THE ANALYSIS OF OPERATION OF PLASMA-FILLED HELICAL TWT TAKING INTO ACCOUNT SPATIAL HARMONICS

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Theoretical and the experimental results of studies of electrodynamics characteristics of the TWT on the basis of helical slow-wave structure (SWS) are presented.

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1. THEORETICAL ANALYSIS

Let's consider an amplification of multifrequency signal in slow-wave structure which is a helix of radius a with step of L and winding angle of θ surrounded with metal waveguide of radius b. The helix has the form of a tape with thickness δ. The inner region of a helix is partially filled by plasma with density n_p The structure is in the strong external magnetic field H directed along an axis of system. The continuous annular electron bunch of radius r_b propagates inside of a plasma column.

Let's find at first eigen waves of plasmafilled helix SWS. The dispersive equation for eigen waves can be obtained by the method similar used at deriving of the dispersive equation of a vacuum helix [1]. We shall note, that the dispersive equation of plasmafilled helix in case of full filling inner region of a helix and being in an infinite magnetic field, it has been recently obtained by authors of paper [2]. As a particular case, it transvers in the equation earlier investigated by other authors. The same authors considered a case of the helix which are being in magnetoactive plasma and derived the dispersive equations for noncoupled spatial harmonics [3]. In both papers there is no numerical analysis of the dispersive equations. For the first time the dispersive equation of the helix which are being in magnetoactive plasma with accounting only of zero spatial harmonic has been received in paper [4].

The dispersive equation of the helix partially filled by plasma with accounting of spatial harmonics of a field has a form:

$$\sum_n \frac{\sin(\pi n\delta / L)}{\pi n\delta / L} D_n = 0, \qquad (1)$$

where:

$$D_n = \left(1 + \frac{n\beta_n}{\kappa_n^2 a} ctg\theta\right)\left(\frac{\beta_0}{\beta_n}\kappa_n^2 + \frac{nk^2}{\beta_n a} ctg\theta\right) F_n(\kappa_n a, \kappa_n b) \times$$

$$\times \frac{J_n(k_{\perp n}d)J_n(\kappa_n a) - \frac{\pi}{2}\kappa_n d \cdot \Psi_n \cdot F_n(\kappa_n a, \kappa_n d)}{J_n(k_{\perp n}d)J_n(\kappa_n b) + \frac{\pi}{2}\kappa_n d \cdot \Psi_n \cdot F_n(\kappa_n d, \kappa_n b)} + \qquad (2)$$

$$+k^2 \Phi_n'(\kappa_n a, \kappa_n b)\frac{J_n'(\kappa_n a)}{J_n'(\kappa_n b)} ctg^2\theta,$$

$$\Psi_n = \frac{k_{\perp n}}{\kappa_n} J_n'(k_{\perp n}d)J_n(\kappa_n d) - J_n(k_{\perp n}d)J_n'(\kappa_n d).$$

In (1),(2) the designations are introduced: $\kappa_n^2 = k^2 - \beta_n^2$, $tg\theta = L / 2\pi a$

$$k_{\perp n}^2 = (k^2 - \beta_n^2)\varepsilon_3,$$

$$\beta_n = \beta_{\mathbf{0}} + nk_0, k_0 = 2\pi / L, k = \omega / c, \ \varepsilon_3 = 1 - \omega_p^2 / \omega^2.$$

$$F_n(x,y) = J_n(x)Y_n(y) - Y_n(x)J_n(y), \qquad (3)$$

$$\Phi_n(x,y) = J_n(x)Y_n'(y) - Y_n(x)J_n'(y), \qquad (4)$$

$J_n'(x) = dJ_n / dx$, $Y_n' = dY_n / dx$, $\Phi_n' \equiv d\Phi_n(x,y) / dx$.

Results of the solutions of the dispersive equation (1), (2) are presented on Fig.1. Plasma frequency for the calculations is equal $\omega_p = 4\pi \cdot 10^9 \sec^{-1}$. The dispersive equations plasmafilled helix with accounting only of zero spatial harmonics were investigated in papers [5,6].

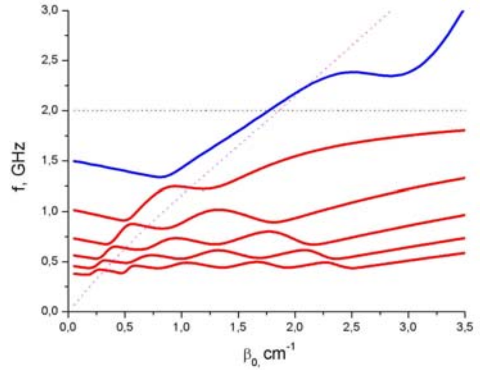

Fig.1. Dispersive curves plasma filled helix structure

The account of a backward spatial harmonic has led to occurrence of backward plasma waves. At crossing with a helix mode and direct plasma modes with n=0 they form the cut-up spectrum of oscillations, typical for hybrid plasma structures [7]. Unlike other hybrid structures dispersive curves of plasma waves are not symmetric concerning a point $\beta_0 = \pi / L$. The reason is that in helix structure there is no translation symmetry. Therefore displaced on longitudinal wave number on $2\pi / L$ the dispersive diagram will not coincide with the initial diagram.

For investigation of a nonlinear stage of interaction of electron bunch and eigen waves of a helix slow-wave structure we shall start with the equation for the amplitude of a longitudinal electric field average on cross-section and the equations of movement for particles of bunch [8]. Coupling resistance $R_{св}^{(n)}$ is calculated according to the following expression:

$$R_c^j(Ohm) = 120\left\langle E_{zj}^2 \right\rangle / \, (2\beta_j^2 \sum_n S_n) \qquad (5)$$

Here S_n - the Poynting flux on n-th harmonic and $\left\langle E_{zj}^2 \right\rangle$ - averaged on bunch cross-section longitudinal field of j -th mode.

Below results of numerical calculation of axial distribution of amplitude of a longitudinal electric field are presented at the fixed current of bunch, but at different values of electron bunch energy. Calculations for value of plasma frequency $\omega_p = 4\pi \cdot 10^9 \text{ s}^{-1}$ is carry out. Coupling resistance was calculated in impedance approximation i.e. when in a microwave power stream the basic spatial harmonic n=0 is considered only. The received values of a longitudinal electric field were compared by the similar distributions received at amplification of a multifrequency signal in vacuum spiral slow-wave structure. The objective of numerical calculations was a finding of values of electron bunch energy, at which both waves achieve characteristic maximal values at the same value of longitudinal coordinate (variants of the best amplification), (at comprehensible value of efficiency on bunch losses, i.e. 15 - 30 %), and as character of influence of partial plasma filling on changes of signal amplification.

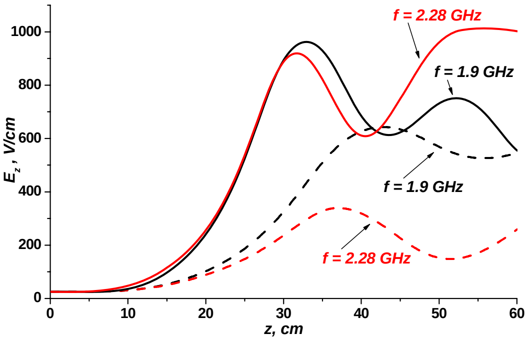

Fig.2. The axial electric field amplitudes for variants of the best amplification of two waves for plasma-filled helix structure (solid line) and for vacuum helix structure (dashed line); bunch energy: 15 keV (without plasma) and 17 keV (with plasma)

In Fig. 2 the results of numerical computations of the best amplification simultaneously two waves. The current of electron bunch was equal 0.8 A, that corresponds to experimental conditions. From graphs results, that two waves with essentially differing frequencies considerably amplify along structure. Thus there is such length of structure where both waves have great amplitude. I.e. the amplifier can simultaneously operate on two frequencies if to choose up corresponding energy of electron bunch.

From Fig.2 results, that plasma fillings leads to significant growth of amplitudes of amplified waves in comparison with a vacuum case, and as to change of a amplitude-frequency spectrum of a output signal. The length of SWS on which both waves achieve the characteristic maximum values changes also. At that time the coupling resistance of plasma-filled spiral structure is greater, than vacuum spiral structure for the same frequencies of amplified waves.

2. EXPERIMENTAL RESULTS

As it's demonstrated [9], investigations with the help of video pulses permit to detect dispersion characteristics of waveguide systems. The registering and processing of the probe pulse and the pulse passed through the structure are necessary. The measuring system operating on the time scale performs the following principal functions: detecting of the slow-wave structure dispersion over a wide frequency range, processing of signals with various algorithms - including the interpretation of the results on the frequency scale, presentation of the experimental results in the form convenient for the further application, and heightening of the precision of signal measurements.

As a probe signal for measurements, the pulse formed by the generator is applied (the duration is 1 ns). For the measurement of the bearing signal, the conducting segments of the coaxial lines are connected together (with the exception of the measuring unit). The probe- and at output pulses are registered with the oscillograph C7-19. Then - through the videocameras - they are introduced into the PC memory.

In Fig. 3, the input pulse 1 and the output pulse 2, which, has transmitted over the whole of helical structure, are depicted. As one can see, the output pulse retardation with respect to the input pulse is 2.9 ns, and the pulse shape is almost the same. This reveals that, in the frequency band determined by the initial pulse, the phase velocity variations are inessential. The output signal amplitude decrease is conditioned by the reflection in the helical structure input.

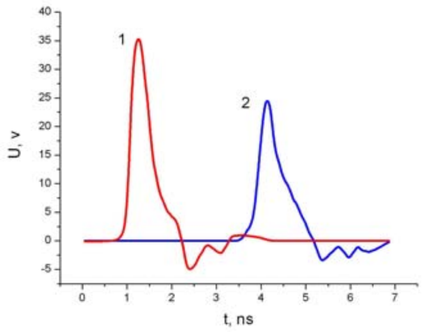

Fig. 3. The oscillograms of the video probe pulse 1 and the video probe pulse 2 transmitted through structure

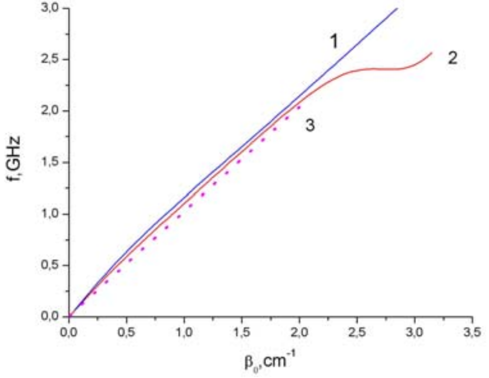

Fig. 4. The measured dispersion (3) in comparison with those calculated (1,2) the system. The line (1) is calculated at the account in dispersion equation only single harmonics n=0, the line (2) is calculated at the account seven harmonics n = -3 … 3

Applying the fast Fourier transform, one can determine the values of the transmission coefficients in the given frequency band. With the known frequency of the phase shift, it's not difficult to determine the coefficient of slowing-down in the structure examined and, correspondingly, the dispersion characteristic of the helical slow-wave structure.

In Fig. 4, for the frequency band 10 – 2000 MHz, the results of experimental investigations of the structure are given. The data calculated by the dispersion equation (1) are presented as well.

CONCLUSIONS

An amplification of a multifrequency signal in plasma-filled helix SWS is investigated experimentally and theoretically. For the first time the numerical analysis is carried out with the accounting of coupling between spatial harmonics of an electromagnetic field. The spectrum of eigen frequencies of plasma-filled helix SWS consists of the modified electromagnetic branches of the oscillations, the modified vacuum helix oscillation mode and spatial harmonics (forward and backward) radial modes of plasma oscillations. In the frequency region that is below plasma frequency all of them form a well-known "dense" spectrum [7]. Unlike other plasma hybrid structures the dispersion of helix plasma-filled structure has no translation symmetry.

Plasma filling leads to an increase in phase velocity of helix oscillation mode, and a coupling resistance.

Numerical simulation of amplification of a two-frequency signal in plasma-filled helix SWS is carried out. As well as in vacuum structure, in plasma-filled structure the simultaneous amplification of two waves at high enough efficiency is possible. At that time the output amplitudes of gained waves in plasma-filled structure are significantly greater.

With the application of the fast Fourier transform, the software is elaborated for the numerical calculation of the experimental data: it permits exactly to determine the dispersion characteristics of helical structure.

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АНАЛИЗ РАБОТЫ ПЛАЗМОНАПОЛНЕННОЙ СПИРАЛЬНОЙ ЛБВ С УЧЕТОМ ПРОСТРАНСТВЕННЫХ ГАРМОНИК

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Представлены теоретические и экспериментальные результаты исследования электродинамических характеристик ЛБВ на базе плазмонаполненной спиральной замедляющей структуры.

АНАЛІЗ РОБОТИ ПЛАЗМОНАПОВНЕНОЇ СПІРАЛЬНОЇ ЛБХ З УРАХУВАННЯМ ПРОСТОРОВИХ ГАРМОНІК

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Представлено теоретичні та експериментальні результати дослідження електродинамічних характеристик ЛБХ на основі плазмонаповненої спіральної уповільнюючої структури.