O-Type Millimeter-Wave Band Devices on the Spiral Bent Rectangular Waveguide

Alexander Kurayev
Belarusian State University of Informatics and Radioelectronics
Minsk, Belarus
kurayev@bsuir.by

Alexey Rak
Belarusian State University of Informatics and Radioelectronics
Minsk, Belarus
rak.aliaksei@gmail.com

Artem Badarin
Innopolis University
Innopolis, Russia
badarin.a.a@mail.ru

Semen Kurkin
Innopolis University
Innopolis, Russia
kurkinsa@gmail.com

Alexey Koronovskii
Department of Nonlinear Processes
Saratov State University
Saratov, Russia
alexey.koronovskii@gmail.com

***Abstract* — The designs of O-type millimeter-wave band devices with two wide tape electron beams are proposed and investigated. It is proposed to use a spirally bent rectangular waveguide on fundamental H10 mode as an electrodynamic structure of the tubes. Analytical estimates have shown the possibility of effective interaction of the electron beam with both direct and backward electromagnetic waves for the certain values of control parameters of the systems.**

Keywords— optimization, traveling-wave tube, TWT, backward-wave tube, BWT, O-type devices, numerical simulation

I. Introduction

High penetration of THz electromagnetic radiation can be adapted for the detection and identification of objects hidden behind obstacles, that is necessary for solution of the security problems. If the object does not contain water molecules or other polar substances that strongly absorb such radiation, then terahertz waves freely penetrate the object with practically no loss of energy. In this case, a resonant interaction of the electromagnetic field with individual molecules and molecular complexes can be observed, which makes it possible to identify various media. Thus, for example, drugs or explosives [1]. In addition, as shown by numerous experimental studies, T-rays allow more effective control of items and weapons hidden under clothing [2]. Terahertz waves are of great interest for radar and telecommunication applications. In most cases, for terrestrial radio electronic systems, the advantages of THz radiation with respect to microwave and IR radiation appear at medium and short distances.

In addition, terahertz instruments and devices are now successfully used in measuring technology, for example, to study submillimeter radiation in beam-plasma interactions. One of the instruments working in the terahertz range and actively being investigated currently is BWT and TWT.

Tubes with a spiral slowing system make it possible to obtain a large gain in a wide frequency range, but power of such devices is limited by the amount of heat dissipation from the spiral. To increase output power of the tubes, slowing systems are made of all-metal elements having good heat dissipation, the most known of which are chains of coupled resonators, counter pins, and volumetric curved waveguides [3].

II. System under Study

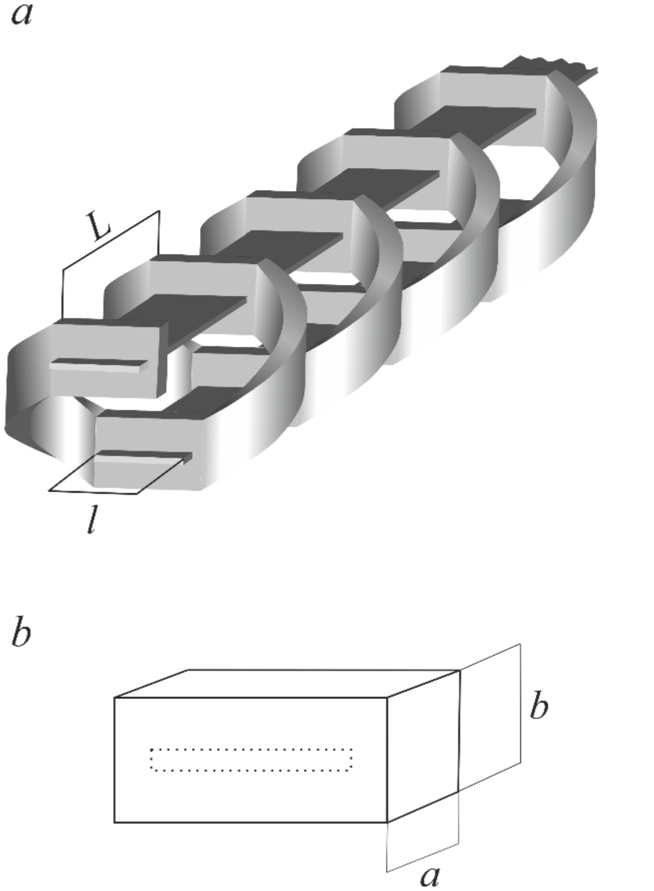

Fig. 1. Segment of spirally bent rectangular waveguide. Here, l is the width of the non-radiating slits in the walls located at the maxima of electric field strength; a, b – geometric dimensions of the rectangular waveguide, L – distance between adjacent sections of the waveguide.

In this paper, we consider new design of millimeter-wave band TWT/BWT with two wide tape electron beams. As an electrodynamic structure, it is proposed to use a spirally bent waveguide on fundamental H10 mode (see Fig. 1). Fig. 1 shows a part (segment) of the waveguide system in which a discrete interaction of electron beams with electromagnetic field occurs. Two electron beams pass through non-radiating slits in the walls of the spirally bent waveguide at the maxima of the longitudinal components of electric field strength.

III. Main Results

We have analyzed the features of discrete interaction of electrons with electromagnetic field of the spirally bent waveguide. As in the first and second beams, the electron velocity modulation develops along the beam width l with phase velocity υ_ϕ equal to the phase velocity of propagation of the H_{10} wave in the waveguide.

We now use the equations of excitation of a regular waveguide by a transverse electron current [4,5]. Avoiding complex math transformations easy to get:

$$\Delta C_s^n = \frac{lb\delta_m e^{j\omega t}}{N_s} M E_y \left(e^{j2hl} - 1\right)$$

$$\Delta C_{-s}^n = -\frac{lb\delta_m e^{j\omega t}}{N_s 2h} M$$

here ΔC_s and ΔC_{-s} is amplitude increments of direct and backward wave in the n^{th} gap.

It is clear, that for the beam width $l=\pi m/b=\lambda_w\ m/2$ (where m is an integer), direct (backward) wave will not be excited by the beam modulated by backward (direct) wave.

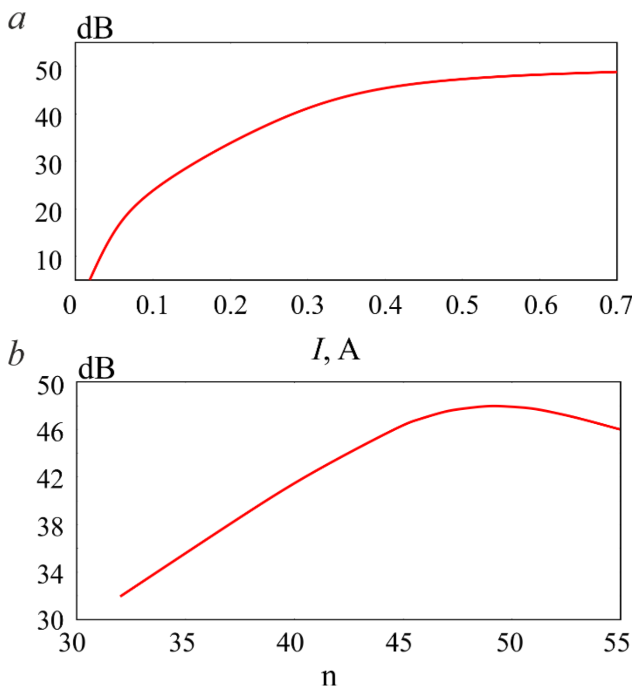

Fig. 2. (a) Dependence of the gain on the beams currents; input signal power = 0.1 W; m=20; n = 48; (b) Dependence of the gain on the number of periods of the waveguide; input signal power = 0.1 W; m=20; current = 0.5 A.

A 3D model of the devices under consideration was developed and a full-scale numerical simulation based on the well-proven particle-in-cell method was performed.
There was made a multiparameter optimization of the devices. Also, the beam dynamics and output characteristics of the systems were studied in detail depending on the control parameters (injected current, number of periods of the rectangular bent waveguide, accelerating voltage, beam width, etc.). In particular, Figure 2 shows the dependencies of the gain on the number of periods of the waveguiding system and the magnitude of injected current. It is clearly seen that the gain increases with increasing injected current and saturates at current I~0.6 A. The dependence of the gain on the number of periods shows that the optimum is observed in the region of 48 periods. In this case, the gain reaches 48 dB.

IV. Conclusion

Two significant advantages of the tubes on spirally bent rectangular waveguide have been revealed in comparison with tubes on wavy bent waveguide: 1) it is possible to use wide tape electron beams with much higher current value than in the case of narrow electron beam; 2) there is a one-sided excitation of only the backward (direct) wave when the beam width $l=m\lambda w/2$. As shown in [6], the signal amplification regime in the considered BWT design is similar to those in TWT. When the above-mentioned condition $l=m\lambda w/2$ is fulfilled, the velocity modulation in TWT does not depend in the linear approximation on the presence in the waveguide of backward wave. Thus, simultaneous independent amplification and generation regimes are possible in the linear approximation in the proposed scheme.

Electromagnetic 3D numerical PIC-modeling of the proposed schemes showed that the considered designs of O-type generators and amplifiers are prospective for using in the millimeter and terahertz ranges.

Acknowledgment

The studies have been supported by Russian Foundation for Basic Research (Projects № 18-32-20135 and 19-52-04016) and President's program (Project MD-2603.2019.2).

References

[1] Kemp M.C. Explosive detection by terahertz spectroscopy – a bridge too far // IEEE Transactions of Terahertz Science and Technology. – 2011. – Vol. 1, No 1. – P. 282–292.

[2] Siegel P.H. Terahertz techonolgy // IEEE Transactions on Microwave Theory and Techniques. – 2002. – Vol. 50, No 3. – P. 910–928.

[3] J. Benford, J. A. Swegle, and E. Schamiloglu, “High Power Microwaves,” 3rd Edition, CRC Press, Taylor and Francis Group, 2016.

[4] A.V. Aksenchyk, A.A. Kurayev, I.F. Kirinivich, “Millimeter and Submillimeter O-type Amplifiers and Oscillators. The Theory and optimization. Germany,” Palmarium Academic Publishing, 2014. – 154 p.

[5] A.A. Kurayev, T.L. Popkova, A.K. Sinitsyn, “Electrodynamics and Electromagnetics Wave Propagation,” Moscow, IN-FRA-M, 2013. – 424 p.

[6] G. Kory, et al., “Overview of W-Band Travelling Wave Tube Programs,” IVEC – 2006, pp. 447 – 448, 2006.