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TAKING INTO ACCOUNT DISSIPATION IN THE WAVE THEORY OF TWT OPERATING AT THE LIMIT OF THE TRANSMISSION BAND

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A form of the equations of the wave theory of TWT, when the dissipation is described by a parameter that remains virtually unchanged when the limit of the transmission band is crossed, is proposed. The conditions for parasitic self-excitation of TWT are analyzed taking into account the effect of dissipation and terminal loads. The limits of applicability of some previously proposed models of TWT are discussed.

One problem in the wave theory of TWT, operating near the limit of the transmission band, is taking into account correctly the dissipation of electromagnetic energy in the walls of the delay system. The traditional parameter of "cold" losses in the theory of TWT is proportional to the imaginary part of the propagation constant and increases rapidly as the frequency approaches the band limit. This fact has given rise to the widespread belief that the presence of dissipation qualitatively changes the characteristics of the device, and dissipation must be in principle taken into account in the theory of TWT operating near the limit of the transmission band [1]. In reality, the excitation equation can be formulated so that the dissipation parameter appearing in it remains virtually unchanged when the limit of the transmission band is crossed. This enables a correct study of the conditions of parasitic self-excitation of TWT at the limit of the transmission band in

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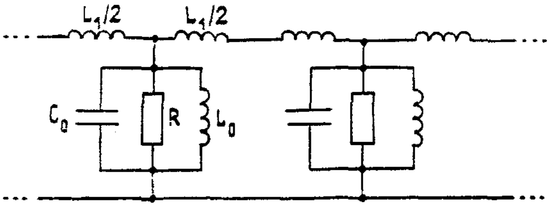

Fig. 1

the presence of dissipation; and makes it possible to indicate the limit of applicability of some models, previously proposed for approximate calculations of TWT at the band limit.

1. Equations of Excition of the Delay System at the Limit of the Transmission Band Taking into Account Energy Dissipation. We shall first study a model problem. Consider the transmission line shown in Fig. 1. It is characterized by the dispersion equation

$$\omega^2 - i\omega/RC_0 = \omega_0^2 + \varepsilon^2(1 - \cos\beta d), \tag{1}$$

where ω is the frequency, β is the wave number, d is the period of the system, $\omega_0^2 = 1/L_0C_0$, and $\varepsilon^2 = 2/L_1C_0$. We shall derive the equation of excitation of the transmission line by external currents. According to the well-known rules of the theory of circuits we easily obtain

$$\left[\omega^2 - \frac{i\omega}{RC_0} - \omega_0^2 - \varepsilon^2(1 - \cos\beta d)\right] U_\beta = \frac{i\omega}{C_0} J_\beta. \tag{2}$$

Here $U_\beta = \Sigma U_n e^{i\beta nd}$, $J_\beta = \Sigma J_n e^{i\beta nd}$, U_n is the voltage at the n-th oscillatory loop, and J_n is the current exciting it. Let the frequency of the exciting current lie near the limit ω_0 of the transmission band (for definiteness we choose the low-frequency limit). We shall expand the coefficients in Eq. (2) in a Taylor series in ω and β near the point (ω_0, $\beta_0 = 2\pi/d$):

$$\left[\omega - \omega_0 - i\gamma - \frac{\omega''(\beta_0)}{2}(\beta - \beta_0)^2\right] U_\beta = \frac{i}{2C_0} J_\beta. \tag{3}$$

Here $\gamma = 1/2C_0R$, $\omega''(\beta) = \varepsilon^2 d^2/2\omega_0$. Transferring from the relation (3) to the wave equation with the help of the standard substitution $i(\beta - \beta_0) \to d/dx$ we obtain the excitation equation sought

$$\frac{d^2U}{dx^2} + \frac{2}{\omega''(\beta_0)}(\omega - \omega_0 - i\gamma)U = \frac{i}{\omega''(\beta_0)C_0} J. \tag{4}$$

The following equation of excitation of a periodic delay system without dissipation at the limit of the transmission band was presented in [2, 3]:

$$\frac{d^2\mathscr{E}}{dx^2} + \frac{2}{\omega''(\beta_0)}(\omega - \omega_0)\mathscr{E} = \frac{i\omega_0\beta_0}{\omega''(\beta_0)} R(\beta_0)J. \tag{5}$$

In the relation (5) $R(\beta_0)$ is the modified coupling resistance [2], $\mathscr{E}$ and J are the complex amplitudes of the field and current, and

$$\mathscr{E} = \tilde{E}e^{i\beta_0 x}, \quad J = \tilde{I}e^{i\beta_0 x}. \tag{6}$$

Here $\tilde{E}$ is the high-frequency field synchronous with the electron beam and is the sum of two spatial harmonics; $\tilde{I}$ is the high-frequency current.

Comparing Eq. (5) with the excitation equation (4) makes it trivial to extend it to the case of systems with dissipation:

$$\frac{d^2\mathscr{E}}{dx^2} + \frac{2}{\omega''(\beta_0)}(\omega - \omega_0 - i\gamma)\mathscr{E} = \frac{i\omega_0\beta_0}{\omega''(\beta_0)} R(\beta_0)J. \tag{7}$$

Here γ is the dissipation parameter. Equation (7) can be justified more rigorously on the basis of the electrodynamic theory of excitation of periodic waveguides [3, 4]. For this the calculations of [3, 4] must be repeated using the expansion of the dissipation equation in a Taylor series:

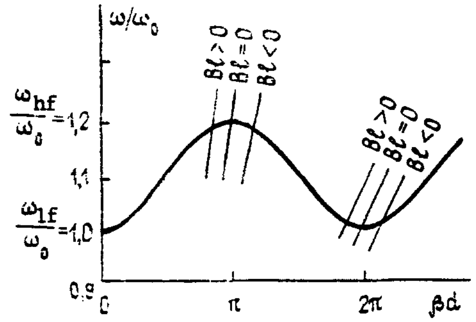

Fig. 2

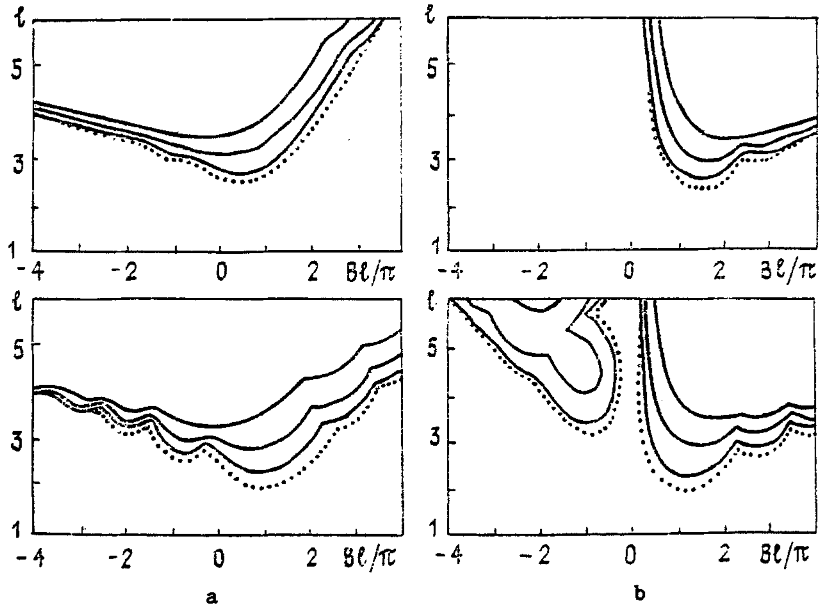

Fig. 3

$$\omega = \omega_0 + i\gamma + \frac{\omega''(\beta_0)}{2}(\beta - \beta_0)^2. \tag{8}$$

We gave a phenomenological derivation of Eq. (7), which is clearer.

We shall now explain the meaning of the dissipation parameter γ. Consider a "cold" system and let it be short-circuited at the ends. In this case Eq. (7) without the right sideholds

$$\frac{d^2 \mathscr{E}}{dx^2} + \frac{2}{\omega''(\beta_0)}(\omega - \omega_0 - i\gamma)\mathscr{E} = 0 \tag{9}$$

with the boundary conditions

$$\mathscr{E}(0) = 0, \quad \mathscr{E}(L) = 0. \tag{10}$$

Here L = Nd is the geometric length of the system and N is the number of periods. The boundary-value problem (9) and (10) is characterized by a collection of modes with complex characteristic frequencies

$$\omega_n = \omega_0 + \frac{\omega''(\beta_0)}{2d^2}\left(\frac{n\pi}{N}\right)^2 + i\gamma, \quad n = 1, 2, 3, \ldots \tag{11}$$

The Q-factors of these modes are determined by the dissipation parameter γ:

$$Q_n = \mathrm{Re}\,\omega_n / 2\gamma. \tag{12}$$

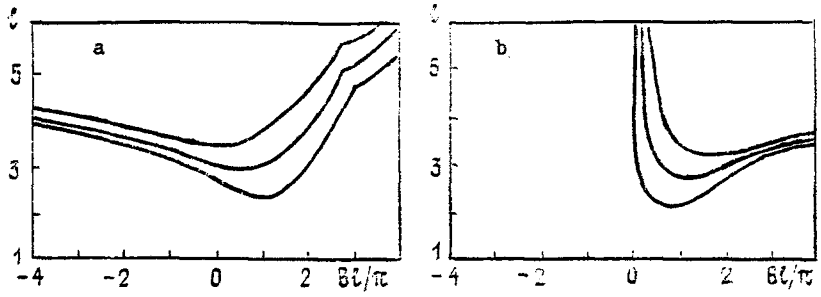

Fig. 4

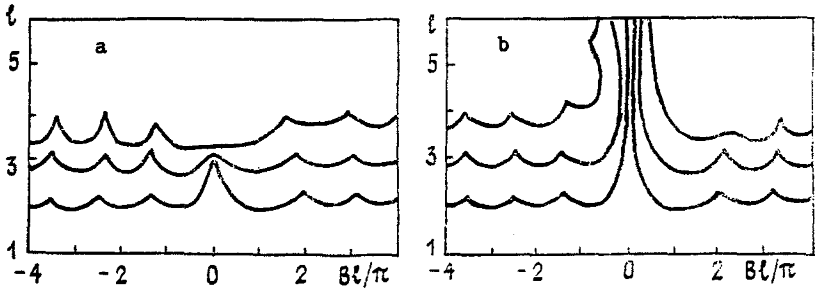

Fig. 5

2. Study of the Conditions of Parasitic Self-Excitation of TWT. Using the equation of excitation (7) we can write down a system of self-consistent equations for the interaction of the electron beam and the electromagnetic field at the limit of the transmission band in dimensionless form:

$$\mu \frac{d^2 F}{d\xi^2} + (\Omega - i\delta) F = iI, \quad \left(\frac{d}{d\xi} - iB\right)^2 I = iF. \tag{13}$$

Here $\delta = 2\gamma N^2 d^2/|\omega''(\beta_0)|\ell^2$; the rest of the notation is the same as that in [2].

We shall study the conditions for parasitic self-excitation of TWT at the limit of the transmission band in the presence of dissipation in the delay system. For this Eqs. (13) must be supplemented with boundary conditions [5]:

$$I(0) = 0, \quad \frac{dI}{d\xi}(0) = 0; \tag{14}$$

$$\frac{dF}{d\xi}(0) = i\alpha F(0), \quad \frac{dF}{d\xi}(l) = -i\alpha F(l). \tag{15}$$

Here we employ the following dimensionless parameters and their combinations: ℓ is the dimensionless length of the system and is proportional to the quartic root of the working current; $B\ell$ is the dimensionless detuning of the accelerating voltage from the value corresponding to exact synchronization with the band limit (Fig. 2); $\Omega\ell^2$ is the dimensionless detuning of the frequency from the limit; $\alpha\ell$ is a parameter characterizing the terminal nonuniformities (input–output devices). For the transmission line shown in Fig. 1 $\alpha\ell$ is determined by the impedance R_L on which the line is loaded: $\alpha\ell = \pm\omega_0 L_1 N/R_L$, where N is the number of cells in the system. At the low-frequency limit of the transmission band $\alpha\ell > 0$, and at the high-frequency limit $\alpha\ell < 0$. For real TWT $10 \leqslant |\alpha\ell| \leqslant 50$ [5].

The quantity $\delta\ell^2 = 2\gamma N^2 d^2/|\omega''(\beta_0)|$ is the dissipation parameter. From (12) we find that in real devices $\delta\ell^2 \sim 0.1$-10.

Figure 3 shows the curves, found by solving numerically the boundary-value problem (13)-(15), of the starting values of the dimensionless length ℓ versus the dimensionless voltage $B\ell$ at the high- (Fig. 3a) and low-frequency (Fig. 3b) limits of the transmission band for different values of the parameters of the boundary conditions and dissipation. For the upper figures $\alpha\ell = \pm 10$ and for the lower figures $\alpha\ell = \pm 30$. The parameter of the curves is $\delta\ell^2$, which assumes the values $0.1\pi^2$, $0.4\pi^2$, and π^2. The dots indicate the dependences corresponding to no dissipation ($\delta\ell^2 = 0$).

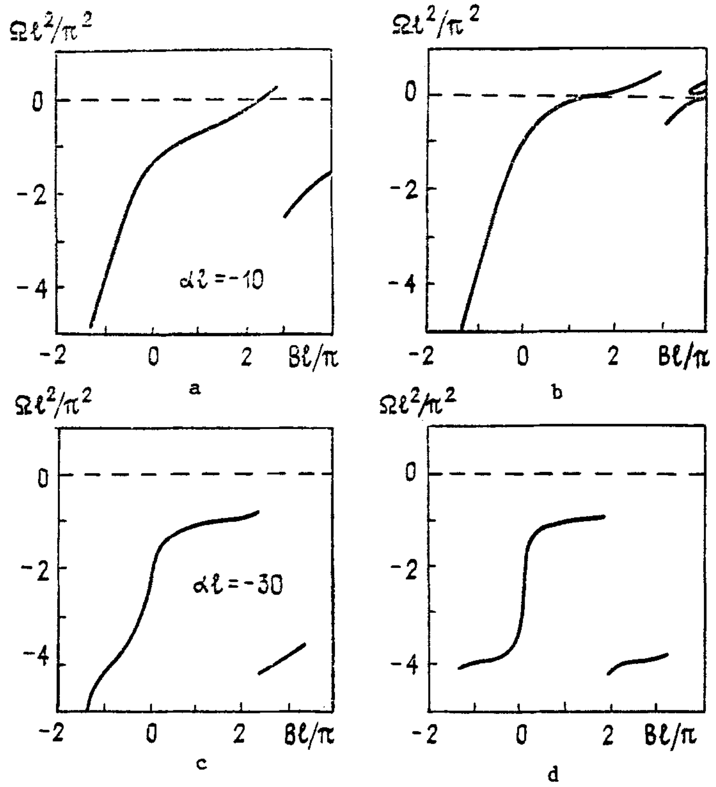

Fig. 6

As the calculations show, at the high-frequency limit of the transmission band the value of the accelerating voltage corresponding to the minimum starting current corresponds to synchronization of the electron beam with the forward waves, while at the low-frequency limit the voltage corresponds to backward waves (Fig. 2, the case $B\ell > 0$). Since for TWT the forward wave is the working wave this means that the danger of parasitic self-excitation is much higher at the high-frequency limit of the band than at the low-frequency limit. This fact is well known from experiments. Characteristically, the indicated features are observed for both low values of the dissipation parameter and with no dissipation. Increasing the dissipation parameter $\delta\ell^2$ increases the starting currents, and also leads to a shift in the point at which the starting current is minimum. For large $\delta\ell^2$ the curves become smooth, and the differences arising owing to the different magnitudes of the impedance of the load become less important.

3. Two Models in the Theory of TWT Operating at the Limit of the Transmission Band of the Delay System. In the theory of self-excitation of TWT developed above both energy dissipation and reflection of electromagnetic waves from the terminal loads were taken into account in a concrete manner. This enables evaluating the usefulness of the two models of TWT, proposed in their time for describing processes at the limit of the transmission band.

The first model, quite widely employed in both the wave theory of TWT and the theory of discrete interaction, is predicated on ideal matching of the system over the entire frequency band [1, 6]. It is assumed that all of the specific phenomena at the limit of the transmission band are determined by the character of the dispersion of the delay system, i.e., by the smallness of the group velocity as well as by the effect of the beam on the properties of the system ("hot mismatch"). The role of "cold" reflections is assumed to be negligibly small. We calculated the conditions for parasitic self-excitation of TWT at the limit of the transmission band on the basis of this model. For this, in our notation, the following boundary conditions must be employed:

$$\frac{dF}{d\xi}(0) = i\mu\sqrt{\mu(\Omega - i\delta)}\,F(0), \quad \frac{dF}{d\xi}(l) = -\,i\mu\sqrt{\mu(\Omega - i\delta)}\,F(l). \tag{16}$$

Figure 4 shows the dependence of the starting values of the dimensionless length ℓ on the dimensionless voltage $B\ell$, found by numerical solution of the boundary-value problem (13), (14), and (16). THe values of the dissipation parameters are $\delta\ell^2 = 0.1\pi^2$, $0.4\pi^2$, π^2; Fig.

4a refers to the high-frequency limit of the transmission band, while Fig. 4b refers to the low-frequency limit. Figure 6b shows the dependence of the dimensionless starting frequency $\Omega\ell^2$ on $B\ell$ at the high-frequency limit of the band; the dissipation parameter $\delta\ell^2 = 0.1\pi^2$.

Comparison of Figs. 3 and 4 leads to the following conclusions. The model of ideal matching describes well the qualitative character of the dependence of the starting current on the accelerating voltage for $|\alpha\ell| \sim 10$ and $\delta\ell^2 \gtrsim 0.1\pi^2$. At the high-frequency limit of the transmission band, in the region of synchronization with the backward wave ($B\ell < 0$), the quantitative agreement is also not bad. In the region of synchronization with the forward wave, however, where minimum starting currents are achieved, the calculation assuming ideal matching can lead to a significant error. For example, for $\delta\ell^2 = 0.1\pi^2$ and $\alpha\ell = -10$ the minimum possible value of the dimensionless length $\ell = 2.68$, while the model of ideal matching gives $\ell = 2.23$. This corresponds to an error of more than a factor of 2 in the determination of the starting current. (We recall that the dimensionless length ℓ is proportional to the quartic root of the working current). Why are the minimum starting currents lower in the model of ideal matching? An ideally matched system has one resonance frequency, equal precisely to the band limit [7]. For this reason, in a definite range of accelerating voltages such a system exhibits the properties of a resonant self-excited generator – the self-excitation currents are low, the dependence of the starting frequency on the accelerating voltage is weak, and the generation frequency is close to the resonance frequency (Fig. 6b). In a system with real terminal loads all characteristic frequencies lie in the transmission band; in addition, for $|\alpha\ell| \sim 10$ even at the mode closest to the band limit the energy losses through the ends of the system are quite significant. For this reason, the starting frequencies are shifted into the transmission band (Fig. 6a), and the system exhibits weak resonance properties in the entire range of accelerating voltages. We note that as the parameter $\delta\ell^2$ increases the dissipative losses start to prevail over the energy losses through the ends of the system, and for $\delta\ell^2 \gtrsim 10$ the model of ideal matching operates well for all accelerating voltages. Such high values of the dissipation parameter, however, are not characteristic for TWT.

The second model of TWT which we shall examine was probably first proposed in [8] and relates the unique phenomena at the limit of the transmission band with the total reflection of the electromagnetic energy in the "cold" system from the terminal nonuniformities. This viewpoint is apparently based on definite experimental results and the well-known fact that precisely at the limit of the transmission band the modulus of the coefficient of reflection from any, arbitrarily small nonuniformity equals unity. To calculate the conditions of self-excitation on the basis of this model we must set

$$F(0)=0, \quad F(l)=0. \tag{17}$$

The corresponding curves of the starting values of the dimensionless length ℓ on the dimensionless voltage have an entire series of minima with approximately the same depth (Fig. 5). Their origin is explained as follows. The system with total reflection of electromagnetic energy from terminal nonuniformities is characterized by a collection of high-Q modes, whose characteristic frequencies lie in the transmission band. For any mode there exist values of the accelerating voltage for which the conditions of energy exchange with the beam are most favorable and it is excited. At some optimal value of the voltage the extraction of energy from the beam into the given mode has a maximum efficiency – a minimum start current is realized. As the voltage is further changed the mode gradually becomes desynchronized and a different mode starts. The generation frequency, in this case, jumps from one characteristic frequency to another (Fig. 6d).

This model permits explaining the existence of local minima in the dependence of the start current on the accelerating voltage for $|\alpha\ell| \gtrsim 30$. It has the important drawback, however, that it predicts approximately identical values of start currents on both the forward and backward waves and therefore does not explain the tendency of TWT to become self-excited at the high-frequency limit of the band on forward waves. This happens because in this model the actual energy losses through the terminal loads are neglected, and these losses strongly affect the mode number. They are lowest for the fundamental mode closest to the limit of the transmission band. It is precisely this mode that is excited in TWT at the high-frequency limit of the transmission band on the foward branch of the dispersion magnetic field of the delay system (Fig. 6c).

Thus the wave theory of TWT admits a formulation in which the dissipation of electromagnetic energy is described by a parameter that is weakly frequency dependent at the limit of the transmission band and outside it. Analysis of the conditions for self-excitation of TWT at the limit of the transmission band showed that it is incorrect to regard the energy dissipation as the only factor limiting the resonance effects in real TWT at the limit of the transmission band. The complete qualitative and quantitative picture of the processes occurring in TWT can be understood only if the terminal loads are taken into account correctly.

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CARRIER REDISTRIBUTION AND NONLINEAR SHF PROPERTIES OF INHOMOGENEOUS SEMICONDUCTOR FILMS

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An experimental study is performed of detection of impulsive radiation at a frequency of 75 GHz in inhomogeneous n-GaAs films. It is shown that a distributed nonlinearity mechanism exists, caused by carrier redistribution between regions with differing mobility under the action of the Lorentz force; it is established that at a frequency of 75 GHz this mechanism manifests no inertia. The studies performed indicate the suitability of this nonlinearity mechanism for detection of impulsive radiation in the 4 mm range at power levels incident on the detector of up to 1 kW.

Spatial redistribution of charge carriers and conductivity anisotropy in semiconductor films in crossed electric and magnetic fields parallel to the film surface were studied in [1-3]. Interest has developed in this phenomenon because it provides information on physical processes and parameters in inhomogeneous structures. On the other hand, with intensely nonequilibrium charge carrier redistribution under the action of a Lorentz force within a film clearly expressed nonlinear galvanomagnetic properties develop, which have found various applications in semiconductor devices [4, 5]. Thus, use of the dependence of integral conductivity on magnetic field in intrinsic semiconductors, in which the nonequilibrium spatial redistribution is expressed most intensely, has permitted development of a new type of magnetoresistive element, having record magnetic sensitivity [4]. However use of these devices is limited to the relatively low frequency range $f \lesssim 10^5$-10^7 Hz, since in intrinsic semiconductors the inertia of redistribution is determined either by the characteristic recombination time τ_r or the transverse diffusion time τ_D.

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