UHF-GENERATION IN A COAXIAL SLOWING DOWN STRUCTURE FILLED WITH PLASMA

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Microwave generation by an electron beam in a coaxial transmission line in which the inner and outer conductors are both corrugated is studied theoretically. An annular electron beam propagates in a transport channel filled entirely with plasma. The results of nonlinear modeling of amplification of eigen waves in that structure are represented. The wave saturation amplitudes for various plasma densities are found. The influence of wave damping on the output power of this amplifier is studied. It is shown that the threshold current, at which one there is no amplification in whole wide passband.

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1. INTRODUCTION

It is well known that a vacuum slow-wave structure acquires hybrid properties when the beam transport channel is filled by plasma [1]. In research on hybrid plasma structures, the first experiments were carried out with vacuum slow-wave structures in the form of a chain of coupled cavity resonators. In such hybrid plasma structures, generation is most efficient when the frequency of the synchronously excited microwaves is equal to the plasma frequency. As a result, in a waveguide with a given plasma density, the spectrum of the excited microwaves is narrow (on the order of the instability growth rate). Kornilov *et al.* [2] suggested that filling a vacuum structure in which a broadband cable wave can propagate with plasma makes it possible to increase the amplification coefficient, while maintaining the broadband amplification.

Investigations of the electrodynamic parameters of a coaxial plasma-filled slow-wave transmission line have shown that it holds promise for creating high-power plasma-based microwave devices [3]. The plasma waveguide, like the vacuum one, is characterized by a broad frequency passband. Moreover, in a plasma waveguide, the amplification efficiency is higher and the frequency amplification band is broader in comparison with the vacuum case. In the first (lower frequency) passband, the amplification coefficient depends linearly on the plasma density. The electron beam interacts most strongly with the T-wave. The generation efficiency of the plasma modes corresponding to the eigenmodes of an annular plasma column in which the electron beam propagates is low, and the frequency band over which the plasma modes are amplified is narrow. In the first passband, the wave impedance of the slow-wave structure is only weakly dependent on frequency; in a plasma-filled structure, the frequency interval over which the wave impedance is constant is even broader than in a vacuum structure.

In this work we represent the results of nonlinear numerical modeling of a plasma-filled slow-wave structure.

2. MAIN PART

The slow-wave structure under consideration is a coaxial transmission line in which the inner and outer cylindrical conductors (of radii ρ and b , respectively) are both corrugated. The transport channel with an inner radius σ and outer radius a is filled entirely with a plasma of density n_p. The microwaves in the transport channel are generated by a thin annular electron beam with radius r_b, velocity v_0 , and current I_b. The period of the structure is D and the resonators have the same width equal to d . The nonlinear stage of the interaction between an electron beam and eigen waves of a coaxial slow-wave transmission line was investigated by using of standard procedure of microwave electronics [4]. The full set of equations for nonlinear analysis is: the equation for the averaged (over the cross section of the transport channel) amplitude E of the longitudinal electric field

$$\frac{dE}{dz} + i(\beta_e - \beta_0^0 - i\kappa)E = (\beta_0^0)^2 I_b R_c^0 \frac{1}{2\pi}\int_0^{2\pi} e^{i\theta}\, d\theta_0$$

and of the equations of motion of the beam electrons

$$\frac{dv(z)}{dz} = \frac{e}{mv(z)}\left(1 - \frac{v^2(z)}{c^2}\right)^{3/2} Re\left(Ee^{-i\theta}\right),$$

$$\frac{d\theta}{dz} = \beta_e\left(\frac{v_0}{v(z)} - 1\right),$$

where $\beta_e = \omega / v_0$, β_0^0 is the longitudinal wavenumber of the eigenmode of the structure without beam, ω is wave frequency, $v_0 = v(z = 0)$, κ is wave damping coefficient, R_c^0 is the of coupling impedance. The expression for R_c^0 of coaxial transmission line is adduced in [3]. Ibidem the dependence of coupling impedance from plasma density is studied.

Figure 1 shows how the amplitude of the longitudinal electric field depends on the length of the slow-wave structure without of wave damping account ($\kappa = 0$). Each of the profiles was calculated for the frequency and wave vector corresponding to the maximum amplification coefficient in the linear regime. For a plasma density $n_p = 1.8 \times 10^{11} cm^{-3}$, the longitudinal electric field saturates at 1.42 kV/cm , the optimum length of a hybrid structure being 43.6 cm . For a plasma density of $n_p = 7.2 \times 10^{11} cm^{-3}$, the saturation level is 1.93 kV/cm and the optimum length of the structure is 34.8 cm For the vacuum case, the relevant parameters are equal to 1.3 kV/cm and 48 cm .

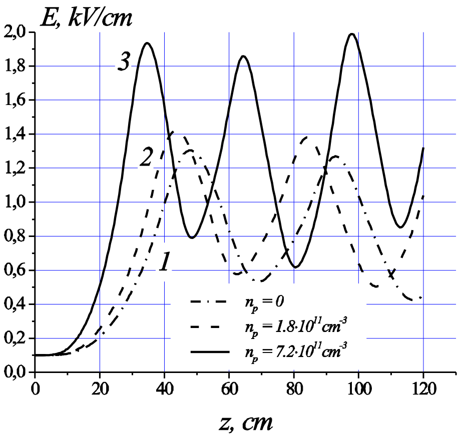


Fig.1. The amplitude of electric field vs. structure length. The experimental setup parameters were taken: $b=5.3$, $a=4.0$, $\sigma=3.5$, $\rho=1.9$, $D=0.7$, $d=0.5$, $r_b=3.6(cm)$; $I_b=5.0A$, $W_b=35keV$

In practical experimental conditions the microwave signal fed on an entrance, damps along slowing down structure. It is conditioned by signal reflection from inhomogeneity, metal walls faultiness and particles collisions. For numerical calculations of levels of microwave power with account of a signal damping the dependence of signal damping vs. frequency obtained experimentally was used.

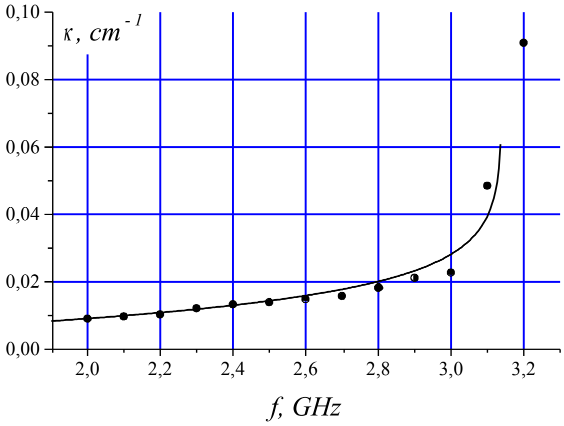


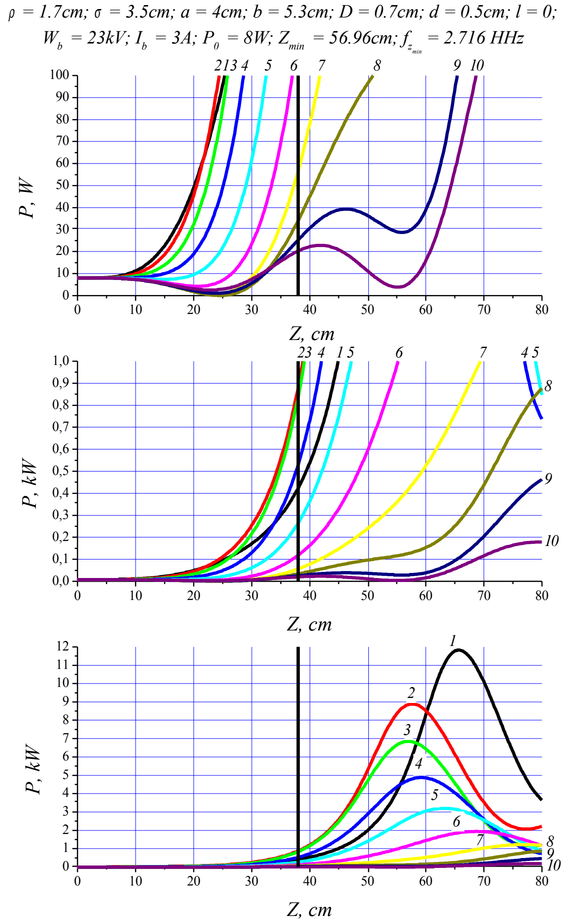
Fig. 2. Damping factor of a wave amplitude κ *: points obtained experimentally and an interpolation curve, used in calculations*

In Figure 2 the experimental points and used in calculations interpolation curve of the wave amplitudes recounted on a decay coefficient κ are adduced. The measurements of decay coefficient κ were carried out for first passband of vacuum slow-wave structure, i.e. for the cable wave.

For convenience of comparison of numerical calculations with outcomes of experimental measurements it is useful to joint the longitudinal electrical field amplitude E calculated according to (1)–(2) to the power distribution along of the amplifier P measured in the experiment. As a result of not complicated transformations we shall receive following relation:

$$P(W)=\frac{\left[E(kV/cm)\right]^2}{240\pi}\,\frac{\left[\int_{S_b}\tilde{E}_{z,0}^2dS\right]^2}{\left[\int_{S_b}\tilde{E}_{z,0}dS\right]^2}\,\frac{c}{8\pi}\int\tilde{E}_{r,0}\tilde{H}^*_{\varphi,0}dS,$$

where $\tilde{E}_{z,0}$, $\tilde{E}_{r,0}$, $\tilde{H}_{\varphi,0}$ are components of an electromagnetic field of eigen waves of slowing down structure without beam.



Curve number	1	2	3	4	5
Frequency f, GHz	2.815	2.766	2.716	2.667	2.617
Curve number	6	7	8	9	10
Frequency f, GHz	2.568	2.519	2.469	2.420	2.370

Fig. 3. Distribution of microwave - power along slowing down structure for beam current $I_b=3A$ *and electrons energy* $23\,keV$ *without of wave attenuation account;* $\rho=1.9cm$, *other parameters are same as in Fig.1*

In Figs 3 and 4 are adduced the distribution of microwave power along slowing down structure for a beam current $I_b = 3A$ and electrons energy $23\,keV$ without account (fig. 3) and with account (fig. 4) of wave attenuation. The calculations are made for various eigen frequencies of a cable mode of vacuum coaxial structure. The value of an input power $P = 8W$ corresponded to the power of a driving generator used in experiment. The vertical straight line demonstrates the length of slowing down structure used in the experiment, that is equal to $38\,cm$. The attenuation account results in decreasing of maximum output power in 1,5 times, and on the structure length $L = 38\,cm$ the decreasing of output power caused by damping is yet more. The microwave power drops down from $0.9\,kW$ to $0.4\,kW$. For more clear representation of microwave power dependence vs. a signal frequency hereinafter charts are shown in three different scales.

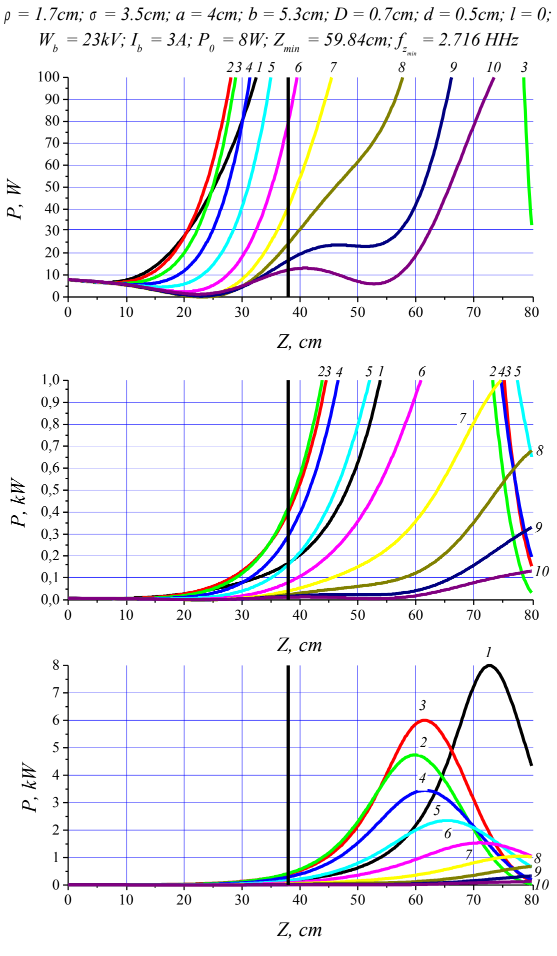


Fig. 4. The same as on fig. 3, but with wave attenuation account

For definition of a threshold electron beam current necessary to obtaining the microwave signal amplification, the similar calculations for different electron beam currents were carried out. The input power at the same time was fixed. The numerical analysis outcomes have shown following. The decreasing of an electron beam current results in narrowing of enhanced frequencies band. Threshold current, at which one there is no amplification in whole passband, corresponds to a case, when the maximum gain factor of an eigen wave is equal to a damping factor. The value of beam current $I_b = 0{,}5\,A$ is close to this threshold current. The minimum signal amplification is observed in a very narrow bandwidth, approximately $f = 2{,}67$ ё $2{,}77\,GHz$. At further current decreasing the input signal of any frequency in the first pass band will not amplify.

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