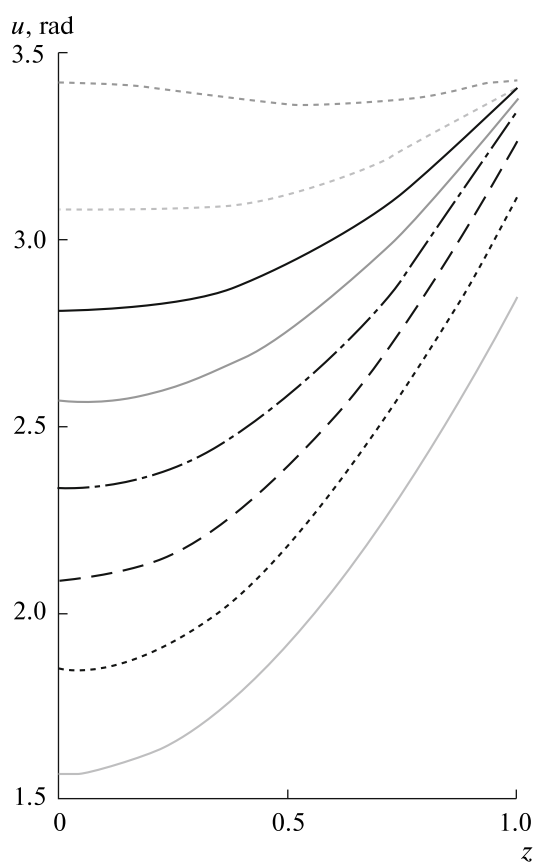

Fig. 2. Phase trajectories of electrons in the beginning of oscillation excitation, $\tau = 2$.

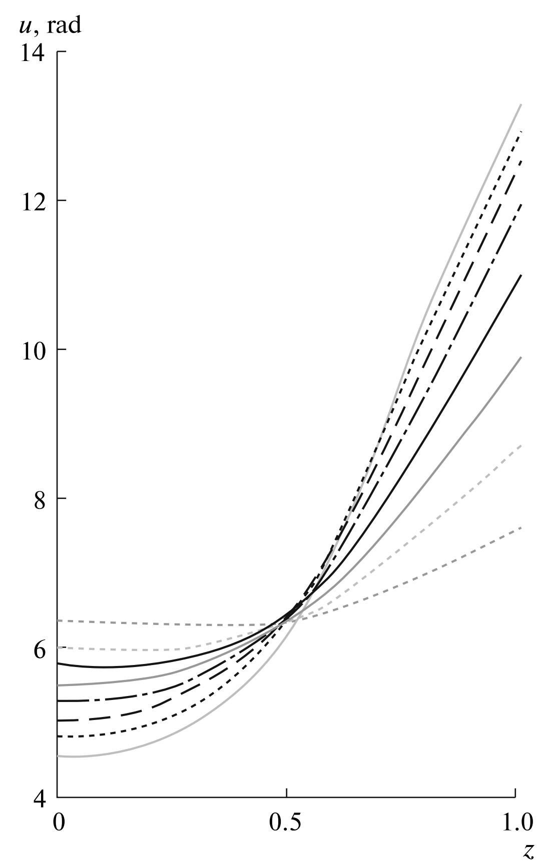

Fig. 3. Phase trajectories of electrons during the transition to the high-efficiency regime, $\tau = 3$.

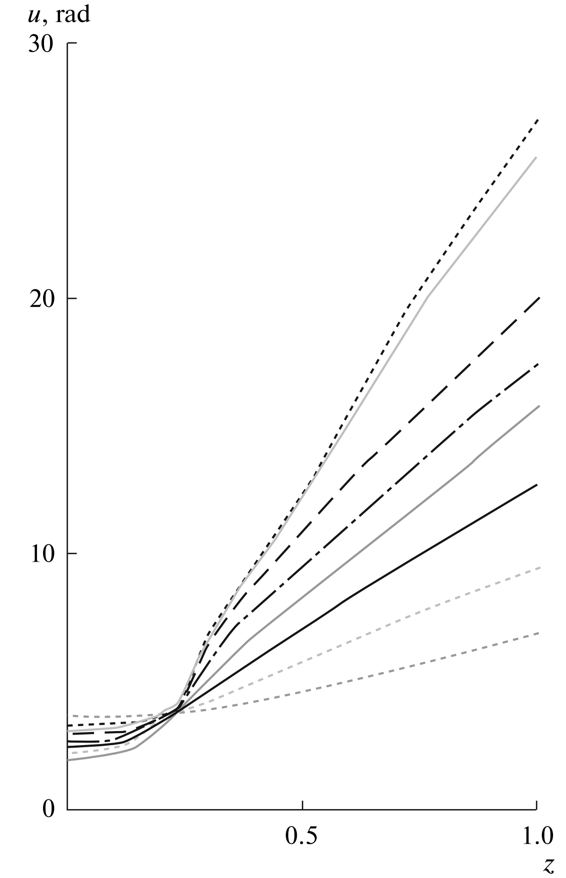

Fig. 4. Phase trajectories of electrons in the steady-state operating regime with an efficiency of 80%, $\tau = 5$.

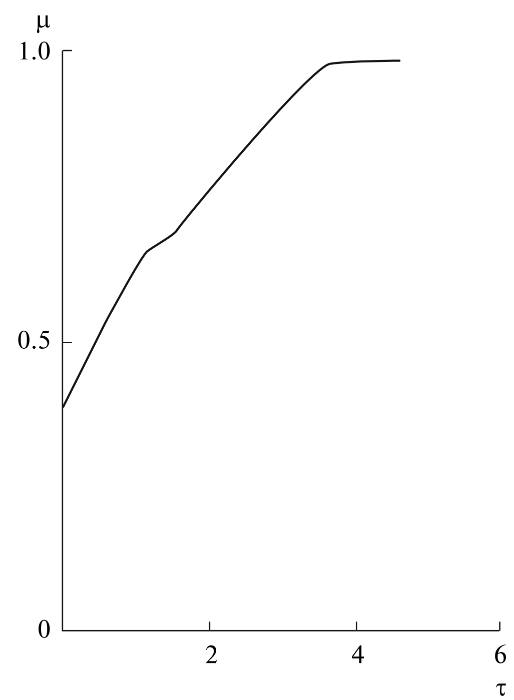

Fig. 5. Variations in the field modulation index at the cathode during oscillation excitation.

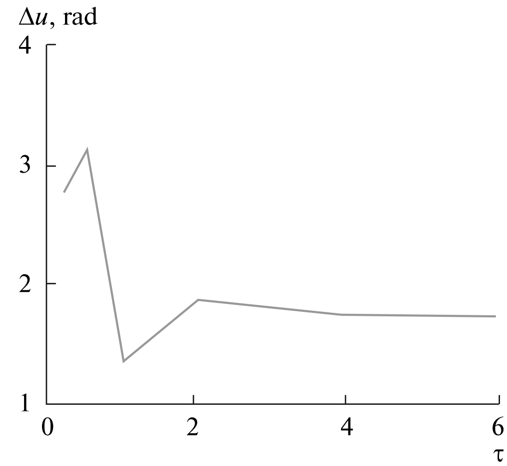

Fig. 6. Variations in the electron phase spread in the bunch.

CONCLUSIONS

In the beginning of the transient process at small amplitude of oscillations, the emission modulation is weak and a sufficiently large length is required for the self-excitation of the carcinotrode. For the correctly chosen feedback phase, the emission modulation increases, the electron bunches become denser and transfer their energy to the field at the initial part of the SWS. As a result, a single-frequency steady state with high (80%) efficiency is set. At other values of CFB parameters, it is possible to obtain self-modulation and chaotization of oscillations, as was pointed out in [4]. These processes can also be considered using the GAMS3 program.

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research, project no. 10-02-00859-a.

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