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Simplified theory of gyro-BWO with zigzag quasi-optical system

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Abstract. The theory of the gyrotron backward-wave oscillator based on a sectioned quasi-optical system with a zigzag trajectory of the operating wave beam is developed. The peculiarities of changing the operating frequency and output signal power in the process of broadband tuning of the generation frequency are explained.
Keywords: gyrotron, backward-wave oscillator.

1. Introduction

Currently, subterahertz cyclotron masers (gyrotrons) with relatively high (tens of Watts – units of kilowatts) power in continuous generation regime are being actively developed, intended for use in spectroscopic applications. However, from the point of view of a number of such applications, it would be ideal to have a source that provides a combination of stability (a narrow band) of the generated wave signal together with the possibility of its smooth adjustment in a frequency band with a width of at least several percent. At the same time, the fundamental disadvantage of gyrotrons is that the use of selective cyclotron excitation by electrons of the near-cutoff axial mode of an open cavity with high Q-factor significantly limits the possibilities of frequency tuning in these auto-oscillators.

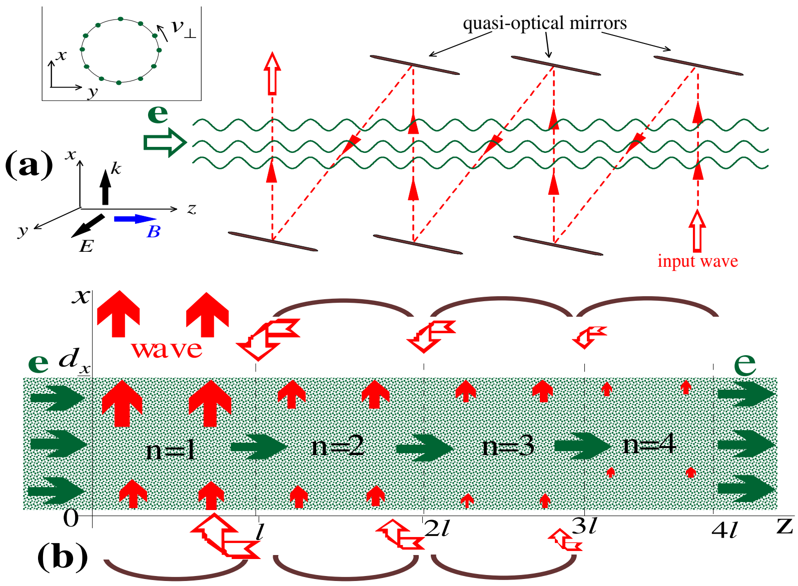

Fig.1. (a) Gyro-BWO with a zigzag quasi-optical system. (b) 2-D model of a system consisting of four sections of electron-wave interaction.

Recently, a microwave system in the form of a quasi-optical transmission line has been proposed as an electrodynamic gyrotron system [1]. It consists of focusing mirrors that are periodically spaced along the longitudinal z axis and provide transportation of a Gaussian wave beam along a zigzag trajectory Fig.1. Electron-wave interaction occurs in areas where the wave, as in a gyrotron, propagates strictly across the electron beam, which leads to interaction with minimal sensitivity to the spread of particle velocities. The simulation demonstrates the attractiveness of this scheme for the implementation of a backward-wave oscillator (BWO) with a uniquely wide frequency tuning band. In this work, we develop a quasi-analytical theory of the zigzag gyro-BWO described above, which explains the peculiarities of changes in the operating frequency and output signal power in the process of broadband frequency tuning provided by a change in the operating magnetic field.

2. Model and equations

We use a simple two-dimensional model described in detail in [2]. The electrons move along the longitudinal magnetic field $\boldsymbol{B}_0 = z_0 B_0$ (Fig.1a), while the transverse size of the electron beam d_x is large enough on the scale of the wavelength of the emitted wave. Along with translational motion along the z-axis, the particles also undergo cyclotron oscillations in the x–y plane. Fig.1b illustrates the 2-D model used in our analysis in the case when the system consists of four sections of an electrodynamic system. We assume that the amplitude of the wave a_n is uniform in the z-coordinate inside each section n, since this structure is supported by a quasi-optical mirror system.

Let us use the known [3] asymptotic equations of motion describing the change in the normalized energy of particles $u = (\gamma_0 - \gamma)/p_{11}C$ and their phases θ in the field of the operating wave.

$$\frac{du}{d\zeta} = Re\ a_n e^{i\theta}, \frac{d\theta}{d\zeta} = \frac{\delta - u}{1+\varepsilon}, \frac{da_n}{d\xi} = \frac{1}{L}\int_{\zeta_n}^{\zeta_n+L} \left\langle e^{-i\theta} \right\rangle d\zeta . \tag{1}$$

Here $\zeta = Ckz$ is the normalized longitudinal coordinate. The traditional normalization for the Pierce factor C, describing the intensity of the electron-wave interaction, is used. The amplification of the wave is described by the evolution of its amplitude along the transverse coordinate $\zeta = Ckx$. In the equations above, n is the section number, L is the normalized length of the section. The factor $\varepsilon = \Delta V_Z/V_Z$ describes accounting for the spread of translational velocities of different fractions of the electron beam, $-S/2 \le \varepsilon \le S/2$.

The boundary conditions describe the reflection of the wave from the “upper” mirror of the “n+1” section into the “lower” mirror of the “n” section with a phase shift Ψ, describing the movement of the wave packet from one section to another, as well as the absence of an external signal at the entrance to the last (in our example, the fourth) section (here, ξ_0 is the normalized transverse size of sections):

$$a_4(\xi = 0) = 0,\ \ a_n(\xi = 0) = a_{n+1}(\xi = \xi_0)e^{-i\Psi} . \tag{2}$$

The evolution of the system in time is described by the introduction of the time variable $\tau = CkV_Zt$, so that $d\zeta/d\tau = 1$. In this case, the boundary conditions (2) are transformed as follows:

$$a_n(\xi = 0, \tau) = a_{n+1}(\xi = \xi_0,\ \tau - T), n = 1,2,3\ ,\ a_4(\xi = 0,\ \tau) = 0\ . \tag{3}$$

Here $T \sim L$ is the normalized delay time during the passage of the wave from section to section.

Note that in our problem, the longitudinal and transverse coordinates can be re-normalized as follows

$$\overline{\xi} = \xi / \xi_0, \overline{\zeta} = \sqrt{\xi_0}\zeta . \tag{4}$$

3. Stationary small-signal theory

When modeling equations (2), we find the normalized length of the section, $(\xi_0 L)^{0.5}$ and the mismatch of the electron-wave resonance δ which provide the starting conditions for this system, while considering the phase shift of the wave between the sections as an independent parameter. According to Fig.2, $\delta L = -\Psi$, which has a simple physical meaning. The formula $\delta \sim (\omega - \Omega)/V_Z$ corresponds to the resonant condition $\omega - \Omega \approx hV_Z$, where $h = -\Psi/L$ is the effective longitudinal wavenumber of the excited wave. Accordingly, at $\Psi \to 0$ we have a gyrotron mode of electron-wave interaction, and at large Ψ we have modes of the type gyro-BWO ($h < 0$) and gyro-TWT

($h > 0$) critical to the velocity spread. The law of frequency tuning with a change in the magnetic field is piecewise, which is explained by the periodic dependence of the starting characteristics (Fig.2) on the phase Ψ. It differs from the simple law $\omega = \Omega$, since both the electron-wave synchronism mismatch $\delta L = D(\omega\text{-}\Omega)$ and the phase jump of the wave between the sections $\Psi = A\omega$ depend on the frequency. Taking into account the formula $\delta L = -\Psi$, this leads to the fact that the derivative $\partial\omega/\partial\Omega$ turns out to be less than one:

$$\omega(\Omega) = \frac{1}{1 + A/D}\Omega. \tag{5}$$

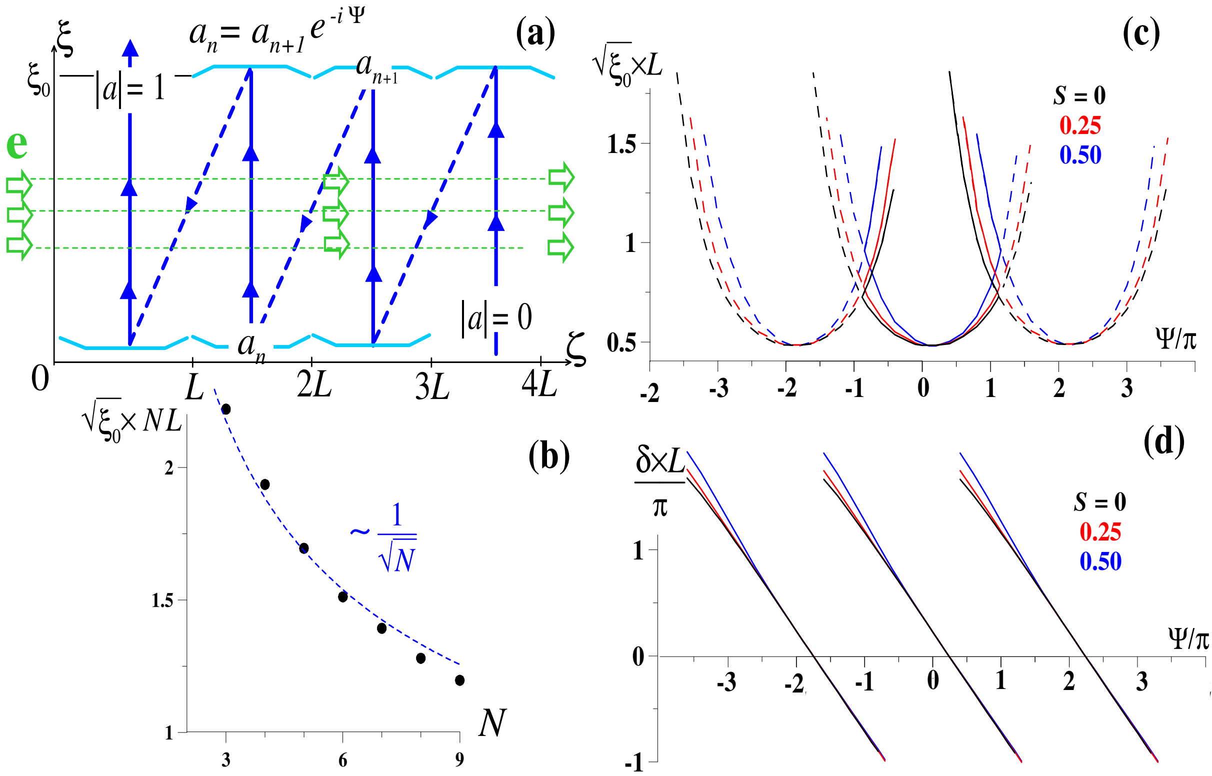

Fig.2. (a) Model illustration. (b) The full normalized starting length of the system depending on the number of sections in the case Ψ = 0. (c, d) The normalized initial length of one section and dimensionless detuning depending on the phase shift of the wave between the sections Ψ at different electron velocity spreads S.

4. Non-linear spatial-temporal theory

The predicted piecewise nature of the dependence of the generation frequency on the magnetic field $\omega(\Omega)$ is also confirmed in the framework of nonlinear space-time calculations. Fig.3 illustrates the dependences of the normalized generation power (electronic efficiency) $\eta = \langle u \rangle$ and of the normalized frequency of the generated wave $\Delta[a \sim \exp(i\Delta\tau)]$ from the synchronism mismatch δ "responsible" for the change in the magnetic field (in this case, the dependence $\omega = \Omega$ in terms of normalized parameters corresponds to the dependence ($\Delta = -\delta$) in the case when the normalized length of the section $L = 0.7$ exceeds the starting length by 40% ($L_{st} \approx 0.5$). At the same time, the size of the intervals of continuous frequency tuning decreases with the growth of the normalized time T, which describes the delay of the wave during its transition from section to section.

Fig.3c illustrates the dependences of the normalized power of the output wave signal η on the time τ for different values of the normalized magnetic field -δ (points A, B and C in Fig.3b). It can be seen that the generation power in steady-state mode is approximately the same in all three cases, however, the scenarios for the system to be stationary are somewhat different. In the case of *B*, corresponding to the center of the considered interval (branch) of the dependence $\Delta(\delta)$ of continuous frequency tuning, the output to the stationary occurs in an almost single-frequency oscillation mode, while in modes *A* and *C*, corresponding to the edges of this branch $\Delta(\delta)$, fluctuations in the generation power are observed, which correspond to the competition of the wave from this branches of dependence $\Delta(\delta)$ with waves at frequencies corresponding to neighboring branches.

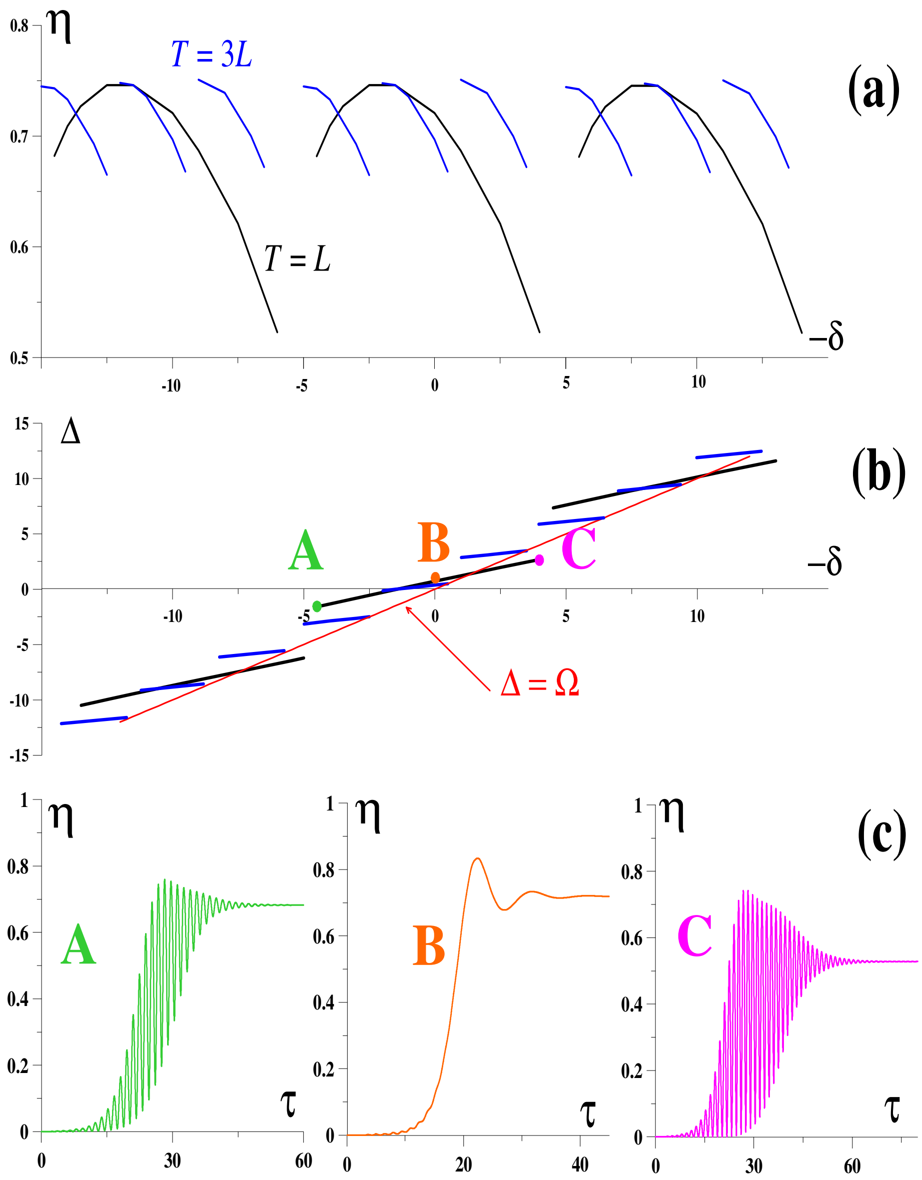

Fig.3. The dependences of the output efficiency η (a) and the normalized frequency of the excited wave Δ (b) on the normalized magnetic field (detuning) -δ in the stationary generation mode in the cases of delay times $T = L$ (black curves) and $T = 3L$ (blue curves). Fig.3c illustrates the dependences of the normalized power of the output wave signal η on the time τ for different values of the normalized magnetic field -δ (points *A*, *B* and *C* in Fig.3b).

5. Conclusion

Summarizing the above, we can say that the quasi-analytical linear theory, developed within the framework of the simplest stationary single-frequency 2-D model of the zigzag gyro-BWO, allows us to explain the main features of this device predicted earlier [1] by a more complete simulations requiring much more computer resources. The small-signal part of this theory explains peculiarities found earlier in the PIC simulations of changing the operating frequency and power of the output signal in the process of the broadband frequency tuning provided by changing the operating magnetic field. In particular, the theory predicts different types of the electron-wave resonance at different shifts of the wave phase between the sections of the system and, as a result, a piecewise character of changing the operating frequency and power of the excited wave in the process of changing the operating magnetic field. The development of our simplest quasi-analytical 2-D model to the nonstationary spatial-temporal approach allows us to describe dynamics of mode competition in such a system. This problem arises due to the existence of two different solutions corresponding to the two different waves from different segments of the piecewise frequency characteristic of the oscillator at the same operating magnetic field. In addition, our nonstationary theory predicts the existence of regimes of both periodic and stochastic automodulations of the output power realized in this system at relatively high operating currents.

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6. References

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