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 the 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. The results of non-linear analysis and calculations show that in both cases the BWO efficiency can be increased 3-4 times. The analysis of above mentioned BWOs 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 that 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.

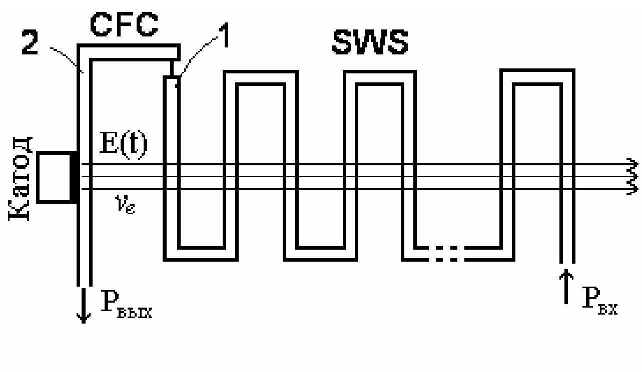

Figure 1. Carcinotrode.

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.

1. CARCINOTRODE

The principle schematic of the carcinotrode is shown in Fig. 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 positive feedback at the oscillating frequency.

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

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

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

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

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

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

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

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

For thermo-cathodes

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

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

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

where $\zeta = \varepsilon z\omega/v_e$ is the normalized longitudinal coordinate (normalized length), I, E are normalized amplitudes of the 1^{st} harmonic of the beam current and the field normalized intensity, $\xi = b + id$, 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:

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

where L is the whole normalized length of the structure, Y is a parameter defined by the feedback and the efficiency of the cathode modulation. Here and further of, we assume $\zeta = 0$ at the beginning end of the SWS.

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

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

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:

$$A_1\exp(i\eta_1\zeta)+A_2\exp(i\eta_2\zeta)+A_3\exp(i\eta_3\zeta)=\frac{1}{K},$$
$$i\left(\frac{A_1}{\eta_1^2}+\frac{A_2}{\eta_2^2}+\frac{A_3}{\eta_3^2}\right)=-Y, \qquad \frac{A_1}{\eta_1}+\frac{A_2}{\eta_2}+\frac{A_3}{\eta_3}=0 \quad (10)$$

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

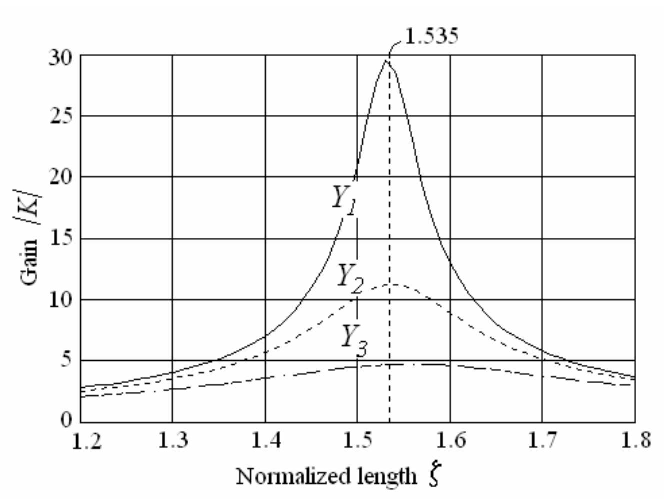

Figure 2. Gain factor K dependence on the normalized length calculated for three different values of the feedback coefficient.

Solutions of equations (6) for different values of the beam modulation at cathode (different values of Y) demonstrate a strong increase in the gain factor (Fig. 2). It is seen that 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. 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 also that a proper adjusting of the signal phase in the CFC allows to save the possibility of frequency variation in the wide operation band.

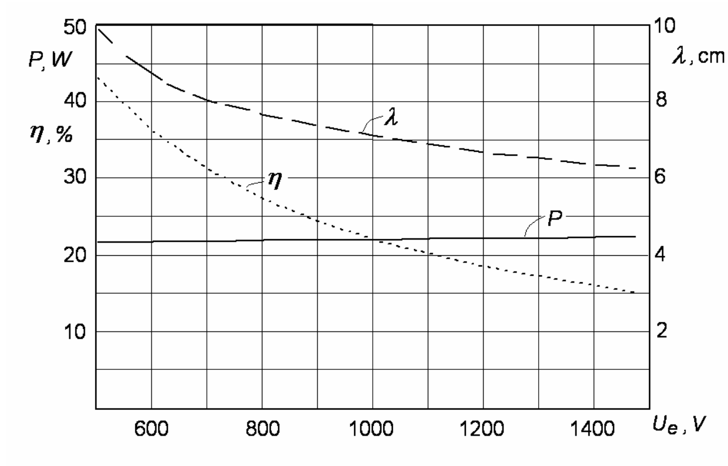

Figure 3. Output power P, efficiency η, and wavelength λ dependence upon voltage U_e for a carcinotrode.

2. TWO-SECTION, BWO-TWT, OSCILLATOR

There is another possibility to increase a BWO efficiency: adding an additional section of a slow-wave structure, operating in the forward wave mode (Fig. 4) [4]. As it was mentioned already, the second section in BWO was used earlier for operation 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 section.

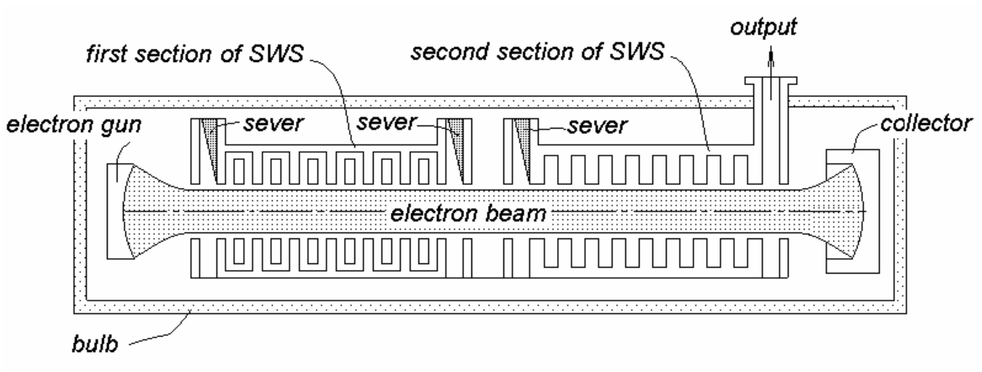

Figure 4. Backward-wave oscillator with BWO and TWT sections.

Some results of analysis 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 severs, 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 [9] was used to optimize parameters of both section. This analysis included solutions of the motion equation,

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

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

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

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

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

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 results of calculations based on the non-linear analysis show that it is not true.

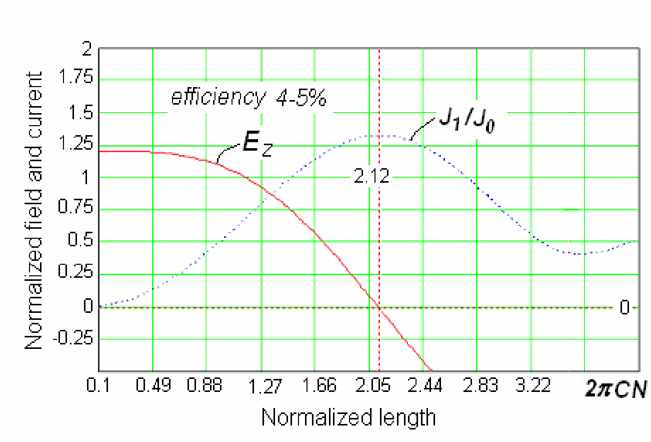

Figure 5. Distribution of the relative field intensity E_z and the ratio the first harmonic of the beam current I_1 to the average beam current I_0.

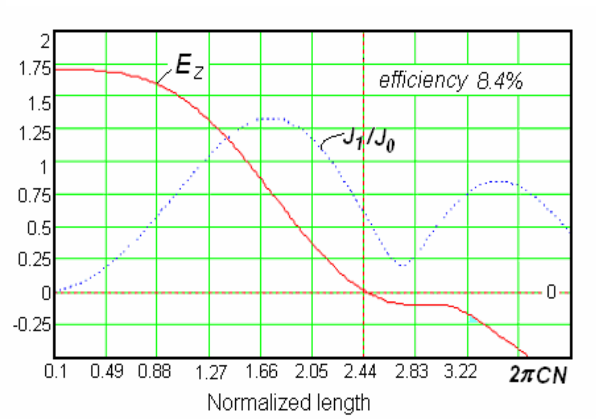

Figure 6. Distribution of the relative field intensity E_z and the ratio of the first harmonic of the beam current I_1 to the average beam current I_0 at the first section in the case of the maximum efficiency.

It is found that in the case of a small space charge (Pierce's gain parameter $C=0.059$), 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 %* (Fig. 6). In this case efficiency of the backward mode drops to *4-5%* instead of mentioned above 8.4% in the regime, which we'll call mode *I*. It should be noted that the normalized length may be expressed through a number of the slow waves *N* along the considered sections

$$\varsigma = 2\pi CN$$

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 maximum bunching 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 an 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. 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*.

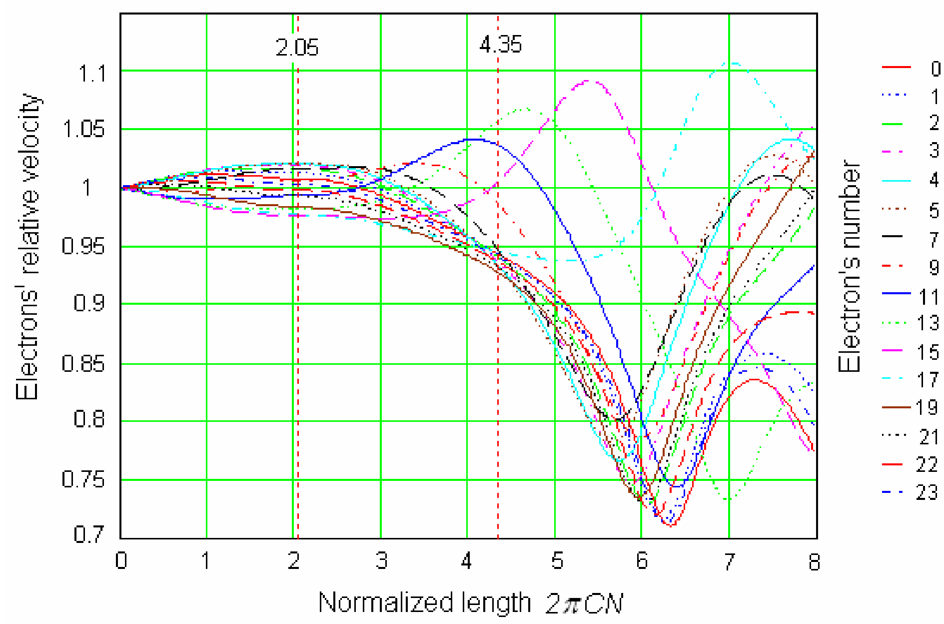

Figure 7. Phase trajectories for electrons in two-section BWO.

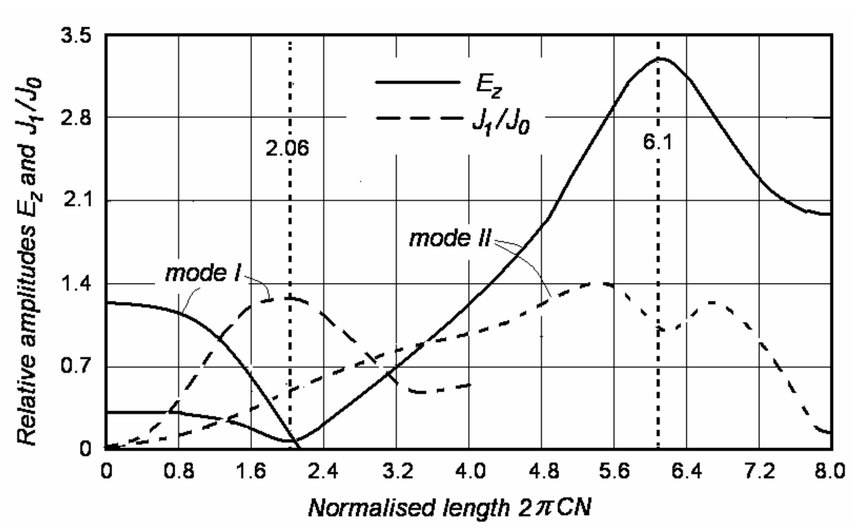

Figure 8. Distribution of relative values of longitudinal component E_z and the first harmonic of the beam current J_1 along the both sections of BWO-TWT for two different modes.

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 possibility of the oscillated frequency changing in the bandwidth *50%* with practically constant output power.

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 [10].

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thin which the first section operates as a beam modulator and the second section converts the dc energy of the modulated beam into the microwave energy at the output of the device is presented in this paper.

The first section, operating in the backward wave mode, is loaded at both ends by matched severs, while the second section is connected to the matched output. The input end of the second section can also be loaded by a sever.

Parameters of a slow-wave structure (SWS) forming the first section and the RF beam current are chosen to obtain the optimum modulation of the beam at the output of the first section. Parameters of the SWS forming the second section are chosen to provide the optimum interaction with the modulated beam at the forward wave mode. Results of calculations based on the non-linear analysis [6] allow one to optimize parameters of both sections of the considered device. It is found that in the case of a small space charge (Pierce's gain parameter $C = 0.059$), the maximum amplitude of the first harmonic J_1 in the beam current at the end of the first section can be achieved when the normalized length of this section $2\pi CN$ is equal to 2.06, and the relative value of electric field intensity E_z is equal to 1.2, while $J_1 = 1.3\ J_0$. Here, N is a number of the slow waves at the first section. Note that the normalized length mentioned above exceeds