Properties of Spatial Harmonics Selection in Pseudoperiodic Waveguides

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Abstract - **The selection spatial harmonics in pseudoperiodic waveguides depending on frequency is studied. Selection method is based on coordinated variation of the step and phase distribution of elements along the waveguide, which provides the constant phase velocity of one spatial harmonic and destroys other spatial harmonics. The possibility of application of pseudoperiodic folded waveguide for creation of powerful broadband TWTs is indicated.**

I. Introduction

Papers [1, 2] suggest a new class of electrodynamics systems ("pseudoperiodic" waveguides) for which it is possible to control the spectrum of spatial harmonics and modes including their efficient selection in the process of amplifying and generating powerful microwave oscillation in devices with oversize systems with a large number of modes. It is also possible to anticipate expansion of the bandwidth in powerful TWTs with pseudoperiodic resonator slow-wave systems (SWS) in comparison with TWTs having conventional resonator SWS, for example coupled-cavity systems (CCS).

The essence of the principle of selection consists in employing electrodynamics systems with nonperiodic spacing of its elements and a specified relation between the step L_q and the field-phase Ψ_q of the elements, which makes it possible to select one spatial harmonic or mode and suppress the others. The elements in question may be slots in a comb-type structure (Fig.1), diaphragms in a round waveguide, cavities and electron-field interaction gaps in CCS etc. Such nonuniform systems may be considered as pseudoperiodic, wherein the amplitudes of one or several harmonics remain the same as those in the initial periodic systems where as the amplitudes of other spatial harmonics decrease.

A planar logarithmic spiral or synchronous spirals considered in [3] represent examples of pseudoperiodic systems. In logarithmic spirals the relationship between the step and the length of turn is such that the velocity of the radial wave basic spatial harmonic is constant in spite of the step variation along the radius. In logarithmic spirals all the higher-number spatial harmonics are suppressed whereas in synchronous spirals (Fig.1b) there exists only one higher-number spatial harmonic. Planar spiral systems are used as ultrawide-band antennas [4] and they can be employed as slow-wave structures for TWT [5]. Generally, one can apply the considered principle of selection to any type SWS.

The considered method of selection in slow-wave systems is similar to the method of suppressing the side radiation in nonuniform antenna arrays. However unlined the antennas the phase distribution is not specified by external sources but is determined by the shape and dimensions of the system elements which are to be chosen from the condi-

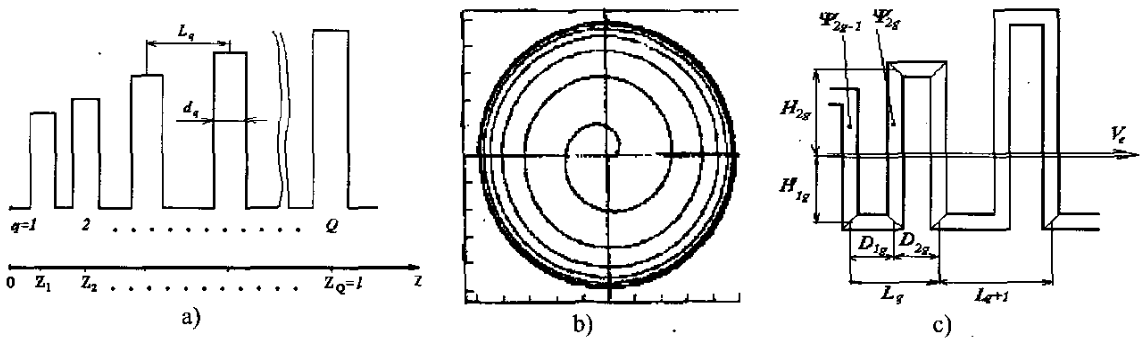

Fig.1. Pseudoperiodic waveguides: a) comb-type structure; b) synchronous spiral; c) folded waveguide, $q=2g-1$ and $q=2g$ for g-th step.

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tions of spatial harmonics selection. Such nonuniform waveguide system represents a filter whose frequency characteristic is also determined by the choice of elements and the steps of their location. A combined application of the conditions of selecting the spatial harmonics and choosing the necessary filter characteristics enables to create new types of broadband one-wave slow-wave systems.

A theory of wave selection in pseudoperiodical slow-wave systems has been suggested in [6] for fixed frequency.

This paper present relationship for calculation of spatial harmonic amplitudes in a pseudoperiodic waveguide depending on the frequency and phase velocity. Furthermore, a dispersion amplitude surface characterizing these relationships for pseudoperiodic folded waveguide is calculated.

II. Amplitudes of Spatial Harmonics and Synchronism Condition

Let us consider a general method of calculating the spatial harmonics amplitudes in the pseudoperiodic SWC. Assume that it the longitudinal electric field distribution along the system comprising Q steps of different length L_q ($q = 1, 2,..., Q$) is given

$$E_z(z,\omega) = E^0 f(z,\omega)\exp[i\psi(z,\omega)] \quad (1)$$

The distribution of the real amplitude $f(z,\omega)$ and phase $\psi(z,\omega)$ at frequency ω is determined by the type of the system (uniform periodic or nonuniform). Applying the Fourier transformation, we define the amplitudes $E(h,\omega)$ of spatial harmonics by the relations

$$E(h,\omega) = \frac{1}{l}\int_0^l E_z(z,\omega)\exp(-ihz)dz \quad (2)$$

In the general case, amplitudes $E(h,\omega)$ are continuous functions of the wavenumber h and frequency ω and differ from the spectral density only by the factor l, where l is the length of the system. Let us represent them as a sum over the Q steps of the system:

$$E(h,\omega) = \frac{1}{l}\sum_{q=1}^{Q} U_q M_q(h)\exp[i(\psi_q(\omega) - hz_q)], \quad (3)$$

where $\psi_q(\omega) = \psi(z_q,\omega)$ is the average field phase at the qth step; $M_q(h)$ is the local electron-field interaction coefficient; U_q is the rf voltage at the qth step; z_q and d_q are the mean coordinate and effective width of the qth gap.

If the field is constant in the gap, $f(z)=f_q$, we have the familiar expression

$$M_q = \frac{\sin(h\, d_q/2)}{h\, d_q/2}$$

The maximal values of $E(h,\omega)$ can be obtained, according to (3), for the wavenumbers $h = h_m$ that satisfy Q conditions:

$$h_m z_q = \psi_q + 2\pi q m, \quad q = 1,2,...,Q \quad (4)$$

where the integer m = 0, ±1... determines the number of the field spatial harmonic with the maximal amplitude. Physically, conditions (4) mean the in-phase addition of the electron radiation from individual gaps where interaction takes place when electrons move synchronously with the mth spatial harmonic to the velocity $v_e = v_m = \omega/h_m$.

Introducing the field-phase shift $\varphi_q = \psi_{q+1} - \psi_q$ at the qth step and taking into account that $L_q = z_{q+1} - z_q$, we can write the equivalent conditions of synchronism for every step:

$$h_m(\omega)L_q = \varphi_q(\omega) + 2\pi m, \quad q = 1,2...Q$$

In a periodic waveguide $L_q \equiv L, \varphi_q \equiv \varphi$, and $\psi_q = q\varphi$; therefore, conditions (4) are met for an infinite series of spatial harmonics $m' = m$ when $h_{m'} = h_m + 2\pi(m'-m)/L$, the difference in their amplitudes being determined only by $M_q(h)$.

In a nonuniform waveguide with different steps L_q, condition (4) can be satisfied for one harmonic by choosing the appropriate phases ψ_q. For $h \neq h_m$, this condition is either not satisfied or holds for the wavenumber spectrum, which is less dense than in a periodic waveguide. Thus, selection of spatial harmonics takes place.

III. Pseudoperiodic Folded Waveguide

Let us consider the spatial harmonic selection in a pseudoperiodic folded waveguide (Fig.1c) which can be used in millimeter wave-range TWTs. Such a waveguide is also a good CCS model.

Assuming the interaction gaps as being similar and the wave attenuation as being small we have in (3) $M_q \equiv M$, $U_q \equiv U$.

Separating the sums of q=2g and odd q=2g-1 gaps (q=1,2,…, G=Q/2), we obtain,

$$F(h,\omega) = \frac{1}{G}\frac{E(h,\omega)}{2UM/l} = \frac{1}{G}\sum_{g=1}^{G} M_{Lg}\exp(i[\psi_{2g-1}(\omega) - hz_{2g-1}]),$$

where coefficient M_{Lg} characterizes the interaction in the g-th pair of adjacent gaps.

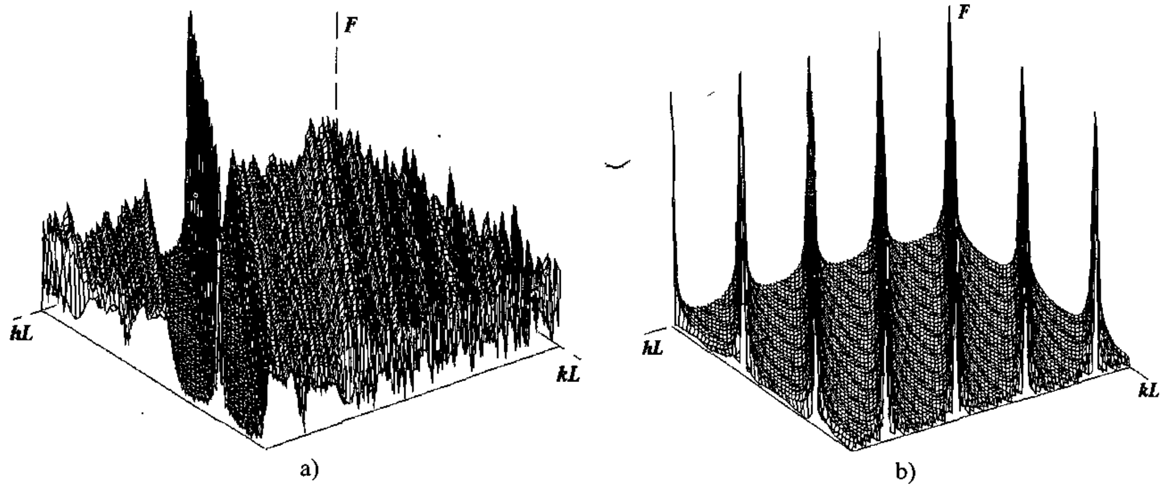

Fig. 2. Dispersion amplitude surfaces for pseudoperiodic ***a*** and periodic ***b*** folded waveguide length of $G=Q/2=20$ steps; $4\pi<hL<4\pi$, $0<kL<\pi$, $c/v_o=5$, $\Delta L/L=0.05$.

$$M_{Lg}=\frac{1}{2}\left[1+\exp\left(i\left[\psi_{2g}(\omega)-\psi_{2g-1}(\omega)-h\left(z_{2g}-z_{2g-1}\right)\right]\right)\right]$$

The phases ψ are determined by the wave moving along the bent waveguide and having a wavenumber $h_s(\omega)=\sqrt{k^2-k_s^2}, k=\omega/c, k_s=\omega_s/c$, where ω_s is cutoff frequency. In this case taking into account the phase geometric turn π between the adjacent gaps we have:

$$\psi_{2g-1}(\omega)-hz_{2g-1}=\sum_{j=1}^{g-1}\left[h_s(\omega)S_j-hL_j\right],$$

$$\psi_{2g}(\omega)-\psi_{2g-1}(\omega)=h_s(\omega)\left(2H_{1g}+D_{1g}\right)+\pi,$$

where $S_g=2\left(H_{1g}+H_{2g}\right)+D_{1g}+D_{2g}$ in the length of the loop on the g-th step.

In a periodic folded waveguide or CCS the 1-st spatial harmonic is used for TWT operation. The basic forward spatial harmonic is absent dew to the subtraction of the interaction in the adjacent gaps during the electron motion over the system center (when $H_{1g}=H_{2g}$). Here we shall prove the possibility of achieving a large amplitude of the basic forward spatial harmonic in a pseudoperiodic folded waveguide in broad bandwidth dew to a matched choice of the step variation and other waveguide dimensions. The phase velocity of this harmonic v_o is constant along the system if

$$\frac{S_g}{L_g}\equiv\frac{S}{L}=const,\frac{c}{v_0}=\frac{S}{L} \qquad (5)$$

To sum up the interaction in adjacent gaps of each step at the chosen frequency ω_o it is necessary that

$$h_s(\omega_0)(2H_{1g}+D_{1g})-h_0D_{1g}=-\pi, h_0=\omega_0/v_0 \qquad (6)$$

Then the length of the waveguide loop between the adjacent gaps compensates the phase geometric turn at π.

Considering the linear variation of the step

$$L_g=L+\Delta L(g-1) \qquad (7)$$

and constant quantities of $D_{1g}\equiv D_1, H_{1g}\equiv H_1$ we obtain

$$F(h,\omega)=\frac{M_L}{G}\sum_{g=1}^{G}\exp\left\{i\left[h_s(\omega)\frac{S}{L}-h\right]\times\right.$$
$$\left.\times L(g-1)\left[1+\frac{\Delta L}{2L}(g-2)\right]\right\}, \qquad (8)$$
$$M_L=\frac{1}{2}\left[1-\exp\left(i\left\{\left[h_s(\omega)\frac{S}{L}-h\right]D_1-\pi\frac{h_s(\omega)}{h_s(\omega_0)}\right\}\right)\right]$$

Function F is represented by the dispersion amplitude surface [7]. In Fig.2 it is plotted when $S/L=5$ and $k_s\to 0\ (k>>k_s, h_s=k)$. The highest of this surface corresponds to the line of electron synchronism with a basic spatial harmonic whose velocity v_o does not depended on the frequency:

$$h=k\frac{S}{L}=k\frac{c}{v_0} \qquad (9)$$

In this case the TWT bandwidth is determined by the amplitude variation $E(h,\omega)$ along this line due to the variation of $M_L(h,\omega)$. For the system corresponding to

Fig.2 the fields of the adjacent gaps are summed up, i.e. the condition (6) and $M_L = 1$ is satisfied at frequency ω_0 corresponding to $k_oL=0.6\pi$, $h_oL=3\pi$. Varying the frequency we obtain an in complete compensation. However, as seen from (8) in case of synchronism (9) we have $|M_L| > 1/\sqrt{2}$ in a broad bandwidth $(\omega_{max} - \omega_{min})/\omega_{min} \approx 2$. In this bandwidth it is possible to obtain a high coupling impedance between the electron beam and the field.

However in TWT with periodic SWS it is hard to make use of such property due to the presence of intensive backward spatial harmonics (Fig.2b) and discontinuity of SWS bandwidth, which results in self-excitation in the TWT and irregularity of the amplification. As seen from Fig.2a it is possible to suppress the backward spatial harmonics corresponding to $hL<0$ in a pseudoperiodic folded waveguide. Moreover, it is possible to avoid the discontinuity of the bandwidth in specified frequency range similar to what takes place in microwave filters.

The bandwidth of the pseudoperiodic folded waveguide is defined by reflection coefficient Γ on the waveguide curves. To find the bandwidth the reflection coefficient Γ_{in} was calculated at the waveguide input by means of recurrent relationships. The calculation results show that in a periodic folded waveguide the cutoff frequencies correspond to main peaks of the reflection coefficient Γ_{in} and to the field phase shifts $h_0L \approx 2\pi, 4\pi$. In a pseudoperiodic folded waveguide the main reflection coefficient peaks are absent (Γ_{in} <0.2), so that the bandwidth increases considerably.

IV. Conclusion

The obtained results show that in pseudoperiodic waveguides it is possible to combine the following properties important for slow-wave systems: selection of an operating spatial harmonic along with suppression of spurious spatial harmonics including backward waves, increase of the bandwidth, and load matching.

These properties of the pseudoperiodic waveguide can be used to create powerful broadband TWTs.

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