IMPROVING SELECTIVITY OF 1D BRAGG RESONATOR USING COUPLING OF PROPAGATING AND TRAPPED WAVES

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Abstract

In the paper FEM oscillator operation based on coupling of quasi cut-off mode with propagating wave, which is amplified by the electron, is considered. The coupling is realized by periodical corrugation of sidewall of microwave system. The cut-off mode provides the feedback while the efficiency in steady-state regime of generation is almost completely determined by the propagating mode, synchronous to the beam. The main advantage of a discussed scheme is provision of higher selectivity over transverse index than traditional scheme of FEM with a Bragg resonator. The novel feedback scheme should be tested on a JINR- IAP FEM as a method of increasing operating frequency.

INTRODUCTION

A number of oscillator schemes based on the interaction between propagating and locked waves are known in microwave electronics. One of them is a scheme of a gyrotron with an electron beam that excites a quasi cut-off mode while the output of radiation is provided by the propagating wave coupled with the locked one via corrugation of the waveguide side walls. Another example is a scheme [1] of CARM or FEM in which the electron beam interacts both with a propagating wave (at the first harmonic) and a quasi-cutoff wave (at the second harmonic). In this case direct coupling of the waves is absent and the waves interact by modulating the beam.

In this paper we discuss one more variant of such a device that uses a beam of electrons interacting only with a propagating wave, and the latter is coupled with a quasi cut-off trapped mode. This coupling is realized by either helical or azimuthally symmetric corrugation. The quasi cut-off mode provides the feedback in the system leading to the self-excitation of the whole system while the efficiency in steady-state regime of generation is determined by the propagating wave, synchronous to the electrons. The main advantage of above scheme is provision of higher selectivity over transverse index than traditional scheme of FEM with Bragg resonators. The novel feedback scheme should be tested at a JINR-IAP FEM as a method of increasing operating frequency for fixed transverse size of interaction space.

MODEL AND BASIC EQUATIONS

Let us consider a model of a FEM oscillator based on coupling of a synchronous wave propagating forward to the direction of the electron beam motion

$$\vec{E} = Re\left(A_+(t,z)\vec{E}_A(r_\perp)e^{-ihz-im_A\varphi}e^{i\omega_c t}\right) \quad (1a)$$

and a trapped feedback mode

$$\vec{E} = Re\left(B(t)\vec{E}_B(r_\perp)f(z)e^{-im_B\varphi}e^{i\omega_c t}\right) \quad (1b)$$

Here ω_c is a carrier frequency, which is chosen equal to the eigenfrequency of the cut-off mode, $\vec{E}_{A,B}(r_\perp)$ functions specify the transverse structure of the modes. Assuming that the Q-factor of the cut-off mode is high, one can consider its longitudinal structure $f(z)$ fixed, as the longitudinal structure of the propagating mode $A(z)$ is changed under influence of the electron beam.

Helical corrugation

$$r = r_0 + r_1\cos\left(\bar{h}z + \bar{m}\varphi\right) \quad (2)$$

(r_0 is a mean radius of the waveguide, $\bar{h} = 2\pi/d$, d and r_1 are the period and the depth of the corrugation correspondingly) under the Bragg conditions

$$h \approx \bar{h}, \ \bar{m} = m_1 - m_2 \quad (3)$$

provides the coupling of the propagating and trapped modes. Dispersion diagrams, showing the coupling of partial waves are presented in Fig.1.

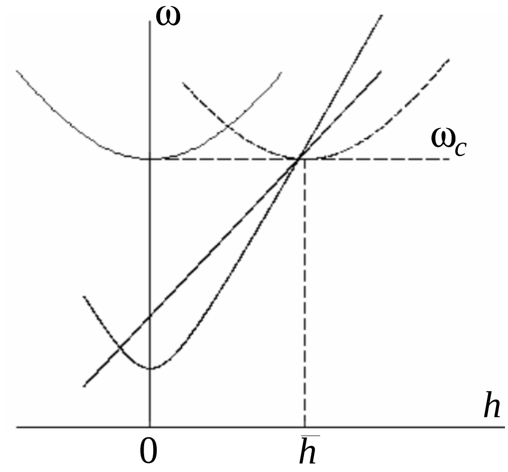

FIGURE 1

Operating frequency is close to eigenfrequency of the trapped mode $\omega_c = \dfrac{c\nu_B}{r_0}$, hence we obtain a relation on the geometrical parameters

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$$\frac{2\pi}{d} \approx \frac{\sqrt{\nu_B^2 - \nu_A^2}}{r_0} \qquad (4)$$

where $\nu_{A,B}$ are the roots of Bessel functions (or their derivatives) corresponding to the modes of a regular waveguide.

Forward wave $A(z)$ is synchronous to the electron beam moving in the $+z$ direction. Corresponding synchronism condition can be represented as

$$\omega - hv_{||} = \Omega, \qquad (5)$$

where Ω is the frequency of oscillations of particles in a spatially periodic wiggler field or in homogenous guiding magnetic field. A system of equations describing both the process of amplification of synchronous wave and its scattering to the trapped mode under assumption that the time Q/ω_c of the changing of the amplitude of the cut-off mode is substantially exceeds the electron transit time can be presented in the form:

$$\frac{\partial \hat{A}}{\partial Z} = i\alpha \hat{B} f(Z) e^{i\delta z} + J \qquad (6a)$$

$$\frac{\partial \hat{B}}{\partial \tau} + \frac{1}{2Q}\hat{B} = -i\alpha \int_0^L \hat{A}_+(Z) e^{-i\delta Z} f^*(Z) dZ \qquad (6b)$$

where $J = \frac{1}{2\pi}\int_0^{2\pi} e^{-i\theta(Z)} d\theta_0$ is an amplitude of RF current, which is determined by the electron motion equations

$$\frac{\partial^2 \theta}{\partial Z^2} = \mathrm{Re}\left(\hat{A}_+(Z) e^{i\theta}\right) \qquad (7)$$

In Eqs. (6), (7) we have used the following dimensionless variables and parameters: $Z = zC\bar{h}$, $\tau = \bar{\omega} t$, $\theta = \bar{\omega} t - hz - \int \Omega dt$ is electron phase in the field of the synchronous wave, $\hat{A}_\pm = e\kappa\mu A_\pm / mc\omega\gamma_0 C^2$, $\hat{B} = e\kappa\mu B\sqrt{N_A} / mc\gamma_0 C^2 \sqrt{\omega N_B}$,

$$C = \left(\frac{eI_0}{mc^3} \frac{c\lambda^2 K^2 \mu}{4\pi^2 \gamma_0 N_A}\right)^{1/3}$$

is a Pierce parameter, I_0 is an unperturbed beam current, μ is a parameter of inertial bunching, K is a parameter of the coupling between the wave and electrons proportional to the amplitude of the electrons transverse oscillation, α is the coupling coefficient of waves on the Bragg grating which is proportional to the depth of the grating r_1, $N_{A,B}$ are the norms of the propagating and the trapped modes correspondingly, Q is the Q-factor of the trapped mode, $\delta = (\bar{\omega} - \omega_c)/C\bar{\omega}$ is the normalized detuning of the Bragg frequency $\bar{\omega} = \bar{h}c$ from the cut-off frequency.

Initial and boundary conditions of the equations (6), (7) are given by:

$$\hat{A}\Big|_{Z=0} = 0, \; \hat{B}\Big|_{\tau=0} = \hat{B}_0,$$

$$\theta\Big|_{Z=0} = \theta_0 \in [0, 2\pi), \; \frac{\partial \theta}{\partial Z}\Big|_{Z=0} = \Delta \qquad (8)$$

where L is the normalized length of the resonator and Δ is initial detuning of synchronism between the electrons and the wave at the carrier frequency.

Obviously, when the coupling between modes is absent ($\alpha = 0$) Eqs. (6), (7) describe the convective mechanism of instability, and self-excitation of the oscillations is impossible. Thus, the self-excitation of the system is provided by the coupling with the cut-off mode $(\alpha \neq 0)$. To obtain starting conditions we linearize the equations of motion. In the assumption that the length of the interaction space is large ($L >> 1$) the main contribution to excitation factor in the right hand of Eq. (6a) related with exponentially growing wave having for $\Delta = 0$ the longitudinal wavenumber $g = -\frac{1}{2} - \frac{i\sqrt{3}}{2}$. As a result for amplitude of trapped wave we get

$$\frac{\partial B}{\partial \tau} + \frac{1}{2Q} B = -\frac{\alpha^2 B}{3} e^{\frac{\sqrt{3}L}{2}} \varphi(\delta, L) \qquad (9)$$

$$\varphi(\delta, L) = \left(\frac{1}{\delta - g + \pi/L} - \frac{1}{\delta - g - \pi/L}\right)^2 e^{-\frac{iL}{2} - i\delta L}$$

The self-excitation condition can be presented in a form:

$$\frac{1}{2Q} < -\frac{\alpha^2}{3} e^{\frac{\sqrt{3}L}{2}} Re\,\varphi(\delta, L) \qquad (10)$$

Self-excitation of the generator is possible if the function $\mathrm{Re}\,\varphi(\delta, L)$ presented in Fig.2 is negative.

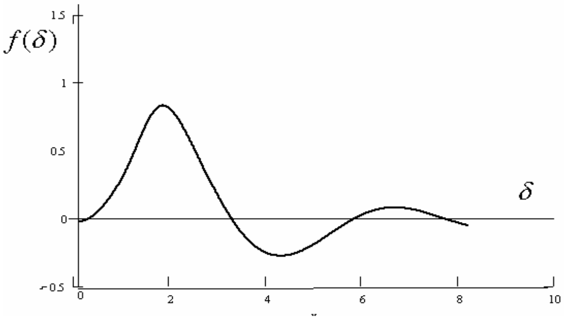

FIGURE 2

RESULTS OF THE SIMULATIONS

Establishment of a stationary regime of generation found from numerical simulation of the nonlinear equations (6), (7) are shown in Fig.3. Efficiency is rather high $\hat{\eta} \sim 3$. It is important to note that in optimal conditions the main part of the energy extracted from electron beam transforms into the radiation of the propagating mode A but not dissipated with the trapped wave B.

According to estimations based on above feedback mechanism it is possible to decrease effective coupling parameter sufficient for an oscillator self-excitation in comparison with traditional Bragg FEM schemes, where a feedback wave possesses rather high group velocity [2]. Correspondingly in oversized microwave system where Bragg conditions are satisfied for a large number of couples of modes with different transverse indices it is possible to provide selective excitation of a single couple consisting of a cut-off mode and operating wave which is amplified by the electron beam. Above method of mode control should be tested in JINR-IAP FEM at Ka band and then used as a method of increasing operating frequency for fixed transverse size.

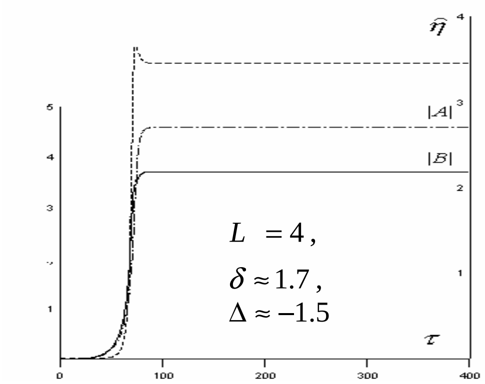

FIGURE 3

REFERENCES

[1] Savilov, A.V. et al., Phys. Rev. E58, 1002 (1998).
[2] Bratman V.L., Denisov G.G., Ginzburg N.S., Petelin M.I., *IEEE J. Quant. Electr.* QE-19, 282 (1983).