A Study of the Discrete Electron-wave Interaction for the Passbands and Stopbands of TWT Slow-wave Systems

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Abstract: *The fourth power algebraic characteristic equation is obtained for the wave number of the individual electron waves that exist in periodic slow-wave systems(SWS) with discrete electron-wave interaction. The study of properties of these waves and the solution of the corresponding boundary-value problem have been performed. It has allowed to find some properties of electron-wave interaction which are different or are identical to the SWS with discrete interactions or "smooth" SWS, for example helical SWS.*

Keywords: slow-wave system; electron beam; interaction; TWT; passband; stopband.

Introduction

The equations of the discrete electron-wave interaction in TWT with periodic slow-wave structures (SWS) of the type of a coupled cavities system or of a disk-loaded waveguide have been analyzed in [1,2] and the interaction equations of small-signal theory have been obtained. Unlike in the previously known works, the equation of excitation of periodic waveguides with second-order finite differences [3] and the local interaction impedance instead of Pierce's coupling impedance are used in the suggested theory. It allows to get the unified description the SWS interaction of electrons with a full field of two waves - forward and backward - in both the passband and the stopband (Fig.1).
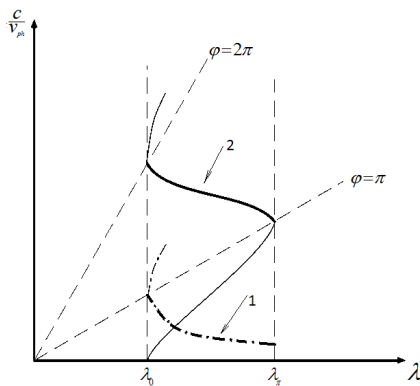

Figure 1. The dispersion characteristics for 1) helical SWS (- · -, φ_0) and 2) coupled cavities system (—,φ_1) in passband

In the small-signal theory equation for the electron beam RF current J has a well-known form, such as shown in [1,2]:

$$\frac{d^2 J}{dz^2} - 2ih_e \frac{dJ}{dz} + (\Gamma h_p^2 - h_e^2)J = -ih_p^2 S\omega\varepsilon_0 \overline{E}, \quad (1)$$

where $h_e = \omega / v_e$ – electron wavenumber, $h_p = \omega_p / v_e$ – wavenumber of plasma, S – effective cross-sectional area of electron beam, $\sqrt{\tilde{A}}$ – reduction coefficient of plasma frequency ω_p. In the interaction gaps on the electron beam operates the total electric field of direct and backward-waves $\overline{E} = E_s + E_{-s} = E_q = -U_q / d$, where d – effective width of gap, U_q – the voltage at q-m gap. The voltage U_q defined beam current and must satisfy the equation excitation periodic SWS. This equation is the excitation finite-difference equation for quadripoles circuit describing periodic SWS (Fig.2).
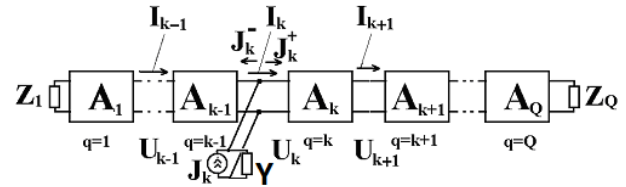
Figure 2. One section of periodic slow-wave system as circuit of quadripoles

$$\Delta^2 U_q + 2U_q(1 - \cos\varphi_s) = iZ_s J_q, \quad (2)$$

where $Z_s = R_s L^2 \sin\varphi_s$ - local interaction impedance, R_s - specific coupling impedance, L - the period of gap distance, φ_s - the phase shift of the field over the period.

The current induced in the q gap is determined from the expression

$$J_q = \frac{1}{d} \int_{z_q^-}^{z_q^+} J(z)\overline{e}_q(z)dz = J_0 \tilde{I}_q e^{ih_e z_q}, \quad (3)$$

where normalized induced current is

$$\tilde{I}_q = I_q M - V_q C[\exp(i\frac{\theta}{2}) - M] + F_q^m C^2 \theta Y(\theta), \quad (4)$$

where $M = \sin(\frac{\theta}{2})\Big/\frac{\theta}{2}$ - interaction coefficient, θ - the gap transit angle, $Y(\theta)$ - complex conductance of electron gap, C – the gain parameter, which is calculated using the local interaction impedance, F_q^m, I_q, V_q - normalized gap field, RF current and RF velocity of electron beam.

Equations (1)-(4) are system of equations describing the discrete small-signal electron-wave interaction in passbands and stopbands.

The properties of electron waves

In this study, the fourth power algebraic characteristic equation is obtained for the wave number of the individual electron waves that exist in this system. The study of properties of these waves and the solution of the corresponding boundary-value problem have been performed. It has allowed to find some properties of electron-wave interaction which are different or are identical to the SWS with discrete interactions or "smooth" SWS.

In case of the SWS with the main spatial harmonic having the phase shift φ_0 at period L ($0 < \varphi_0 < \pi$), at $\varphi_0 \to 0$ (ie. for decreasing of L) the characteristic equation becomes the cubic equation, which coincides with the known equation of the Peirce's theory, obtained for the helical SWS. With the increasing φ_0 an effect of backward wave appears. It leads to a small change of the wave number already in the middle of the SWS passband at $\varphi_0 = \pi/2$. Increasing the phase further to the point of cut-off $\varphi_0 = \pi$ leads to a substantial change in the electron waves wave numbers due to interaction of electrons with the spatial harmonic of SWS backward wave. There is a reactive attenuation after SWS cut-off point, so that $\varphi_0 = \pi + i \cdot \mathrm{Im}(\varphi_0)$. However, gaining one electron waves remains and the gain band expands. The magnitude of expanding that band depends on the interaction parameters and can be calculated from the resulting characteristic equation for the each specific case (Fig. 3).
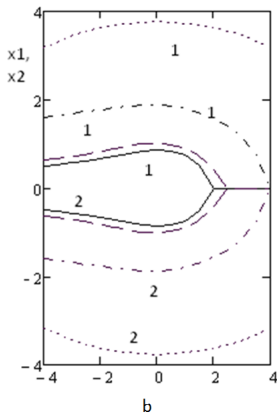
Figure 3. Roots $x_1 = -x_2$ of the characteristic equation calculated for the case main spatial harmonic:

$\varphi_s \to 0$ (—,smooth SWS); $\varphi_s \to \pi/2$ (- - -); $\varphi_s \to 0.9\pi$(-·-·-); $\varphi_s \to \pi(\ldots)$;

Similar results are obtained for using the first spatial harmonic as the working one, in the coupled cavities systems and similarly folded SWS, where $\varphi_1 = \varphi_0 + \pi$. However, the SWS remains as a periodic structure for

$\varphi_0 \to 0$ (ie. $\varphi_1 \to \pi$), and it is then possible to gain in the stopband for $\varphi_1 = \pi + i \cdot \mathrm{Im}(\varphi_1)$ as well.

We give examples of calculating the field distribution and the RF beam current along one section of passband or stopband sections of SWS, showing the possibility of increasing the RF current (and the field in some regime) in the stopband sections.

The calculation was performed by solving the boundary-value problem with given reflection coefficients at the ends of sections and recurrent recalculation of the field and RF current from the gap to the gap without a representation as the sum of the electron waves in the system "periodic SWS-electron beam".

Simulation the multisection TWT with stopband sections

In addition to the study of electron waves in separate sections of SWS, the multisection TWT with stopband sections has been simulated . The methods of individual sections conjugation for the simulation were elaborated, and the distribution of RF currents and fields along the SWS were found. The resulting gain coefficient by small signal is close to the experimental data (Fig 4).
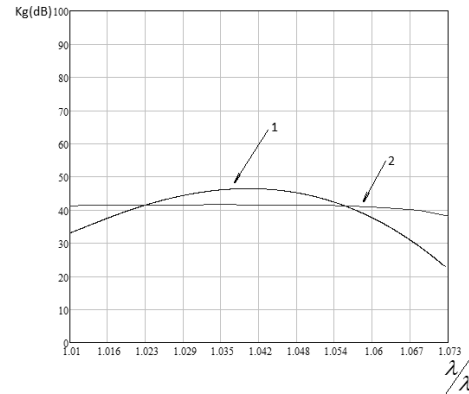
Figure 4. Calculated (1) and experimental (2) gain coefficient in passband, λ_π according to stopsection cut-off.

References
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