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Gyro-Backward-Wave Oscillator Synchronized by Distributed External Action

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Abstract—The possibility of synchronizing oscillations in a gyro-backward-wave tube (gyro-BWT) by means of distributed introduction of a control signal into the interaction space has been theoretically studied for the first time. It is established that the use of coupled waveguide systems for this purpose allows the synchronization bandwidth to be significantly increased as compared to the case when the external control signal is fed to the input of the interaction space (the collector end of a gyro-BWT). *© 2003 MAIK "Nauka/Interperiodica".*

Problems related to the synchronization of distributed autooscillation systems are of considerable interest in modern microwave electronics. Among these problems, of special importance is the task of synchronizing oscillations in a system of the "helical electron beam–backward electromagnetic wave" type (cyclotron resonance maser) [1–5]. Questions pertaining to the synchronization of autooscillations in a gyro-backward-wave tube (gyro-BWT) with an external control signal introduced at the collector end were considered in detail previously [4–7]. These investigations revealed the main laws of synchronization and nonautonomous spatiotemporal dynamics of the active medium containing a helical electron beam in the case of a "lumped" external action.

The most important features of synchronization in distributed electron systems (in particular, in gyro-BWT) include the appearance of quasi-synchronization regimes (manifested by complication of the spectral composition of the output signal of a synchronized microwave oscillator [4, 7]) and the complication of spatial dynamics in the nonautonomous distributed system [5, 7]. The latter phenomenon is observed in a gyro-BWT under the action of a harmonic control signal with amplitude F_0 and frequency Ω introduced at one end of the interaction space ($\xi = A$, where A is the interaction space length of the gyro-BWT). The character of changes in the spatial dynamics consists in the appearance of oscillation modes at the external signal frequency in the synchronization and quasisynchronization regimes. The escape from a quasisynchronization regime is accompanied by the formation of two characteristic regions in the interaction space, featuring different frequencies of the field oscillations. The first of these regions (with the length A_s called the synchronization length [5, 7]), occurring at the gyro-BWT input, features oscillations at a frequency (Ω) of the external control action. The second region features breakage of the induced oscillations (breakdown of synchronization), whereby the base oscillation frequency ω deviates from Ω on approaching the system output ($\xi = 0$). Accordingly, the boundary of the quasi-synchronization wedge is determined by equality of the synchronization length to the total interaction space length ($A_s \equiv A$).

An analysis shows that one possible means of expanding the gyro-BWT synchronization bandwidth consists in maintaining the synchronization regime in a distributed active medium of the "helical electron beam–backward wave" type by providing for the control signal action along the whole system (distributed external action). Such a distributed action can be implemented by a distributed signal input via coupled waveguide systems (CWSs).

Recently [8] we have studied the system of gyro-BWT with CWSs in detail and obtained a system of working equations describing processes in such systems (see also the monographs [9, 10] devoted to the devices with extended interaction of the *O*-type and CWSs). These relationships include the conditions of excitation for each waveguide system and the equations of motion for oscillating electrons in the helical beam:

$$\frac{\partial F_1}{\partial \tau} - \frac{\partial F_1}{\partial \xi} - j\alpha F_2 = -\frac{1}{2\pi}\int_0^{2\pi} \beta\, d\theta_0, \qquad (1)$$

$$\frac{\partial F_2}{\partial \tau} - \frac{\partial F_2}{\partial \xi} - j\alpha F_1 = 0, \qquad (2)$$

$$d\beta/d\xi - j\mu(1 - |\beta|^2)\beta = F_1, \qquad (3)$$

$$F_1(\xi = A) = 0, \quad F_2(\xi = A) = F_3, \qquad \beta(\xi = 0) = \exp(j\theta_0), \quad \theta_0 \in [0, 2\pi]. \qquad (4)$$

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In writing these equations, it was assumed that the helical beam passes through the first waveguide system. The initial conditions (4) correspond to an external synchronizing signal $F_3 = F_0\exp[j\Omega\tau]$ is fed to the input ($\xi = A$) of the second waveguide system. In Eqs. (1)–(4), $F_{1,2}$ are quantities proportional to the slowly varying complex field amplitudes in the first and second waveguide systems, respectively; α is the coupling parameter [8]; $\beta = r\exp(j\theta)$ is the complex radius of the
1 electron trajectory in a helical beam; μ = @?? is the
2 parameter of nonisochronism of the oscillating electrons [11, 12]; and ξ and τ are the dimensionless longitudinal coordinate and time, respectively. Simplifying assumptions underlying the proposed model and the expressions for dimensionless variables are considered in detail elsewhere [8, 12].

Let us consider a gyro-BWT synchronized by a distributed external action under the same conditions and control parameters ($\mu = 2.0$, $A = 3.0$) as in [4, 7], where the signal was introduced at the collector end of the tube.

Figure 1a shows the plots of the normalized synchronization bandwidth $\Delta\omega/\Delta\omega_0$ for a gyro-BWT with distributed introduction of the external high-frequency control signal versus coupling coefficient α for various amplitudes F_0 of the external action. Here, the synchronization bandwidth $\Delta\omega$ is normalized to the quasisynchronization bandwidth $\Delta\omega_0$ for the gyro-BWT under the action of a control signal with the same amplitude F_0 fed to the collector end (see [4, 5, 7]). As can be seen from these data, the width $\Delta\omega$ of the synchronization band (i.e., the band where the external signal frequency locks the base frequency of the gyro-BWT) in the system with distributed external action significantly increases in a certain interval of the coefficient of coupling between waveguide systems through which the control signal acts upon the active medium (i.e., upon the helical electron beam). When the external signal amplitude is small (Fig. 1a, $F_0 = 0.05$) the synchronization bandwidth increases ($\Delta\omega > \Delta\omega_0$) for $\alpha > 0.25$. As the control signal intensity grows, the interval of α values in which the synchronization bandwidth increases exhibits narrowing ($0.35 < \alpha < 0.8$). The increase in F_0 is also accompanied by a decrease in the normalized synchronization bandwidth $\Delta\omega/\Delta\omega_0$.

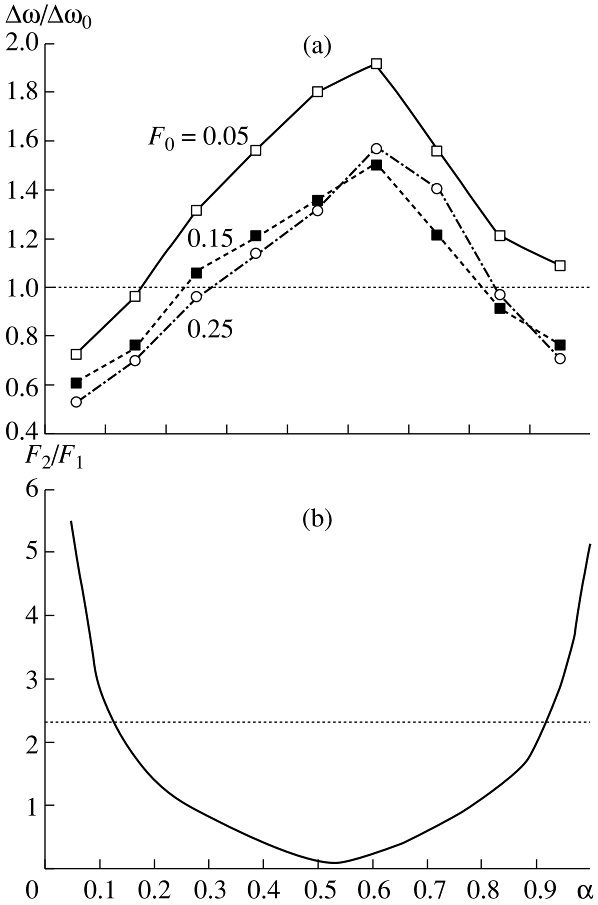

Fig. 1. Plots of (a) the normalized synchronization bandwidth $\Delta\omega/\Delta\omega_0$ for various amplitudes F_0 of the external action and (b) the field amplitude ratio F_2/F_1 at the CWS outputs in the absence of the electron beam versus waveguide coupling coefficient α for a gyro-BWT–CWS system with distributed introduction of the external high-frequency control signal.

Expansion of the synchronization bandwidth in the system with distributed introduction of the control signal is explained by peculiarities of the physical processes in a nonautonomous gyro-BWT. In the case of a "lumped" introduction of the control signal at the collector end, the external field acts upon a well-bunched electron beam. In contrast, the distributed synchronizing field acts upon the helical beam along the entire length of the interaction space. The latter case provides conditions for an effective modulation of the helical beam at the control signal frequency even near the tube output (where electrons are weakly bunched). A helical beam grouped due to phase modulation of the ensemble of oscillating electrons exhibits a more rapid buildup of the grouped current harmonic (with the control signal frequency Ω) toward the collector end as compared to the case when a control signal of the same intensity is introduced at the input of the interaction space ($\xi = A$). As a result, the synchronization length A_s in the system with distributed external action increases up to the total length of the interaction space within a frequency interval $\Delta\omega$ exceeding that ($\Delta\omega_0$) for the "lumped" external action on the same system.

Thus, the synchronization bandwidth in the system with distributed introduction of the control signal significantly increases, provided optimum coupling between s. For the gyro-BWT considered above (with $A = 3.0$), the optimum coupling coefficient $\alpha \approx 0.65$ provides for a (1.5–2)-fold increase in the synchronization bandwidth in the system with distributed external action relative to the gyro-BWT with "lumped" action (at the collector end). In the general case, the optimum

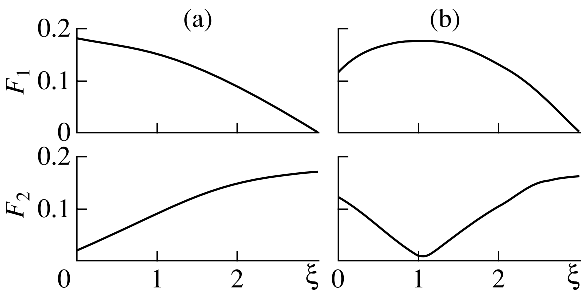

Fig. 2. High-frequency field amplitude profiles in the interaction space for "cold" CWSs with α = 0.5 (a) and 0.8 (b). The external field with a frequency equal to that of the autonomous gyro-BWT operation is fed to the second waveguide system input ($\xi = A = 3.0$).

α value is determined by features of the high-frequency power redistribution between the two CWSs.

Figure 1b shows a plot of the F_2/F_1 ratio at the system output (ξ = 0) versus the coupling coefficient α (F_1 and F_2 are the field amplitudes in the "cold" waveguide systems without the electron beam). The external field with amplitude F_0 and a frequency equal to that of the autonomous gyro-BWT operation is fed to the second waveguide system: $F_1(\xi = A) = 0$, $F_2(\xi = A) = F_0$. As can be seen, only a part of the high-frequency power is pumped from second to first waveguide system when the coupling coefficient is small. In a gyro-BWT synchronized via a CWSs with such α value, the effective field power acting upon the electron beam decreases as a result of incomplete pumping into the interaction space.

The same system with α ~ 0.4–0.7 features almost complete pumping of the high-frequency power is pumped from one to another waveguide system. This is illustrated in Fig. 2a showing the field distribution along the interaction space in each of the "cold" CWSs. As can be seen, virtually all power of the signal fed to the second waveguide system is transferred to the first system: $F_1(\xi = 0) \approx F_0$, $F_2(\xi = 0) \approx 0$. In this case, the synchronization bandwidth is maximum: the whole power of the external synchronizing signal acts upon the helical electron beam along the entire length of the interaction space.

In the case of large coupling coefficients (α > 0.6), the system features reverse pumping of the high-frequency power from first to second waveguide system and the field amplitude at the second output begins to grow (Fig. 1b). As can be seen from Fig. 2b showing the field profiles for α = 0.8, virtually complete pumping of the high-frequency power to the first waveguide system takes place over a length of $\xi = (2/3)A$, after which the reverse pumping begins. This is equivalent to a decrease in the effective length of the interaction space in which the external field acts upon the electron beam (for α = 0.8, this decrease amounts to $(1/3)A$). As a result, the gyro-BWT synchronization bandwidth decreases. In the case of large coupling coefficients (α = 0.9–1.1), the length of the interaction space in which the high-frequency power is effectively pumped from one to another accounts for a small part of the interaction space and the synchronization bandwidth drops especially sharply (significantly below the $\Delta\omega_0$ value for the system with "lumped" introduction of the external signal.

In conclusion, it should be noted that gyro-BWTs operating in a synchronized regime with distributed introduction of the external signal are characterized by increased generation efficiency. For the optimum coupling coefficient (α = 0.65), the efficiency reached η = 23.2% (against 18.7%) in an autonomous regime.

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