

TWO NOVEL SOURCES OF VARIABLE FREQUENCY MICROWAVE ENERGY

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ABSTRACT

Two novel sources of variable frequency microwave energy with increased efficiency are described in this paper - a backward wave oscillator (BWO) with auto-modulation of electron emission and - a two-section BWO, which second section operates in the traveling wave tube (TWT) mode. In the first case, the BWO output is connected through a section of a slow-wave structure to the control electrode of the gun providing a modulation of the current emitted by cathode. This leads to a significant increase in the BWO output signal. In the second case, the electron beam, modulated in the first section (BWO section), excites an electromagnetic wave in the second section (TWT section) and interacts with this excited wave converting its DC energy to the RF signal. It is shown that in both cases the BWO efficiency can be increased 3-4 times. The analysis of above mentioned BWOs is done using the non-linear theory and mathematical calculations, the result of which is presented in this paper.

INTRODUCTION

Variable Frequency Microwave (VFM) technology, developed by Lambda Technologies, is successfully used in Industry and other areas of application [1, 2]. This technology requires variable frequency source of microwave energy, (which is not a simple task). The electronically tuned microwave energy sources, such as backward wave oscillators (BWOs), have very low efficiency and can not be used for commercial heating. Unlike a TWT in which an electron beam and an amplified wave move in the same direction, a BWO is an electron device in which an electron beam and an electromagnetic wave excited by this beam move in the opposite directions. The BWO provides a maximum power at the output adjacent to the gun, while the maximum modulation of the electron beam is achieved near the collector. This is why BWO have a low efficiency, significantly less the TWT efficiency.

The BWO efficiency can be increased significantly by the electron beam modulation in the electron gun [3]. Such device, carcinotrode, has a feedback circuit between the slow-wave structure and the electron gun. Being a section of a slow-wave structure (SWS), such cathode feedback circuit (CFC) transmits signal from the output of the oscillator to the control electrode in the gun, which provides modulation of electron emission of the cathode. This modulation results in the electrons bunching at the entrance of the BWO slow-wave structure that in its turn increases interaction efficiency. Strong electromagnetic field at the beginning of the SWS interacts with bunches already formed by the control electrode.

The BWO efficiency can be increased also by adding an additional section of a slow-wave structure, operating in the forward wave mode [4]. The second section in BWO was used earlier for operating in the regime of frequency multiplication [5]. For that purpose, parameters of the additional section were chosen to operate in the backward wave mode at a multiple frequency. The beam, over-modulated in the first section, transforms its energy into RF radiation mostly in the second structure.

CARCINOTRODE

The principle schematic of the carcinotrode is shown in Figure 1. Here, the end 1 of the main SWS, located near the gun, is connected to the section 2 of an additional SWS, providing a feedback to the control

electrode of the gun. The length of SWS section 2 (CFC) is adjusted for a required feedback at the oscillating frequency.

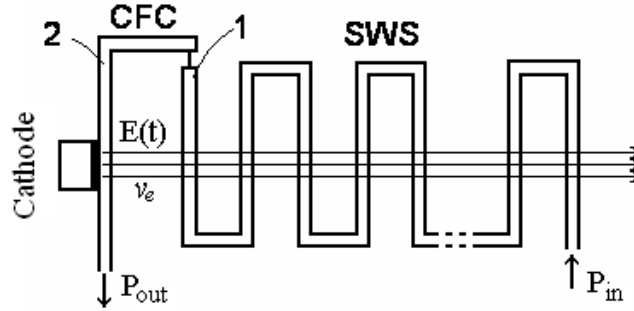


Figure 1. Carcinotrode.

Current $J(0,t)$ at the cathode surface ($z = 0$) of electron devices with modulating of the field emission, is defined as [6]

$$J(0,t) = \begin{cases} -AE^2(0,t) \exp\left(-\frac{B}{-E(0,t)}\right) & \text{for } -E(0,t) > 0 \\ 0 & \text{for } -E(0,t) < 0 \end{cases}, \quad (1)$$

where A , B are positive constants, defined by cathode parameters, $E(0,t)$ – electric field intensity at the cathode surface. In the approximation of a zero space charge

$$E(0,t) = E_0(0) + E_1(0) \cos \omega t = E_{\max} [1 - \mu(1 - \cos \omega t)], \quad (2)$$

where $\mu = E_1(0)/E_{\max}$ – modulation factor, $E_{\max} = E_0(0) + E_1(0)$. An expression for current can be written as

$$J(z,t) = J_0 + \text{Re} \sum_{n=1}^{\infty} J_n(z) \exp(-in\omega t), \quad (3)$$

where $J_n(z)$ is the amplitude of the n th harmonic which, according to the law of charge conservation ($|J(z,t)|dt = J(0,t_0)dt_0$) is defined by the expression:

$$\begin{aligned} J_n(z) &= \frac{1}{\pi(1 + \delta_{0n})} \int_0^{2\pi} J(z,t) \exp(in\omega t) d(\omega t) = \\ &= \frac{1}{\pi(1 + \delta_{0n})} \int_0^{2\pi} J(0,t_0) \exp(in\omega t(z,t_0)) d(\omega t_0), \end{aligned} \quad (4)$$

where $\delta_{00} = 1$, $\delta_{0n} = 0$ for $n \neq 0$.

For thermionic cathodes

$$J(0, t) = -k[-E(0, t)]^{\frac{3}{2}} \quad (5)$$

Taking into account that start conditions for BWO can be found from the linear theory, one may write [6, 7]:

$$\frac{dE}{d\zeta} - i\xi E = I; \quad \frac{d^2 I}{d\zeta^2} + \sigma^2 I = -iE, \quad (6)$$

where $\zeta = \varepsilon z \omega / v_e$ is the normalized longitudinal coordinate (normalized length), I, E are normalized amplitudes of the I^{st} harmonic of the beam current and the field normalized intensity, $\xi = b + id$, b is the velocity parameter (non-equality of electrons' velocity v_e and phase velocity v_p), d is the losses parameter. Space charge parameter $\sigma^2 \approx 4QC = \Gamma \cdot (\omega_p / \omega C)^2$ is defined by plasma frequency ω_p , oscillating frequency ω , depression factor Γ , and the gain parameter

$$\varepsilon \approx C = \sqrt[3]{\frac{K_c J_0}{4U_0}}.$$

Here, J_0, U_0 are the beam current and voltage, K_c – coupling impedance.

In the considered case of auto-modulation of the cathode emission, the microwave current has finite value at $z = 0$ and the boundary conditions for amplification become:

$$E(L) \neq 0, \quad I(0) + YE(0) = 0, \quad \frac{dI}{d\zeta} = 0, \quad (7)$$

where L is the total normalized length of the structure, Y is a parameter defined by the feedback and the efficiency of the cathode modulation. Here and further of, it's assumed that $\zeta = 0$ at the beginning end of the SWS.

The solution of equations (6) can be found as a sum of three waves

$$F(\zeta) = A_1 \exp(i\eta_1 \zeta) + A_2 \exp(i\eta_2 \zeta) + A_3 \exp(i\eta_3 \zeta), \quad (8)$$

where η_1, η_2, η_3 are roots of wellknown characteristic equation of BWO

$$(\eta - \xi)(\eta^2 - \sigma^2) = 1. \quad (9)$$

Boundary conditions (7), give amplitudes of three waves A_1, A_2, A_3 :

$$A_1 \exp(i\eta_1 \zeta) + A_2 \exp(i\eta_2 \zeta) + A_3 \exp(i\eta_3 \zeta) = \frac{1}{K},$$

$$i\left(\frac{A_1}{\eta_1^2} + \frac{A_2}{\eta_2^2} + \frac{A_3}{\eta_3^2}\right) = -Y, \quad \frac{A_1}{\eta_1} + \frac{A_2}{\eta_2} + \frac{A_3}{\eta_3} = 0 \quad (10)$$

where $K = E(0)/E(L)$ is the gain factor.

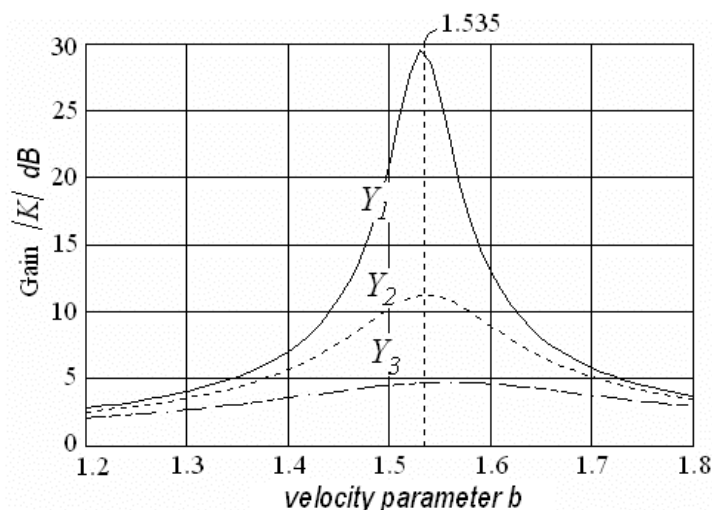


Figure 2. Gain factor K dependence on the velocity parameter b calculated for three different values of the feedback coefficient Y : $Y_1 = 0$ (conventional BWO), $Y_2 = 0.1$, $Y_3 = 0.2$.

Solutions of equations (6) for negative feedback and different values of the beam modulation at cathode (negative values of Y) demonstrate a strong dependence of the gain factor in the regime of amplification (Figure 2). The increase in $|Y|$ is followed by an increase in bandwidth.

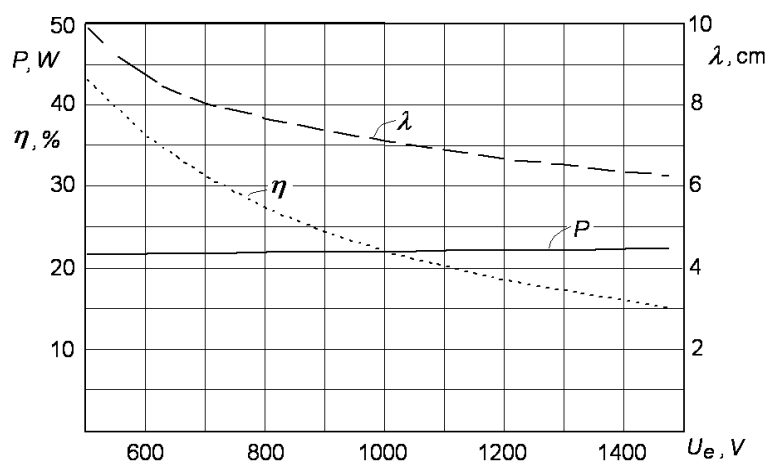


Figure 3. Output power P , efficiency η , and wavelength λ dependence upon voltage U_e for a carcinotrode.

If the feedback is positive, a maximum gain and the starting condition for the carcinotrode are achieved at a much less length, approximately twice less than in the common BWO, while the starting current is eight times less than in the case of a zero modulation at the cathode.

Some results of non-linear analysis and optimization of carcinotrode parameters, based on the method and equations previously considered in [8], are presented in Fig. 3 for thermionic cathode. It is seen from the figure that the output power P changes very little in the chosen band of frequency variation (6.5- 10 cm). It means that the oscillating frequency variation in a wide band can be realized at the efficiency level in the range of 20-30 %.

It had been found that a proper choosing of the phase in the CFC allows to save the possibility of frequency variation in the wide operation band.

TWO-SECTION, BWO-TWT, OSCILLATOR

It is possible to increase a BWO efficiency by adding another section of a slow-wave structure, operating in the forward wave mode (Fig. 4) [4].

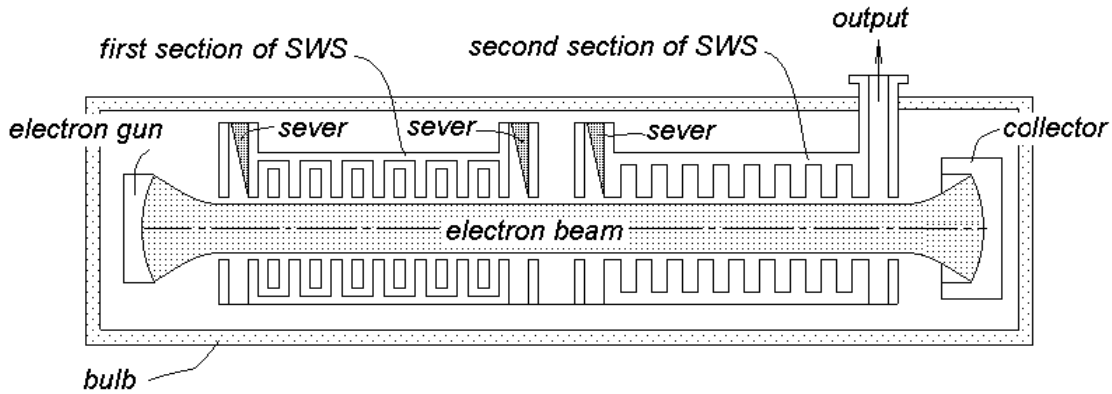


Figure 4. Backward-wave oscillator with BWO and TWT sections.

The analysis results of a two-section backward-wave oscillator, BWO-TWT, are presented below. The first section, operating in the backward wave mode, is loaded at both ends by matched sever, while the second section is connected to the matched output (Fig. 4). The input end of the second section can also be loaded by a sever.

The nonlinear analysis, based on one-dimensional theory of TWT and BWO [8] was used to optimize parameters of both sections. This analysis included solutions of the motion equation,

$$-\frac{d^2 t_j}{dz^2} = \left(\frac{dt_j}{dz} \right)^3 \frac{e}{m} \operatorname{Re} E_{\pm}(z) e^{-i\alpha_j(z)}, \quad (11)$$

where $j = 1, 2, \dots, M$, M is the number of particles at one period, excitation equation

$$\frac{dE_{\pm}(z)}{dz} - ihE_{\pm}(z) = \mp h^2 K_c J_1(z) \quad (12)$$

for TWT ($E+$) and BWO ($E-$), equation for the first harmonic of the beam current

$$J_1(z) = \frac{2J_0}{M} \sum_{j=1}^M e^{i\alpha_j(z)}, \quad h = \frac{\omega}{v_p}, \quad (13)$$

v_p - phase velocity.

As it could be concluded just from a general consideration, parameters of a SWS forming the first section and the RF beam current should be chosen to obtain the optimum modulation of the beam at the output of this section, while parameters of the SWS forming the second section should be chosen to provide the optimum interaction with the modulated beam at the forward wave mode. Presented below are the results of calculations based on the non-linear analysis which demonstrate that it is not true.

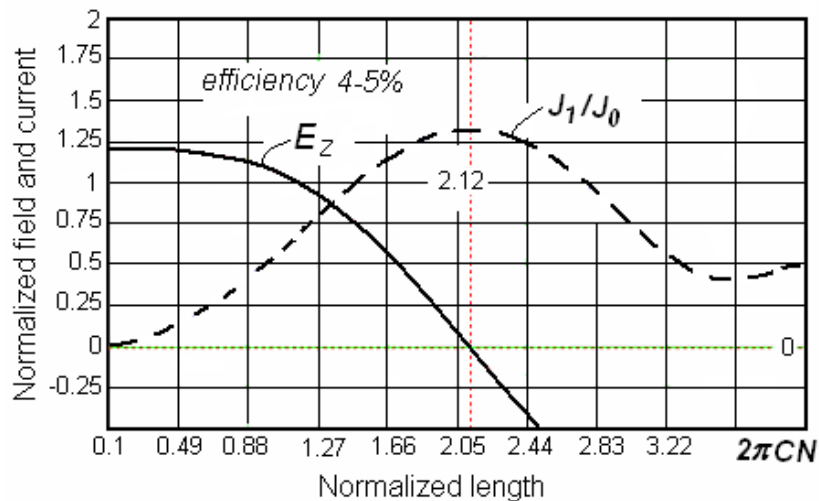


Figure 5. Distribution of the relative field intensity E_z and the ratio the first harmonic of the beam current J_1 to the average beam current J_0 at the maximum J_1 .

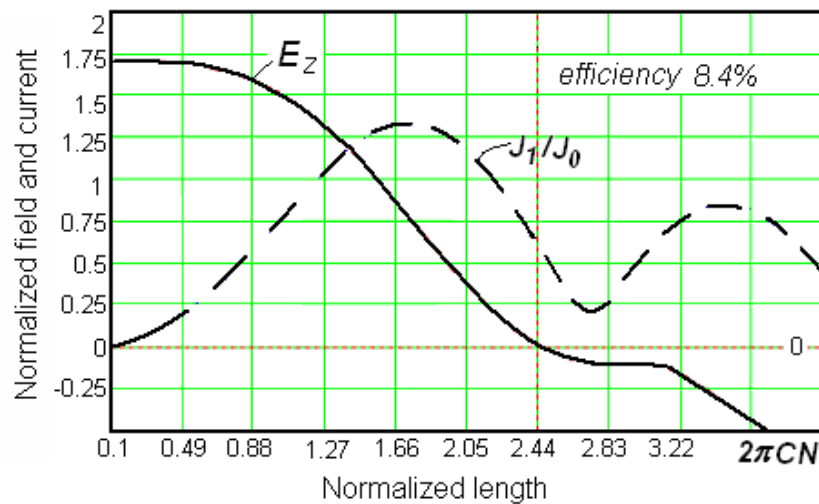


Figure 6. Distribution of the relative field intensity E_z and the ratio of the first harmonic of the beam current J_1 to the average beam current J_0 at the first section in the case of the maximum efficiency in the first section.

It is found that in the case of a small space charge and Pierce's gain parameter $C=0.06$, the beam modulation in the first section achieves its maximum at the normalized length equal to 2.12 (Fig. 5). This length is less than the length required for the maximum efficiency, 8.4 % for one-section BWO (Fig. 6). In this case efficiency of the backward mode drops to 4-5% (mode I) instead of mentioned above 8.4%. It should be noted that the normalized length may be expressed through a number of the slow waves N along the considered sections $\zeta = 2\pi CN$.

As it follows from the non-linear analysis of the modulated beam interaction with the field excited by the beam in the second section, the optimum modulation of the beam in the first section can be achieved for the relative amplitude E_z at the BWO output (at beginning of the first section) equal to 0.3. In this regime (mode II), the electrons bunching can be considered linear and the minimum difference in velocities of electrons takes place in the second section at the normalized distance equal to 4.35 that is demonstrated by the phase trajectories shown in Fig. 7.

The results of the optimization of the considered BWO-TWT are presented in Fig. 8. Here, the distribution of relative field intensity E_z along the first and second sections is shown for both modes. It is seen that the maximum power at the output of the second section exceeds 3.2 that corresponds to 32 % efficiency, defined as

$$\eta = C \frac{E_z^2}{2}. \tag{14}$$

It is seen also that in this regime (mode II) the ratio of currents, J_1/J_0 , achieves its maximum value equal to 1.4, at the normalized length equal to 5, while the maximum field is achieved at 6.1.

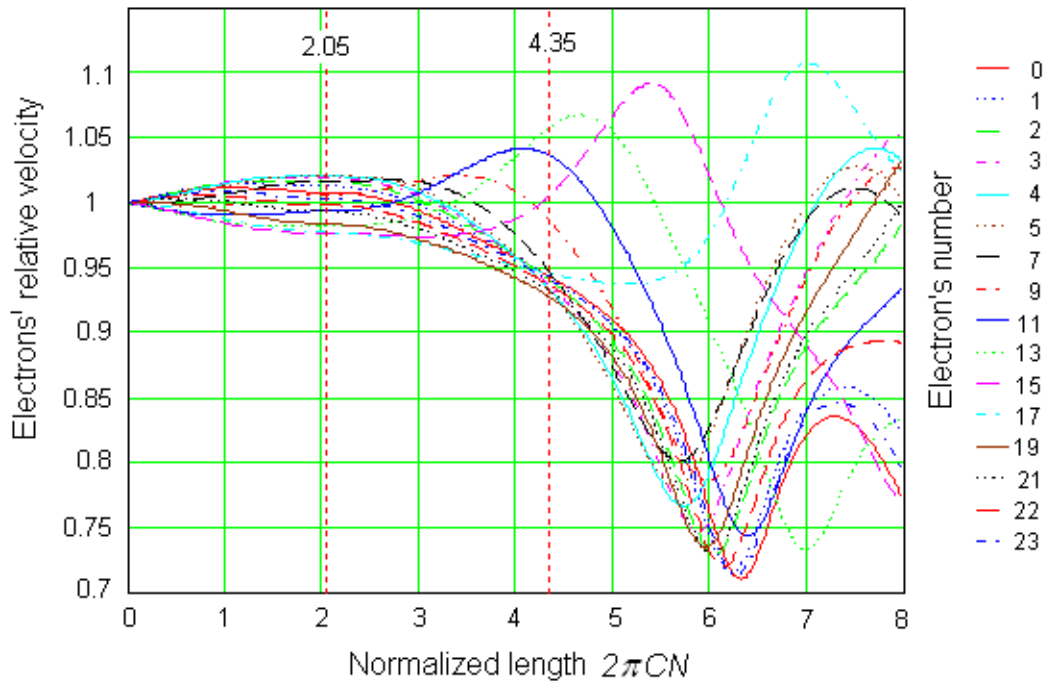


Figure 7. Electrons velocities distribution for the two-section BWO.

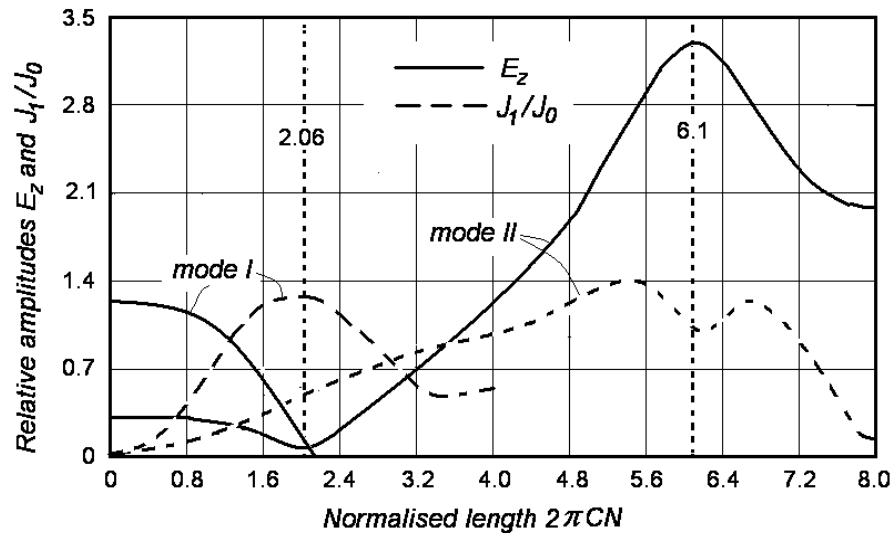


Figure 8. Distribution of relative values of longitudinal component E_z and the first harmonic of the beam current J_1 along the both sections of BWO-TWT for two different modes.

CONCLUSION

Two novel sources of the variable frequency microwave energy were discussed and analyzed in this paper: BWO with cathode emission modulation (carcinotrode) and a two-section BWO. It was shown that the auto-modulation of the cathode emission changes dramatically the process of the beam-backward wave interaction increasing the maximum calculated efficiency from 8.4% for conventional devices to 27% for carcinotrode. The increase in efficiency is achieved with the possibility of constant power output over a 50% bandwidth of the oscillated frequency.

It was shown also that the best efficiency of the offered two-section BWO-TWT can be achieved at relatively low intensity of the field at the BWO section output. In this case, the maximum field at the TWT section output achieves 3.3 for Pierce's velocity parameter b equal to 1.6. It follows from it that the maximum theoretical efficiency of the offered oscillator is 32% that fourfold exceeds the maximum efficiency of a conventional BWO. The relatively long normalized length of the two-section BWO does not mean a large physical length. The real length decreases with the increase in the current density and coupling impedance.

The considered above electron devices can be developed and manufactured on the base of the existing technology of microwave devices. The cathode modulating technology is used already for klystrodes and inductive output tubes [9].

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