

## OSCILLATION MODES OF ELECTRONIC GENERATORS WITH MATCHED WAVEGUIDES

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This paper discusses the physical aspects of "hot" oscillation modes of an end-matched electrodynamic waveguide system with an electron beam, problems of realization of coupled-wave generator modes in frequency regions corresponding to steep sections of the dispersion characteristics near the transmission band boundaries, the distinctive features of the mode composition of generators based on superdimensional waveguides, and transition to electronic modes.

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In microwave electronics the modes of electronic generators are most often determined by the resonant modes of "cold" (without an electron beam) electrodynamic systems [1], and the generation reduces to the induced radiation of the electron beam in the fields of these modes. In the case (important for relativistic electronics) when waveguide systems are employed, resonant modes appear owing to the reflection of the propagating waves from the entry and exit ends of the waveguide. In this connection, a special group of generators is formed by devices based on matched reflection-free waveguides, e. g., of the type of a backward wave tube (BWT). The BWT generation is due to an interference mechanism accompanying processes in coupled waves, and the frequency is determined by the beam velocity [2]. In what follows we shall consider powerful relativistic generators based on smooth and periodic waveguides with "cold" (without an electron beam) and "hot" (with an electron beam) types of matching. Such a waveguide can be one-mode or multimode (superdimensional).

Transition to matched waveguide systems facilitates the solution of the mode selection problem because in this case there are no "cold" resonator modes and only "hot" modes, oscillations of the actively coupled system, and generator electronic modes are selected. In all these processes the electron medium plays a fundamental role. Also of importance are resonance effects in the waveguides at frequencies in the neighborhood of the transmission band boundaries, when the group velocity turns out to be small and the coupling impedance is rather large.

The very possibility of constructing generators based on superdimensional matched waveguide systems is closely related to resonances at transmission band boundaries and to the effects of the electron beam on the resonances, namely to the "hot" shift of the boundary cutoff frequencies, the electronic anisotropy, the important role of the slow wave in the beam, etc.

The corresponding electronic selection for heavy-current devices based on superdimensional waveguides was proposed in [3]. It employs the resonance properties of periodic surfaces and additional effects that appear owing to the directional radiation of relativistic particles.

At the present time many versions of generators are realized in which the electromagnetic radiation is emitted within superdimensional resonant decelerating systems that are quite well input- or output-matched [4]. These include the BWT-TWT (traveling wave tube) type generator [5], the relativistic surface-wave (SW) generator [6], the maser with cyclotron resonance and anomalous Doppler's effect [7], the relativistic generator of diffracted radiation [8], and the various relativistic many-wave [9] and bulk-wave (BW) generators [10]. For example, in the relativistic surface-wave generator [6] the matching occurs through a smooth transition from a corrugated surface to a smooth waveguide and then to a large-diameter horn.

In generators with matched waveguides the oscillation modes of the "cold" system are unstable, the coupling of the many beam and field waves plays a fundamental part, and the process is substantially complicated by the interaction between the waveguide and the electron medium [4, 9]. Because of the difficulties encountered in the analysis, many details of the transition from a many-wave coupling system to one-mode self-excitation systems remained unclear. In particular, this refers to the distinction of the generator modes from the "hot" and "cold" waveguide modes and to the description of specific properties of the modes of a coupled system and of the electronic modes. A special classification of generators with matched waveguides is needed to clarify the place of such devices among other electronic radiation sources.

### 1. APPROXIMATE DESCRIPTION. "HOT" OSCILLATION MODES

In the general analysis of interaction, matching, and reflection conditions for waves of preferred modes in smooth and periodic waveguides with positive or negative dispersion one can use a simplified equivalent representation of the system in the form of chains of four-terminal networks with capacitances ( $Y = i\omega C(\omega)$ ) or inductances ( $Y = 1/i\omega L(\omega)$ ) connected in parallel (Fig. 1 a). The impedance  $Z(\omega)$  is often represented as series- and parallel-type contours, and also as contours of a complex form (Fig. 1 b). It is assumed that the longitudinal and the transverse interactions between the beam and the field take place in the equivalent capacitive gaps introduced in various circuit branches. This technique makes it possible to take into account the effect of the beam on the matching conditions and on the longitudinal structure of curling fields and thus to examine the transition from waves of given modes of the matched waveguide to "hot" oscillation modes in the electrodynamic system.

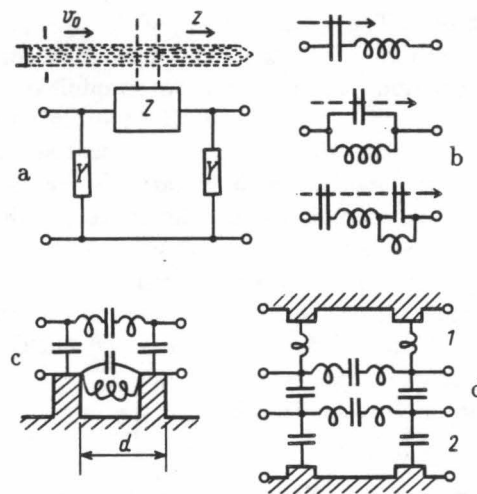


Fig. 1

Equivalent circuits: (a) general scheme; (b) schemes of the contours; (c) circuit for the range of  $\pi$ -form frequencies of a system with positive dispersion; (d) two coupled lines with negative (1) and positive (2) dispersion for the range of  $2\pi$ -form frequencies.

In the case of periodic waveguides, equivalent circuit are most suitable for describing the surface field in the range of  $\pi$ -form frequencies (Fig 1 c) or for obtaining data on the coupling of the surface and bulk fields at  $2\pi$ -form frequencies (Fig. 1 d).

If a waveguide has a finite length, then it is assumed that the ideal "cold" matching conditions hold in the operating frequency range  $\Delta\omega$ :  $Z_w(\omega) = Z_0(\omega)$  at the input and  $Z_w(\omega) = Z_L(\omega)$  at the output ( $Z_w$  is the wave impedance). To facilitate the matching, the frequency range  $\Delta\omega$  is taken at some distance from the boundary cutoff frequencies. Smooth transitions and horns are used in the concrete realization of the matching.

It is assumed that long-term longitudinal and transverse interactions between the beam and the field occur in the waveguide sections. The energy is taken from the slow waves of the beam, including the slow space charge wave and the slow cyclotron or synchrotron waves. It is also assumed that the negative sign of the power of the slow wave is due to the negative transferred energy at a positive group velocity  $v_g$  equal to the average longitudinal velocity  $v_0$  of the beam ( $v_g = v_0$ ) (see Fig. 1 a).

To attain generation and formation of a generator mode a feedback is needed. It depends on the wave reflections from the waveguide ends owing to the "hot" mismatching and also to the internal feedback. In the first case one can speak about producing a "hot" mode of the waveguide with a beam and in the second, to pass to special mode problems for the system of coupled waves during the "hot" and the "cold" matching. Sometimes a combined feedback is considered. The latter is often realized at frequencies near those of the transmission band boundaries which correspond to the steep sections of the dispersion characteristics [4]. Operation at the steep sections corresponds to the inclusion of the resonance properties of periodic surfaces.

In what follows we describe in detail the physical aspects of the transition from coupled waves to generator modes for currents close to the starting ones. Use is made of the calculation data obtained by the methods described in [4, 9].

## 2. COUPLING WITH THE SLOW WAVE IN THE VICINITY OF TRIPLE POINTS

The calculation results make it possible to single out two versions of wave coupling in the frequency ranges corresponding to the steep sections of the dispersion curves in the vicinity of triple points (the  $n\pi$ -forms;  $n = 0, 1, 2, \dots$ , Fig. 2): one version for positive values of the second derivative of the frequency  $\omega$  with respect to the wavenumber  $k_z$  ( $d^2\omega/dk_z^2 \equiv \omega'' > 0$ ) and the other version for negative values ( $\omega'' < 0$ ). The couplings of the field waves with the slow electron waves will be regarded as base processes. In particular, we shall bear in mind that the weak coupling of the slow beam wave and the forward field wave characterizes the BWT-type amplification condition. The weak coupling of the slow and backward waves is characterized by periodic energy exchange with amplification (the BWT operation condition). For fast beam waves the regimes of two-wave aperiodic and periodic coupling without amplification are realized.

The coupling of the field with the slow wave can be realized for both the fundamental wave and for waves of spatial harmonics of waveguide systems with positive and negative dispersion. There can be bulk and surface waves. A triple point may correspond to the boundaries of the fundamental and higher transmission bands. It is thought that the surface or bulk waves manage to attain steady-state conditions, and the operating frequency range of the bulk wave is selected with consideration for possible repeated reflections of the waves from lateral walls (a nearly transverse propagation).

Note that coupling with the slow wave is realized for values of the generalized electron wave parameter  $\sigma = \Omega/(\omega C) \geq 1$ , where  $\Omega$  is the characteristic beam frequency and  $C$  is the amplification parameter in the TWT theory. In the case of space charge waves we have  $\Omega = \omega_q$ , where  $\omega_q$  is the plasma frequency determined with consideration for the waveguide walls. In the case of cyclotron waves we have  $\Omega = \omega_B$ , where  $\omega_B$  is the cyclotron frequency.

## 3. GENERATORS WITH TWO-WAVE COUPLING. THE BWT AND THE RESONANCE TWT

Oscillations in a matched electrodynamic system appear owing to the field amplification under the effect of the slow beam wave. In a system with a fast wave there are no noticeable oscillations. When there is a two-wave BWT-type interaction the oscillations are due to the interference mechanism of coupling of the backward field wave and the slow beam wave. Under the synchronism condition in the range of currents equal to the starting currents, the BWT generator mode is characterized by longitudinal distributions of the powers of the backward wave ( $P < 0$ ) and the slow ( $P_e < 0$ ) wave, which are demonstrated in Fig. 3 a. The zero value of the field is attained at the output cross section  $z = L$ . The energy propagation directions are shown by arrows. The power fluxes in the beam and in the waveguide have opposite signs, which indicates the presence of the internal feedback. The distinction between the "hot" and "cold" types of matching results in the appearance of an additional weak standing wave that is not shown in the figure.

In a TWT generator the feedback is due only to the distinction between the "hot" and "cold" types of matching. Typical curves of dependence of the powers of the forward field wave and the slow beam wave on

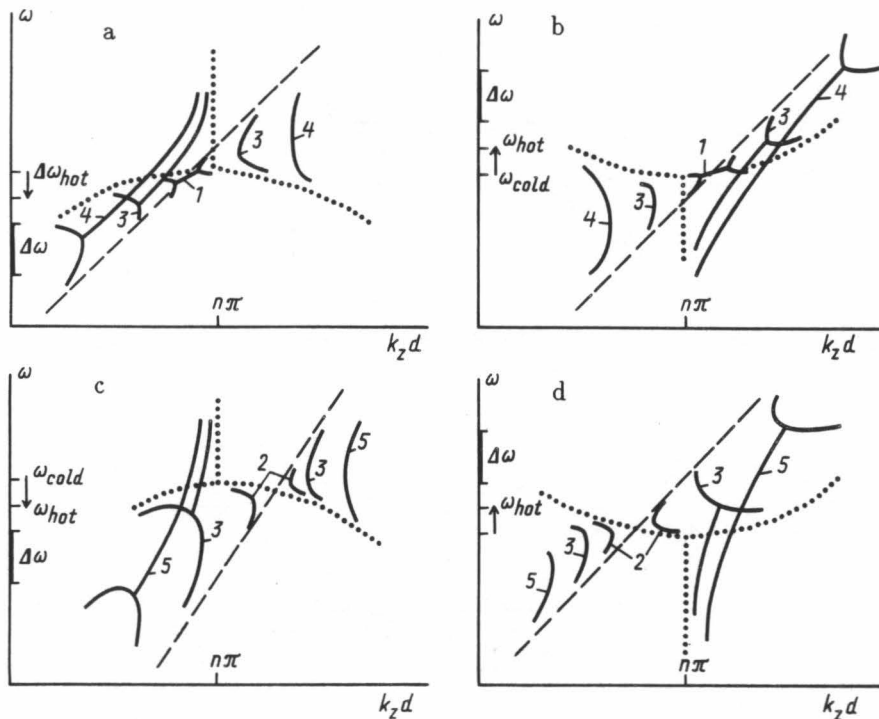


Fig. 2

Dispersion characteristics for systems with high-frequency (a, c) and low-frequency (b, d) transmission band boundaries. The dotted line, system without a beam; the dashed line, slow wave; (1) weak TWT-type coupling; (2) weak BWT-type coupling; (3) coupling in the presence of considerable perturbations; (4) TWT-BWT regime; (5) BWT-TWT regime.

the longitudinal coordinate show periodic pulsations (Fig. 3 b). If we assume them to be small, the zero of the field corresponds to the input cross section of the waveguide ( $z \simeq 0$ ).

It should be noted that when the beam and the field interact in frequency ranges corresponding to steep sections of the dispersion curves, the maximum "hot" mismatching is observed at frequencies of the "hot" band boundaries, where the distinction between the "hot" and the "cold" wave impedances is maximum [4].

#### 4. THE BWT-TWT AND TWT-BWT TYPES OF COUPLING UNDER "HOT" MATCHING

Let the slow and the fast beam waves be separated sufficiently well and let the "hot" matching operating region (formed by smooth transitions for the beam and the field) be at a distance from the triple point of the boundary cutoff. There are no reflections in the system, and we have a three-wave coupling of the slow beam wave with the two (forward and backward) field waves. The principal role in the three-wave coupling is played by the TWT and BWT coupling mechanisms. In the curves of dependence of the field waves power on the coordinate the zero of the field is in the intermediate section of the waveguide (see Fig. 3 c). If the zero point is in the initial part of this section, then the TWT-type interaction dominates, the region where the field power flow is positive is prolonged, and we have the TWT-BWT operation conditions. If the zero falls on the output section, the negative field power flow is greater, and a transition to the BWT-TWT regime occurs.

#### 5. THE EFFECT OF THE BEAM ON THE WAVE COUPLING UNDER "COLD" MATCHING

A typical variation of dispersion characteristics due to the effect of the beam in the conditions of

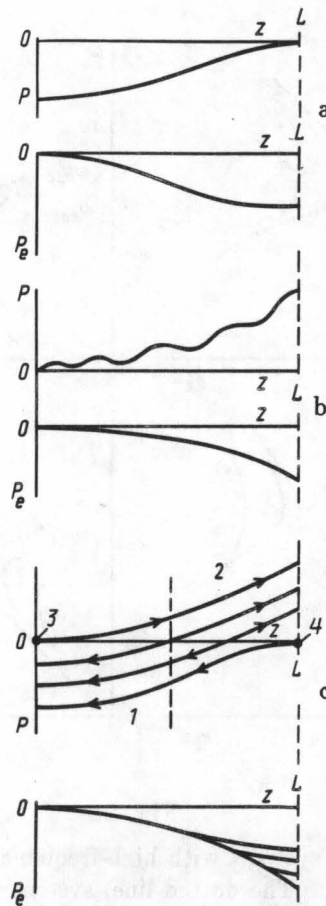


Fig. 3

Power of the field wave ( $P$ ) and of the slow wave ( $P_e$ ) versus the coordinate  $z$  for the BWT (a), TWT (b), and combined operation conditions (c): (1) BWT-TWT; (2) TWT-BWT; (3, 4) zero field point for the TWT and BWT conditions, respectively.

synchronism of the slow electron wave and the backward field wave is demonstrated in Figs. 2 c and d. When there is a weak coupling, the synchronism point corresponds to the BWT regime. As the coupling increases in a system with a high-frequency "cold" transmission band boundary ( $\omega'' < 0$ ; Fig. 2 c), one observes a low-frequency shift of the triple point of the "hot" boundary ( $\omega_{\text{hot}} < \omega_{\text{cold}}$ ). In the range of lower frequencies this point goes into a triple point at the boundary of the TWT amplification region. The BWT-TWT regime is realized in the system. The minimum generation starting current is attained in the vicinity of the "hot" boundary cutoff frequency ( $\omega_{\text{gen}} \simeq \omega_{\text{hot}}$ ), which is found in the calculations of the beam and field powers in the system. At this frequency the power flows change sign, which corresponds to the appearance of mutual transitions of the propagating and entrained fields.

The "hot" shift of the low-frequency boundary cutoff ( $\omega'' > 0$ ) is demonstrated in Fig. 2 d. At first one observes a high-frequency shift of the "hot" boundary. Then the BWT regime passes into a TWT-type interaction regime. The generation is observed in the BWT-TWT regime and, as a rule, in the "hot" boundary frequency region.

If the slow beam wave is in synchronism with the forward field wave and the coupling of these waves is considerable, there is a low-frequency "hot" shift of the band boundary in the system when  $\omega'' < 0$  and a high-frequency shift when  $\omega'' > 0$  (see Fig. 2 a and b). With a sufficiently strong coupling, in the BWT-TWT and TWT-BWT regimes one observes a transition to curves that are in many respects similar to those shown in Fig. 2 c and d.

Typical curves of frequency dependence of the amplification coefficient  $K$  for systems with low-frequency

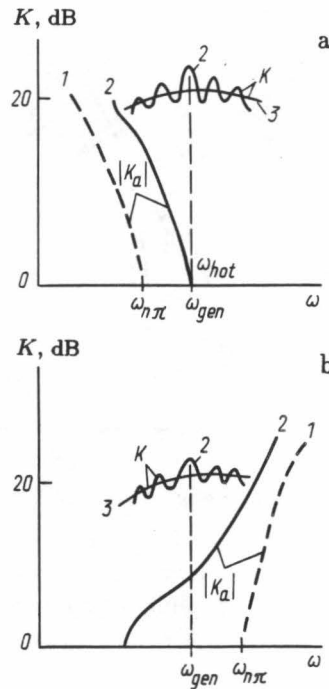


Fig. 4

Dependence of the amplification ( $K$ ) and attenuation ( $|K_a|$ ) coefficients on the frequency for waveguide sections with high-frequency (a) and low-frequency (b) transmission band boundaries: (1) in the absence of the beam; (2) in the presence of the beam; (3) "hot" matching.

and high-frequency boundaries are presented in Fig. 4 a and b. The smooth curves with one maximum indicate amplification in the regime of one increasing wave for an ideal "hot" matching [4]. Transition to the conditions of "cold" matching results in pulsations of the amplification curves. The maximum amplification is at the "hot" boundary frequency. The pulsations strengthen with increasing beam. At the point of maximum amplification the generation self-excitation regime is attained.

## 6. THE BULK-WAVE MODE OF THE GENERATOR UNDER HYBRID COUPLING

The interaction between the surface field and the higher-type bulk waves propagating at a nearly right angle to the system axis is described with the aid of coupled lines [11] (see Fig. 1 d) and is characterized by dispersion curves of hybrid modes for the region of  $2\pi$ -form frequencies ( Fig. 5). This interaction is used in the relativistic diffracted-radiation generator [8, 9] where the waveguide matching is achieved by means of smooth transitions, and the open resonator is unstable. The section of the curve adjoining the  $2\pi$ -form refers to the value of  $\omega'' > 0$  at a triple point. The other two triple points correspond to the boundaries of the additional nontransmission regions for which  $\omega'' < 0$ .

Assume that the slow beam wave is in synchronism with the hybrid mode in the forward wave frequency region (see Fig. 5). With a weak coupling the TWT regime is realized. As the coupling is increased, for instance, by approaching the beam to the waveguide surface, the region of the complex root expands and there appears a unified solution shown in Fig. 5 by solid lines. The solution refers to the complex TWT-BWT regime holding simultaneously for the surface and bulk fields. The dominant field power flow is directed along the beam motion and it facilitates the output of the radiation energy. The BWT-type feedback mechanism is realized for the bulk and surface fields. The "hot" transmission band boundaries are displaced away from the synchronism point, which facilitates the matching of the waveguide systems and improves the mode selection conditions. All these peculiarities of the coupled system result in the formation of a combined mode of the

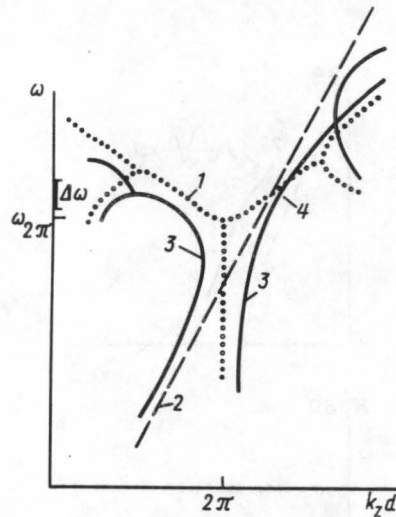


Fig. 5

Dispersion characteristics for the hybrid coupling of the beam and field waves in the  $2\pi$ -form frequency region: (1) hybrid mode without a beam; (2) slow beam wave; (3) coupled system with a beam; (4) region of the combined coupling regime in a relativistic diffracted-radiation generator.

relativistic diffracted-radiation generator (the TWT-BWT-SW-BW regimes) and in the attainment of higher radiation powers in the millimeter wavelength band [9].

## 7. MODES OF A SUPERDIMENSIONAL GENERATOR OF SURFACE WAVES

In a periodic waveguide of a large diameter ( $D_W \gg \lambda$ ), when the beam interacts with the surface field there can appear asymmetric higher-type generation modes. They can be found by representing the generator with a superdimensional waveguide in the form of a ring-shaped active line.

The interaction between the beam and the surface field is largely related to the BWT-TWT or TWT-BWT mechanisms. Directional radiation of relativistic bunches is also important. As follows from theory and experiment [9], generation can be realized within the limits of a longitudinal active strip with transverse dimensions of the order of a wavelength. It is acceptable to consider a system of many generating strips interconnected in a given angular (tangential) direction as a distributed active line closed as a ring (Fig. 6 a).

If the ring line is homogeneous, then, depending on the current and some other parameters, angular field distributions set in which are characterized by the mode indices  $N$  ( $N = 0, 1, 2, \dots$ ). They are shown schematically for several modes ( $N = 0, 2, 3, 4$ ) in Fig. 6 b. The minimum starting current, the constant level of the oscillation amplitude, and the axially symmetric field and generator radiation pattern correspond to the lowest mode ( $N = 0$ ). The radiation patterns in the form of two, three, and four separate arcs (Fig. 6 c) correspond to the higher line modes ( $N = 2, 3, 4$ ).

If the beam and the electrodynamic system are inhomogeneous in the transverse direction, then the arcs in the radiation pattern become different, and the symmetry is broken (Fig. 6 c).

The example under consideration demonstrates the mechanism of transition of the many-wave interaction regime in matched waveguides of partial systems into the one-mode generation regime of a superdimensional system. In the quantum language, for the limiting case of weak fluctuations one should speak about a transition from the many-quantum (according to the number of waves) coupling process to the one-quantum coherent radiation of the generator with a complex structure of the curling field.

## 8. INCLUSION OF DISTRIBUTED LOSSES. TRANSITION TO ELECTRONIC MODES

In superdimensional waveguides with relativistic particle energies, the observed additional energy radiation directly from the internal regions of the device is due to the antenna mechanism of directional

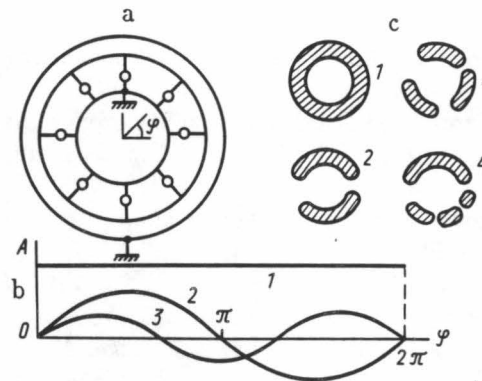


Fig. 6

Equivalent ring-shaped active line: (a) schematic representation of the line; (b) field amplitude as a function of the angle  $\varphi$ ; (c) radiation patterns for  $N = 0$  (1), 2 (2), 3 (3), and 4 (4, the inhomogeneous line).

radiation [9]. In an approximate description, the additional losses are taken into consideration by introducing supplementary resistances and coupling elements in branches of equivalent circuits. This is legitimate in the cases when the additional radiation does not produce substantial changes in the interaction conditions, the feedback, or the matching.

In the case of long systems with distributed losses, the general character of the processes does not change. Although degeneration disappears (there are no triple points), the behavior of the nondegenerate dispersion curves remains similar to that of the curves in a system without losses [4], the resonances, the "hot" shift of the boundary cutoff, etc., are retained.

In short sections, when losses are distributed, the coupling mechanisms generally operate in the range of fundamental critical frequencies (the zero,  $\pi$ -,  $2\pi$ -, ...-forms of oscillations) for surface and hybrid modes.

With growing distributed losses there occurs a transition to the limiting case of large radiation losses, when the generator field structures are almost completely determined by the electron beam. These regimes are characterized by the formation of electronic modes of radiation sources. An example of this kind is the formation of the mode of the generating autoresonance synchrotron maser with a tubular electron beam in a totally absorbing waveguide [9].

The generator electronic modes can also be formed in a system consisting of short sections of a superdimensional periodic waveguide excited by a relativistic tubular beam with a sufficiently high particle energy. At large energies the longitudinal and transverse structures of the field and beam waves are not attained, the coupling processes undergo disruption, and the characteristics of the electronic modes of the generators are to a large degree determined by the beam, the near-surface resonances, and the directional particle radiation.

## CONCLUSION

In this paper we considered a specific class of electronic generators with matched waveguides in which the processes are primarily determined by the couplings of many waves of the beam and the field and also by a substantial effect of the electron medium on the waveguide properties. The corresponding many-wave generation mechanism occupies an intermediate position between the generation mechanisms on "cold" and electronic modes. The formation of the modes mainly depends on the effects of amplification and the internal BWT-TWT or TWT-BWT type feedback and also by the distinction between the "hot" and "cold" matching conditions.

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