EXPERIMENTAL AND THEORETICAL STUDY OF SYNCHRONIZATION OF MICROWAVE OSCILLATIONS IN BACKWARD WAVE OSCILLATOR

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Abstract – **Synchronization of the oscillations in the system «electron-beam with backward electromagnetic wave» (BWO) is investigated theoretically and experimentally. The characteristics of non-autonomous oscillations are examined; physical processes in the distributed auto-oscillation system transiting to synchronization regime are analysed**.

Index terms – **Synchronization, microwave oscillator, backward wave tube, distributed electron active media.**

I. Introduction

Recently investigations of the phenomenon of synchronization in self-oscillating systems of different nature attract great attention, which can be proved by many publications concerning this problem (for example, the reviews [1–4]). However, the questions of the influence of the external signal upon the processes in auto-generators have been explored in detail only for the low-dimensional systems. In last years the special interest is caused by the problem of chaotic synchronization in non-linear finite-dimensional dynamical systems demonstrating dynamical chaos [1,2,4,5].

The non-autonomous oscillations of distributed auto-oscillation systems are much less investigated. One of the classical distributed auto-oscillating microwave systems is the backward-wave oscillator (BWO) [6,7], in which the interaction between the electron beam and the synchronous backward electromagnetic wave leads to the generation of the high-frequency signal. The paper [8] describes the possibility of experimental synchronization of the BWO by the external signal, brought in by the electron beam. In the works [9–11] the characteristics of the synchronous and non-synchronous regimes of BWO in the framework of stationary theory are investigated. In the works [12–14] some peculiarities of harmonic synchronization of the active medium “spiral electron beam – backward electromagnetic wave” are analysed (in the framework of non-linear non-stationary theory).

In the present report we discuss the experimental and numerical (based on the non-linear non-stationary theory [6,7]) investigation of the influence of external harmonic signal upon the auto-oscillations in distributed electron-wave medium “electron beam – backward electromagnetic wave”.

II. Experimental Setup

The experimental investigations of the influence of external harmonic signal upon the auto-oscillations generated by electron beam interacting with backward electromagnetic wave have been made upon the industrial exemplar of BWO OV-4, working in 10-sm diapason. The “cold” measurements show that the voltage standing-wave ratio (VSWR) of the BWO power output has the order 1.2–1.3. This allows to conclude that the amplitude of the wave reflected from the BWO local attenuator settled on the collector edge of the system, can be rather large.

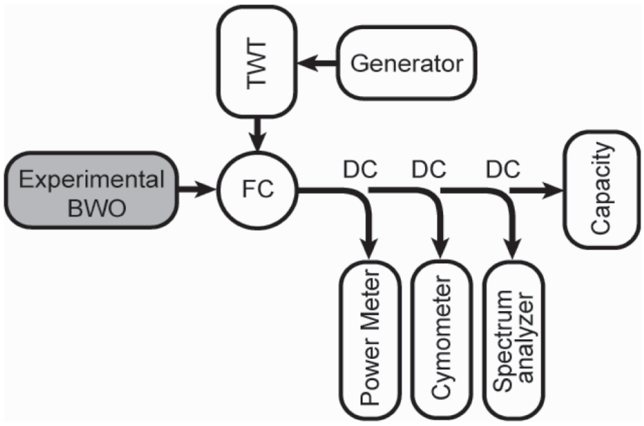

Fig.1. The scheme of the experimental plant.
Here DC means directional coupler, FC – ferrite circulator

For the purpose of synchronization, the external harmonic signal amplified by the traveling-wave tube of medium power is given to the BWO energy outlet via the ferrite circulator (see Fig. 1). The falling signal, of course, does not influence essentially upon the interaction of the electron beam with the backward wave. But the signal reflecting from the directional coupler affects greatly on the BWO output signal. It is necessary to note that this signal is separated from the incident wave by the ferrite circulator (FC) and is directed with the help of the directional couplers (DC) to the measure block which includes the power meter, digital counter timer, spectrum analyzer, crystal detector and resistor.

During the experiment it is possible to change widely the BWO operating current, accelerating voltage, frequency and amplitude of the external harmonic signal. By the way, the plant allows to measure the power of the signal reflected from the local absorbent with the electron beam being switched off.

III. Theoretical Model

For the investigation of the influence of external harmonic signal on the auto-oscillations in distributed active medium "electron beam – backward electromagnetic wave" the equations of non-stationary non-linear BWO theory [6,7] are taken. The set of dynamical equations of BWO includes the motion equation for large particles in wave field of complex F with the account of space charge influence, and the equation of wave excitation

$$\frac{\partial^2 u}{\partial^2 \xi} = -\mathrm{Re}\left[F - jqI\right]e^{ju}, \quad I = -\frac{1}{2\pi}\int_0^{2\pi} e^{-ju}du_0,$$

$$\frac{\partial F}{\partial \tau} - \frac{\partial F}{\partial \xi} = I, \quad u\Big|_{\xi=0} = u_0, \quad \frac{\partial u}{\partial \xi}\Big|_{\xi=0} = 0, \quad u_0 \in [0, 2\pi]$$

$$F\Big|_{\xi=A} = F_0 \exp[j\Omega\tau].$$

Here τ and ξ are dimensionless space and time coordinates, u is the phase coordinate of the large particle relative to the wave, I is the complex amplitude of the first harmonic of the high-frequency beam current, A is the parameter of normalized length ($A \sim I_0^{1/3}$, where I_0 is beam current), q is the parameter of space charge.

IV. Results of BWO synchronization by the external signal: experimental results

In Fig. 2 the experimental (2*a*) and numerically derived (2*b*) regime maps of the non-autonomous BWO on the plane of the control parameters "frequency – power of the external signal. The experimental map is plotted for the beam current I=1.2I_{st} (where I_{st} is the starting current value), and the theoretical – for the non-dimensional length A=2.2 (in non-autonomous system the regime of stationary generation is observed) for the case q=0 (without space charge). Fig. 3 demonstrates the experimental (using spectrum analyzer S4–27) and theoretical power spectrums of the exit signal of non-autonomous BWO for the different parameters of the external signal. In Fig. 3 the external signal frequency is marked as Ω. The spectrums are plotted for the constant values of the power and the changing value of the frequency of the external signal. By the way, in the experimental model of BWO the influence of the space charge is rather significant, so the corresponding theoretical spectrums are calculated for the case of large space charge q=1.3.

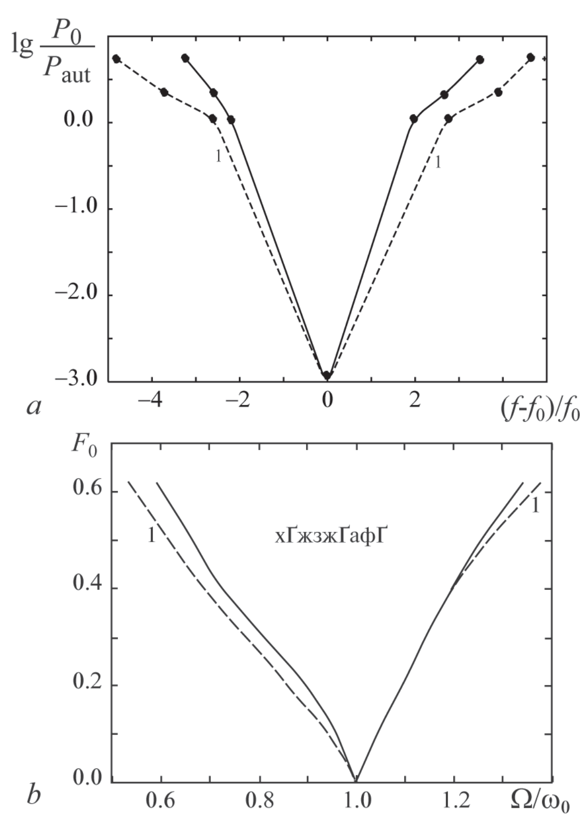

Fig.2. The bounds of the areas of stationary generation and frequency capture of the non-autonomous BWO (experiment (a) and numerical modeling (b))

When the mistuning between the frequency of autonomous generation ω_0 and the frequency of the external signal Ω is essential, the regime of beating can be observed in the system (Fig. 3*a*). In this case the power spectrum shows many modulation components, составляющих, and the distance between them is close to the value (Ω–ω_0). When the external signal frequency is close to the autonomous frequency, the BWO demonstrates the regime of synchronization (marked by firm line on Fig. 2), where the frequency of output signal ω is determined by the frequency of external influence, and the amplitude of external signal $|F(\xi=0,\tau)|$ states constant after the end of transient process (the power spectrum corresponding to stationary generation is on Fig. 3*c*). When the values of the control parameters cross the border of synchronization area (firm line on Fig. 2) the system passes to the regime of external signal modulation. In this case the amplitude of the signal changes periodically in time. Nevertheless, in this case in some diapason of the value of external signal frequency (between the fine line and the dashed line *1*) the regime of frequency capture remains. This is illustrated by the power spectrums on Fig. 2*b* and 2*d* which are in keeping with the area between the firm line and the dashed line on the regime map. It can be seen that the most intensive spectral component corresponds to the frequency of the external influence Ω.

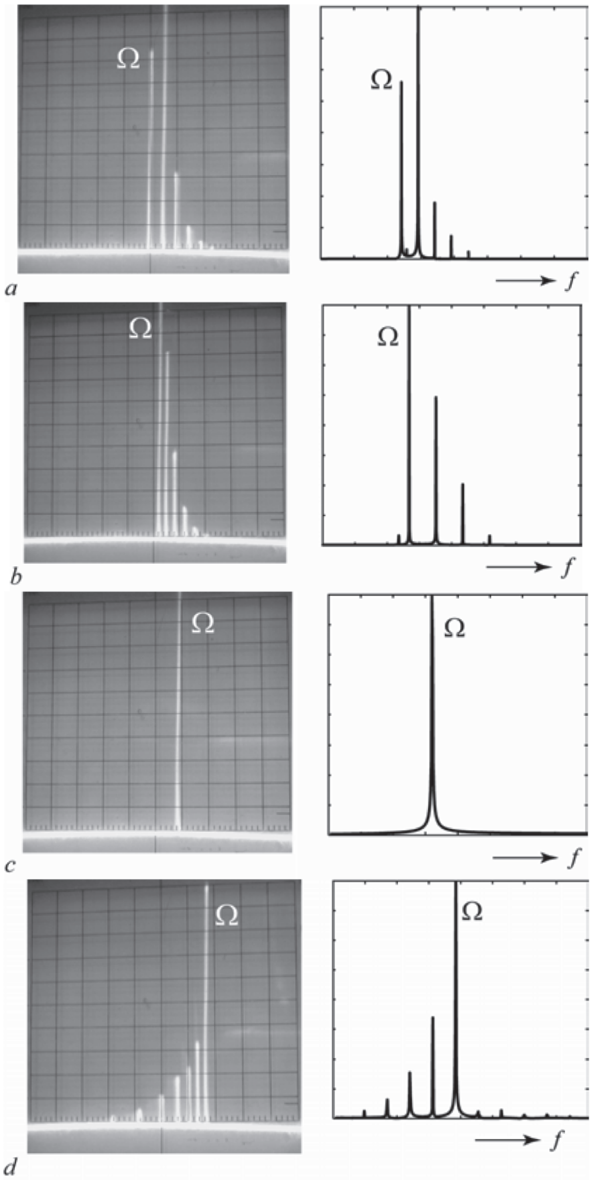

Fig. 3. Experimental and theoretical power spectrums of the non-autonomous BWO: a – the beatings, b, d – frequency capture together with the modulation of output signal at the low frequency bound and the high frequency bound of the synchronization tongue, c – stationary generation on the frequency of the external signal

So, on the dashed line *1* the regime of frequency capture is destroyed (at that in the regime of frequency capture the modulation of output field amplitude can be observed). When crossing the firm line on Fig. 2 in non-autonomous BWO the destruction of the regime of stationary generation takes place.

In Fig. 4 the experimental and theoretical dependence of synchronization bond width from the beam current (non-dimensional parameter *A*) without space charge (q=0) is represented. It can be seen from the theoretical functions (Fig. 4*b*) that the bond width decreases with the increase of the beam current, and with A>2.2÷3.0 (this means that the current exceeds the starting current in 1.5÷3 times) it practically stop to change with the further enlarging of *A*. The latter is well confirmed by the experimentally derived dependence of the normalized synchronization band width upon the beam current (Fig. 4*a*) from which it can be seen that the band width swiftly diminish with the increase of *I*.

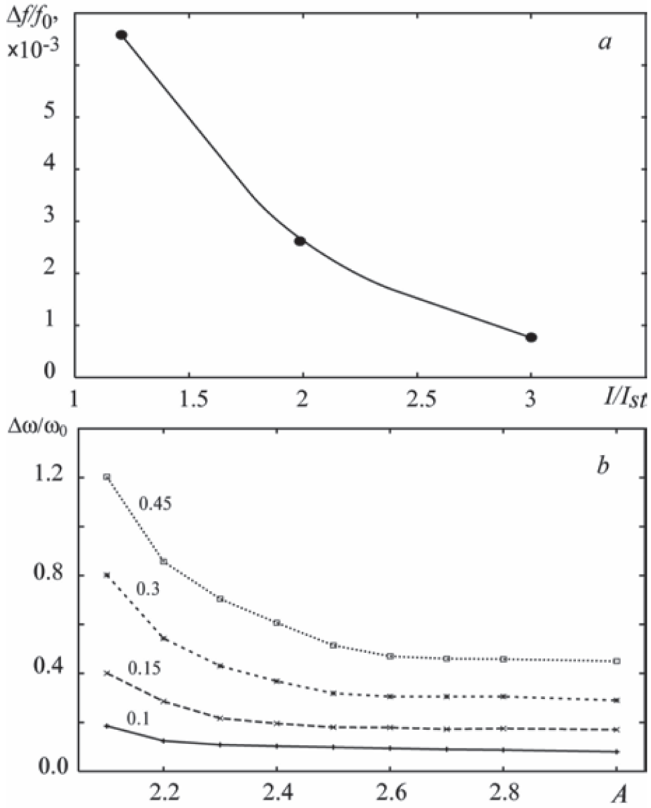

Fig.4. (a) Experimentally derived dependence of the normalized synchronization band width from the beam current of the BWO; (b) theoretical dependence of the synchronization band width from the dimensional length of the system A within the different amplitudes of the external signal F_0

V. Physical Processes

For the analysis of physical processes in the synchronized BWO the behaviour of the field amplitude and phase $F(\xi,\tau)$ in non-autonomous regime is examined. In Fig. 5 one can see the distribution of the field phase $\arg F$, derived from numerical modeling, which determines the frequency of oscillations in BWO. As it can be seen on the Fig. 5*a,* in non-synchronous regime the interaction space can be divided into two regions. In the region connecting with the collector edge of the system $\xi=A$, we can see that the frequency of the oscillations of the phase $\varphi(t)=\arg F \bmod 2\pi$ is equal to the external signal frequency. Then, in the narrow range of the interaction space the field phase value $\varphi(t)$ noticeably leaps on π. In the region near the output $\xi=0$ the frequency of phase oscillations ω differs from the frequency Ω. The oscillation frequency ω approaches to the frequency of the autonomous generation ω_0, when the external signal frequency Ω moves off from the boundary of the area of BWO frequency capture.

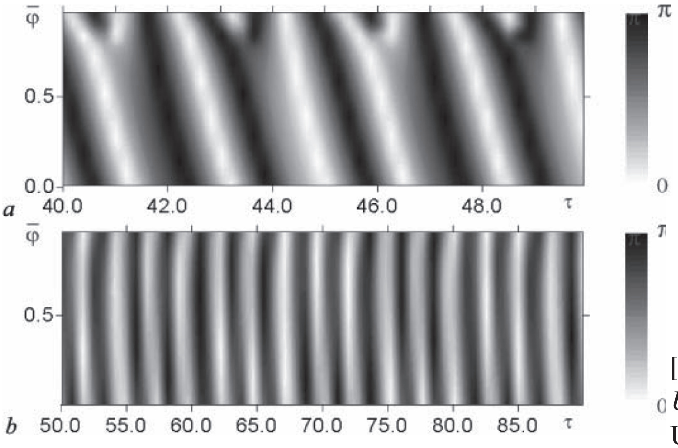

Fig. 5. Theoretical distributions of the phase φ(τ) of the high-frequency field along the interaction space in the synchronous (a) and non-synchronous (b) regime (space charge parameter q=1.3, non-dimensional length A=2.2)

In the regime of frequency capture the oscillations frequency is equal to the external signal frequency Ω in the whole interaction space. On the projection of the field phase distribution (Fig. 5*b*) the regular picture of the phase modulation can be observed, and the period of the modulation is equal to the period of external influence. The similar results have been obtained earlier from the theoretical and numerical analysis of non-autonomous dynamics of the cyclotron resonance maser with backward wave [12–14].

VI. Conclusion

In this work the influence of the external harmonic signal upon the auto-oscillations in BWO is investigated theoretically and experimentally. The characteristics of synchronous and non-synchronous regimes of the non-autonomous work of the device are considered. The physical processes in non-autonomous active medium are investigated. It is shown that the outcome from the synchronization regime is accompanied by forming of two typical areas in the interaction space, in one of which oscillations with the frequency of external signal take place, and in the other the destruction of synchronization regime is observed and the oscillations on the frequency differing from the external begin.

Acknowledgment

We are grateful to Corresponding Member of Russian Academy of Science, Prof. D.I. Trubetskov for their interest in this work, repeated discussions, and helpful critical remarks.

The work is supported by RBRF (projects 03–02–16269 and 02–02–16351), scientific program "Universities of Russia. Fundamental Researches", the program of support of the leading scientific schools of Russia, U.S.~Civilian Research & Development Foundation for the Independent States of the Former Soviet Union (CRDF), grant REC–006. A.E. Hramov also acknowledges "Dynasty" Foundation and International Center for Fundamental Physics in Moscow.

REFERENCES

[1] Pikovsky A., Rosenblum M., Kurths J. *Synchronization. A Universal Concept in Nonlinear Sciences*. Cambridge University Press, 2001.

[2] Rulkov N.F., Sushchik M.M., Tsimring L.S., Abarbanel H.D.I. *Phys.Rev.E*. 1995. Vol. 51, No 2. P. 980.

[3] Rosenblum M.G., Pikovsky A.S., Kurths J. *Phys. Rev. Lett*. 1996. Vol. 76, No 11. P. 1804.

[4] Pecora L.M., Carroll T.L., Jonson G.A., Mar D.J. *Chaos*. 1997. Vol. 7, No 4. P. 520.

[5] Dmitriev A.S., Panas A.I. Dynamical chaos. *New bearer of information for communications systems*. Moscow, Fizmatlit, 2002. (*In Russian*)

[6] *Electronics of backward wave tubes*. Saratov, Saratov State University, 1975.

[7] Trubetskov A.E., Hramov A.E. *Lectures on microwave electronics for physicists*. Vol. 1. Moscow, Fizmatlit, 2003. (*In Russian*)

[8] Kahavets V.I. *Vestnik MGU*. Ser. III. 1961. No 2. P. 32.

[9] Rapoport G.P. *Radiotechnika i Electronika*. 1964. Vol. 9. No 1. P. 118.

[10] Solntsev V.A. *Electronnaja Technika. Ser. Microwave Electronics*. 1966. No. 9. P. 30.

[11] Zhelezovskii B.E., Kal'janov E.V. *Multifrequency regimes in microwave devices*. Moscow, Svaz', 1978. (*In Russian*)

[12] Koronovskii A.A., Trubetskov D.I., Hramov A.E. *Radiophysics and Quantum Electronics*. 2002. Vol. XLV. P. 773.

[13] Trubetskov D.I., Hramov A.E. *Journal of Commun. Techn. and Electron*. 2003. Vol. 48. P. 116.

[14] Trubetskov D.I., Hramov A.E. *Izv. Rus. Akad. Nauk, Physical series*. 2002. Vol. 66. P. 1761.