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RADIOPHYSICS

Prospects of Application of Superconducting Electrodynamic Structures in Electronic Devices for Their Advancement to the Terahertz Range

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Abstract—It is shown that the application of superconducting electrodynamic structures in microwave electronic devices not only improves their characteristics, but also creates premises for implementation of devices like the autophase traveling-wave tube (TWT) and peniotron operating in the millimeter range with their further advancement to the terahertz range, which is impossible for conventional electrodynamic structures with Ohmic losses. Superconducting corrugated waveguides make it possible to suspend limitations imposed on the output power of pulsed relativistic Cherenkov oscillators, which are associated with thermal degradation of the working surface of conventional waveguides with Ohmic losses.

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INTRODUCTION

Superconducting electrodynamic structures have been widely and successfully employed for many years in linear accelerators of electrons and positrons [1–6]. The application of such structures not only considerably improves the parameters of accelerators, but also makes their implementation feasible. An equally strong effect from application of superconducting structures can also be expected among other fields in high-power microwave electronics for the advancement of instruments and devices to the subterahertz and terahertz frequency ranges, which are important and topical scientific problems at present [7].

In this study, we consider the situations in which the application of superconducting systems makes it possible not only to improve the characteristics of microwave electronic devices, but also paves the ways for implementation of potentially effective instruments such as the autophase traveling wave tube (TWT) [8, 9] and millimeter- and submillimeter-range peniotrons [10–18]. Their implementation is impossible when conventional electrodynamic systems with Ohmic losses are used because almost the entire electromagnetic field energy generated by the electron beam under optimal conditions of its interaction with the field in such systems is absorbed.

The application of superconducting electrodynamic systems (corrugated waveguides) in ultrahigh-power pulsed relativistic Cherenkov oscillators is equally important. As a matter of fact, for a pulse duration of 1–40 ns, the removal of heat (due to Ohmic losses) from the working surface has no time to occur, and this surface is destructed when the oscillator power attains a certain level. The application of superconducting structure obviously removes this limitation on the oscillator power.

1. AUTOPHASE TWT

Various versions of methods for increasing the efficiency of the O-type traveling wave tube (TWT-O) were proposed by using the variable-length region of interaction of the cold phase velocity of the slow-wave system. Even at early stages of TWT-O investigation, Pierce [19] and Slater [20] proposed a method for increasing the efficiency of energy exchange in the TWT-O by compensating the electron deceleration effect by the enhancement of wave retardation at the tube outlet so that $v_{\rm ph} \approx \mathbf{v}_e(z)$ ($v_{\rm ph}$ is the cold phase velocity of the wave, $\mathbf{v}_e$ is the mean velocity of electrons, and z is the longitudinal coordinate). Later, such TWT-Os were called isochronous [21]. A slightly different idea for elevating efficiency of TWT-O formed the basis of isophase TWT-Os: at the end of the interaction region, the phase difference $\Delta\varphi$ between the first harmonic of the beam current and the wave field strength is maintained constant and close to π [22]. Detailed analysis [22] has proved, however, that for high gain parameters ε, the increase in the efficiency

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of isophase and isochronous devices is insignificant as compared to that of regular TWTs in spite of complex (for isophase TWTs) laws of variation of $v_{ph}(z)$. As a matter of fact, both proposed methods for compensating the withdrawal of the electron bunch from the decelerating phase of the wave field simultaneously lead to its defocusing and relatively fast "spilling." Therefore, it is necessary to choose a method for accompanying the bunch in the field of the traveling wave in which the grouping conditions are improved together with the conditions of energy removal.

The required laws of $v_{ph}(z)$ variation ensuring the electron efficiency of a TWT-O of about 70–80% for a moderate gain $G \approx 20$ dB were obtained in [23–25] by direct optimization. Optimal versions are typically obtained by a considerable increase in the cold phase velocity of the wave of the slow-wave system in the region of electron bunch grouping.

Here, we report on the results of investigation of the autophase regime of TWT-O with increased length. The efficiency is optimized by the "synchronous (model) electron" method [26–28]. The result of these investigations is the conclusion that the "cold" phase velocity of the wave in the slow-wave system in the first half of the length of the interaction region must be substantially higher than the synchronous velocity (the extent of the increase in the cold phase velocity of the wave in this region is in quantitative agreement with the values obtained in [23–25], but differs significantly from that in [26]). The physical reasons for this effect are explained in this study. This also indicates that an autophase TWT-O cannot be treated directly as a reversed autophase accelerator, which is apparently possible in the case of microwave devices with a preset field [27, 28].

In analysis of nonlinear processes of interaction in a TWT-O by the particle-in-cell method, a slightly transformed and simplified system of self-consistent 1D equations (3.18) from [25] was used in the form

$$\begin{aligned}
\frac{d\beta_i}{dT} &= -\varepsilon\theta_0\frac{\beta_0^2}{\beta_i}(1-\beta_i^2)^{3/2}[\sqrt{\rho}A\cos(u_i+\vartheta-\Phi)-F_i],\\
\frac{du_i}{dT} &= \frac{\theta_0}{\varepsilon}\left(\frac{\beta_0}{\beta_i}-1\right),\\
\frac{dA}{dT} &= \sqrt{\rho}\frac{2\theta_0}{N}\sum_{i=1}^{N}\cos(u_i+\vartheta-\Phi)-k_m\frac{\theta_0}{\epsilon}S_T(T)A,\\
\frac{d\vartheta}{dT} &= -\sqrt{\rho}\frac{2\theta_0}{NA}\sum_{i=1}^{N}\sin(u_i+\vartheta-\Phi),
\end{aligned} \tag{1}$$

with the boundary conditions

$$u_i(0) = \frac{2\pi i}{N}-\frac{\pi}{2},\quad A(0) = A_0,\qquad \vartheta(0) = 0,\quad \beta_i(0) = \beta_0. \tag{2}$$

Here, we have used the notation described in [8]. In contrast to equations given in [8], the last term on the right-hand side of the equation for A is introduced for describing damping due to heat loss in the slow-wave spiral [25]:

$$S_T(T) = \frac{x^2(T)}{\rho^2\beta_0}\frac{0.1205}{W_0}\sqrt{f\,[\mathrm{GHz}]},$$

$W_0 = 337$ is the impedance of vacuum and k_m is the coefficient describing the spiral material ($k_m = 1$ for a perfectly smooth surface of the copper wire spiral; in actual practice, $k_m > 1$; in our calculations, we assumed that $k_m = 2$).

In the presence of distributed losses in the slow-wave system ($S_T \neq 0$), waveguide efficiency η_w is found to be lower than electron efficiency η_e.

Since the phase incursion

$$\Phi(T) = \frac{\theta_0}{\varepsilon}\int_0^T\frac{\beta_0-\beta_{ph}(T)}{\beta_{ph}(T)}dT$$

is determined by the relative cold phase velocity $\beta_{ph}(T)$, we assume that it is chosen so that relative phase ψ_s of an electron with $i = s$ in the self-consistent field can be set in advance as follows [8]:

$$\psi_s = u_s+\vartheta-\Phi(T) = \frac{\pi}{2}-\delta_0+\delta_1T^n. \tag{3}$$

If $\delta_1 = 0$, the value of ψ_s is preset and constant [8], and the electron with $i = s$ is equivalent to the center of the bunch moving synchronously with the "hot" wave and separated in phase by angle δ_0 from the node of the field of this wave (synchronous electron). The addition of the term δ_1T^n ($n > 0$) in formula (3) corresponds to the displacement of the bunch center at the end of the tube to the slow-wave phase of the hot wave, which accelerates the energy transfer and maintains the efficiency at a high level in the presence of distributed loss in the slow-wave system of a short TWT.

Under condition (3), the relative phases ψ_i of electrons are defined as

$$\psi_i = u_i-u_s+\frac{\pi}{2}-\delta_0-\delta_1T^n,$$

and the running relative phase velocity can be determined from the solution of the equation

$$\frac{\beta_0-\beta_{ph}(T)}{\beta_{ph}(T)} = \frac{\varepsilon}{\theta_0}\left(\frac{du_s}{dT}+\frac{d\vartheta}{dT}+n\delta_1T^{n-1}\right).$$

Thus, with the help of the modified synchronous electron method described here, with preset values of λ, θ_0, ε, k_m, β_0, and n, the problem of optimization of the TWT-O efficiency can be solved by selecting the values of A_0, δ_0, and δ_1 that maximize η_w (1).

Let us analyze the autophase regime of the TWT, assuming that the slow-wave system (e.g., a spiral made of a hollow niobium wire with circulating liquid helium) is superconducting. In this case, in contrast to the copper spiral, we can approximately assume that $S_T(T) = 0$.

Analysis of the autophase regime was carried out in a wide range of variation of $\beta_0 = 0.1–0.3$ for $\varepsilon = 0.09$, $b/a = 0.7$, $p = 2$, $\theta_0 = 25$, and $N = 20$. It was found that all versions for the same θ_0 have almost identical characteristics and output parameters: $G \approx 40$ dB and $\eta_w \approx 80\%$. In optimizing the values of A_0 and δ_0 only the regimes in which there are no strongly decelerated and reflected (inverse) electrons exist were admitted. This (as well the fixed value of θ_0) explains the limited maximal value of efficiency. It should be noted that strongly decelerated electrons falling out of the potential well of the wave were disregarded in calculations in [25]. However, these electrons in their subsequent motion could be accelerated in the strong field of the wave, which would reduce the efficiency of energy transfer. Since such electrons constituted 70%, their exclusion could lead to overestimated values of electron efficiency in [25].

Figures 1–3 show the phase, energy, and integrated characteristics, respectively, of the autophase regime of TWT-O for $\beta_0 = 0.15$ and $A_0 = 0.036$. Analysis of the curves shown in the figures lead to the following conclusions concerning the features of the autophase regime of TWT-O.

1. On the initial segment $T = 0–0.5$, the preliminary quite effective process of grouping takes place for the exact equality of mean electron velocity β_0 and the hot phase velocity $\beta_{h\,ph}$ of the wave (i.e., the actual phase velocity of the self-consistent field of the wave taking into account the reaction of the phase electron bunch with the center permanently coinciding with the node of the wave field owing to the corresponding dependence $\beta_{ph}(T)$). On this segment, the main portion of electrons is trapped into the bunch (see Fig. 1); grouping increases rapidly and monotonically (curve *5* in Fig. 3), and there is no energy exchange up to $T = 0.3$ ($\eta_v \cong 0$; see Fig. 3). The cold phase velocity β_{ph} in the slow-wave system on the same segment increases monotonically and attains its maximal value at $T = 0.2$, ensuring the required regime of grouping. The peak value of β_{ph} is considerably higher than the synchronous level ($\beta_{ph\,max} \approx 0.32$, while $\beta_{ph\,max} \approx \beta_0 = 0.15$).

2. On segment $T = 0.5–1$, the autophase regime proper is activated: electrons trapped into the bunch perform phase oscillations relative to the center of equilibrium (see Fig. 1) so that none of these electrons falls out of the potential well ($|\Delta\psi_i| < \pi$ up to $T = 0.8$); their velocity (energy) also oscillates, but decreases on the average due to deceleration of the well (see Fig. 2). It should be noted that the bunch has a compact central part consisting of electrons performing synchronous small oscillations and a “halo” represented by periphery electrons performing asynchronous phase oscillations with a large amplitude (see Fig. 1). Energy oscillations of the latter electrons (see Fig. 2) are also out-of-phase and have a large amplitude. Grouping function $G_r(T)$ on segment $T = 0.5–1$ slightly

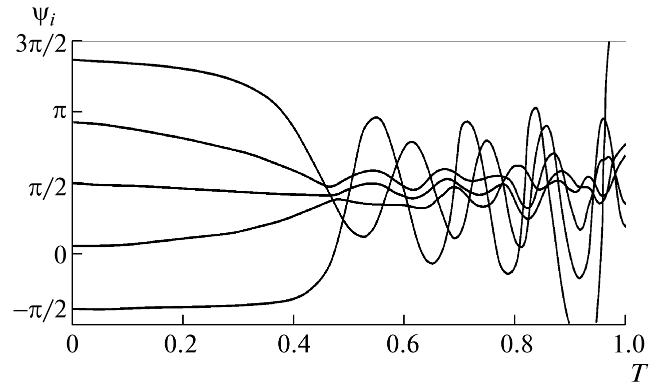

Fig. 1. Dependences $\psi_i(T)$ for 5 from 20 electrons used for calculations.

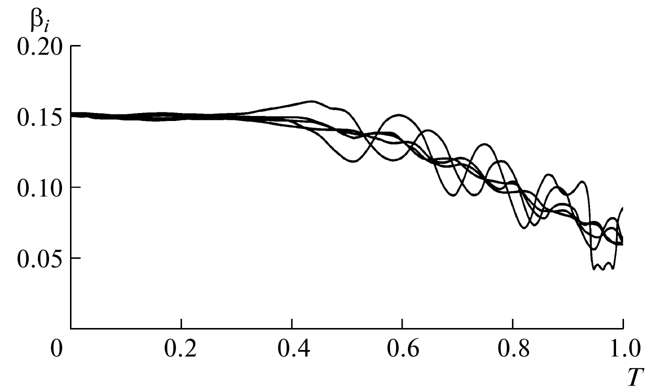

Fig. 2. Dependence $\beta_i(T)$ for electrons the same as in Fig. 1.

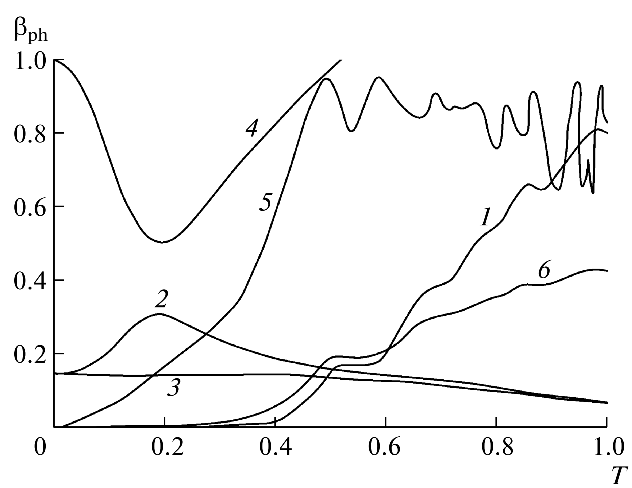

Fig. 3. Integrated dependences $\eta_w(T)$ (*1*), β_{ph} (*2*), $\beta_{h\,ph}(T)$ (*3*), $g(T)$ (*4*), $G_r(T)$ (*5*), and $A(T)/10$ (*6*).

decreases on the average. The $G_r(T)$ dependence becomes nonmonotonic, reflecting oscillatory phase processes in the bunch. The cold wave velocity β_{ph} in the slow-wave system monotonically decreases on the entire segment $T = 0.3–1$, ensuring the required decrease in $\beta_{h\,ph}$ leading to general deceleration of all electrons (see Fig. 3). It is significant, however, that $\beta_{ph} > \beta_{h\,ph}$ on the entire segment of energy extraction. The energy is mainly extracted on the output part of the region of interaction (curve *1* in Fig. 3). The energy extraction is nonmonotonic again due to oscillatory processes in the electron bunch.

3. It is interesting to note that distributions $g(T)$ and $\beta_{ph}(T)$ in the autophase regime, which were obtained on the basis of the synchronous electron method, are in qualitative agreement with those obtained in [22–24] using direct optimization for a short TWT-O; this indicates the general nature of physical features of processes with optimal efficiency (in particular, the processes of formation of phase bunches) both in a short and in a long TWT with a large gain.

4. The resultant $\beta_{ph}(T)$ dependence not only contradicts the existing intuitive ideas about its optimal nature [19–22], but also the $\beta_{ph}(T)$ dependences obtained earlier for the autophase regime of orotron [28]. This can easily be explained taking into account the fact that the field in the orotron is assumed to be preset (i.e., the amplitude and phase spatial dependences are specified). Conversely, the structure of the field of the traveling wave in the TWT-O is not fixed and, hence, the influence of the phase bunch with the center artificially made to coincide with a node of the field of the wave being excited in the autophase regime leads to strong dynamic deceleration of the wave relative to the cold phase velocity (without the action of the electron beam). This mechanism is manifested especially strongly on the initial segment $T = 0–0.5$, where the bunch is regular, and the wave amplitude is small. Therefore, it turns out that to obtain the appropriate law of variation of the hot phase velocity $\beta_{ph}(T)$ of the wave, the phase velocity of the wave in the cold system must be substantially increased on the initial segment relative to the synchronous level. In the orotron, the law $\beta_{ph\,preset}(T) = \beta_{h\,ph}$ is specified directly, and the form of the dependence of this quantity on T naturally coincides with that obtained in this study.

It should be recalled that the above results were obtained for $S_T(T) = 0$; i.e., these results are valid only for a superconducting slow-wave system.

The calculations performed in [9] for a copper slow-wave system gave negative results: on the extended segment of autophase extraction of energy from the electron beam, the power is absorbed almost completely in the slow-wave system due to Ohmic losses. As a result, the wave efficiency of all versions of the autophase TWT considered here tends to zero.

2. PENIOTRON

The peniotron was invented at the beginning of the 1960s [10, 11]. It belongs to a few microwave devices in which an almost ideal (as regards its efficiency) mechanism of interaction operates; namely, all electrons of a thin-wall tubular beam rotating in the longitudinal magnetic field B_0 coaxially with an azimuthally periodic electrodynamic system irrespective of the initial relative phase in the T field ($v_{ph} = c$) give away their energy to the rf field identically on the average. This is observed when the peniotron synchronism condition

$$1 - v_z/v_{ph} = P\Omega, \quad p = n - 1, \quad \Omega = \frac{eB_0}{\gamma m_0 \omega},$$

holds, where v_z is the longitudinal velocity of electrons, v_{ph} is the phase velocity of the wave with n azimuthal variations, and p is the number of the synchronous harmonic. Simplified analytic models [9] show that the efficiency of peniotron interaction remains high when the number p of a synchronous harmonic increases to $p = 10$; this raised hopes for designing (on the basis of this mechanism) an effective medium-power source ($P \approx 1–10$ kW) operating in the millimeter range on permanent magnets ensuring the required level of B_0.

The inadequacy of the single-electron model under certain conditions was pointed out for the first time in [12], where a significant dependence of the efficiency on the initial phase of electrons for $v_{ph} > c$ was detected in calculations based on the unaveraged mode in the relativistic case also. Unaveraged models of a peniotron amplifier and an oscillator operating on the T wave of a multiconnected electrodynamic system were proposed in [12]. Such a system is the best for effective implementation of the peniotron mechanism not only due to the condition $v_{ph} = c$, but also the possibility to bring closer the electron orbits of a weakly relativistic beam to the lamels of the electrodynamic structure in the region of the strong field.

Analysis of the optimal versions obtained on the basis of these models taking into account the effect of forces of the field produced by a space charge indicates noticeable deterioration of the efficiency of the peniotron amplifier due to the action of space charge field forces, leading to the dependence of the energy of interaction on the phase of the oncoming electron (especially upon an increase in the number of the synchronous harmonic). The results of calculations performed in [13–15] have shown that the efficiency of the peniotron oscillator with optimally selected parameters is still quite high (efficiency attains 72% for $p = 3$ and 34% for $p = 10$) in spite of the fact that the counterpropagating partial wave produces a negative effect when conditions close to those ensuring its gyroresonant interaction with the beam are created.

Analysis of the optimal variants of the peniotron oscillator shows that the action of space charge field forces in them is compensated by the conditions in which the rf field amplitude considerably exceeds these forces. In actual practice, this is possible when the Q factor of the resonator and the beam power are appropriately balanced. Analysis of experimental results [17] shows that for $p = 3$, by choosing the loaded Q factor of about 2000, it is possible to ensure the required rf field amplitude and obtain the efficiency of 70% corresponding to the rated value. For $p = 10$, the rated efficiency is 33%, while the experimentally attained value was only 6%. Calculations show that the optimal efficiency is attained for the resonator Q factor five times higher than the experimental value. Analogous result was obtained in experiment [18].

The results considered above indicate that the application of superconducting resonators in peniotrons will make it possible to implement regimes with $p = 10$ at a high efficiency, thus facilitating uptaking of the terahertz range for experimentally attainable values of the magnetic induction.

CONCLUSIONS

It has been shown that the application of superconducting electrodynamic structures in microwave electronic devices not only improves their characteristics, but also creates premises for designing such devices as autophase TWT and millimeter-range peniotron; this is impossible for ordinary structures with Ohmic losses.

It should also be noted that the application of corrugated superconducting waveguides in ultrahigh-power relativistic Cherenkov oscillators will make it possible to remove the thermal load from the electrodynamic system of the generator. This in turn will make it possible to substantially increase the output power of the instruments because thermal damage of the working surface, which limits the level of generated power in available devices with conventional (nonsuperconducting) electrodynamic structures), will be eliminated.

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