Experimental Proof-of-Principle Demonstration of Sub-MM Clinotron-Multiplier

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***Abstract*—We demonstrate experimentally a possibility of triple frequency multiplication in a simple CW clinotron (a BWO with inclined beam) oscillator. In the proof-of-principle experiment the device generated $\lambda_b \approx 2.8$ mm (107 GHz) in the buncher section while in the catcher section 10 mW at $\lambda_c \approx 0.935$ mm (321 GHz) were measured. The principal ability of a clinotron-type oscillator to pre-bunch a layer of the electron beam capable of production of terahertz radiation in the short-wavelength part of sub-millimetre waveband is shown.**

I. INTRODUCTION

FOR mastering the sub-millimetre waveband in its long-wavelength part with compact affordable devices good results are obtained in comb-type BWOs with inclined beams (named "clinotrons") [1]. Clinotrons have the output power orders of the magnitude higher than conventional BWOs of the corresponding waveband and millimetre and long-wavelength part of the sub-millimetre waveband are efficiently covered by them [2]. However, extension in the short-wavelength part of the sub-millimetre waveband with this type of devices causes substantial difficulties. Main of them are demanding manufacturing of quality combs with ultrasmall periods (less than 0.1 mm) and growing requirements to electron beam current densities and quality of their focussing in guide magnetic field. Utilisation of frequency multipliers seems one of the possible ways around those difficulties [3,4], although, they produce lesser output powers than the conventional BWOs (when available).

II. RESULTS

In our clinotron-multiplier design, modulating generator, buncher and catcher sections are combined at once in a single device. Sheet electron beam propagates one after another two slow-wave-structures of the comb-type, Fig. 1. Over the first comb, the closest to it part of the beam works in the clinotron-oscillator regime of the 3-mm waveband (cf., e.g., [1]), and is dumped on the comb. With this, (a smaller) bunching also occurs in farther away layers of the beam, which appear over the second comb that works as the catcher section of the device.

Parameters of the both combs and the beam must provide for fulfilment of synchronism conditions. Firstly, an exact

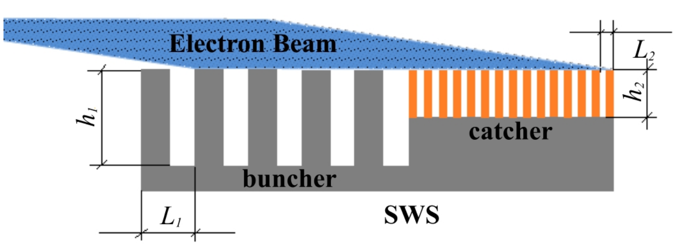

Fig. 1. Interaction space sketch: buncher and catcher section slow-wave-structure (SWS) lengths and depths are $L_1 = 0.27$ mm, $L_2 = 0.1$ mm and $h_1 = 0.61$ mm, $h_2 = 0.17$ mm, respectively. Comb sizes are exaggerated for the sake of visualization.

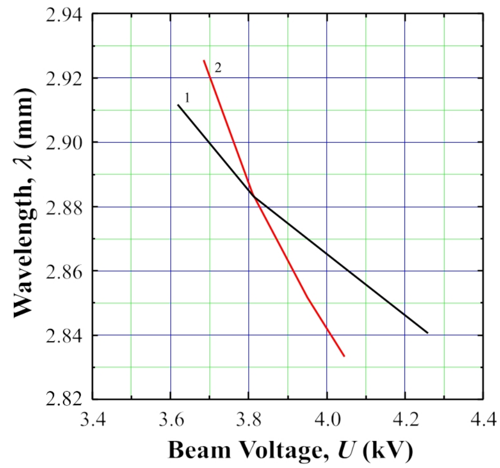

Fig. 2. Dispersion curves of buncher (black, curve 1) and catcher (red, curve 2) section combs for the "-1" spatial harmonics (catcher section comb wavelength is tripled).

multiplicity of buncher section frequency to that of the catcher one
($\omega_c = m\omega_b$, m is a positive integer) and, secondly, synchronism of beam electrons with velocities of the operating spatial harmonics in the buncher section and a harmonics of the catcher section (see Fig. 2)

$$\upsilon_0 \approx \upsilon_n = \omega_c L_2/(\varphi + 2\pi n)\ ;\ n \text{ is an integer;}$$

ω_c and ω_b are frequencies generated in the catcher and buncher sections, respectively; υ_0 and υ_n are the electron beam and n's spatial harmonics velocities; φ is the phase shift of the fundamental on one slow-wave-structure period L_2.

Therefore, generation of the multiplied output signal is possible only in a narrow range of electron beam voltages and, hence, in a small frequency tuning range.

It is worth mentioning that initially the very possibility to use the clinotron for modulation of electron beam was uncertain. Under normal operational conditions, all electrons are dumped on the surface of the comb, while the bunching occurs approximately in the middle of the comb length. However, accomplished numerical simulations allowed us to clarify that in a thick sheet beam bunching occurs father along the beam propagation direction for the beam layers less close to the surface of the comb at the entrance to the interaction region. This feature of the beam bunching in a clinotron (which we call the 'layer-by-layer bunching effect') is caused by the electron beam propagation in the exponentially decreasing in the direction away from the surface of the comb field of the surface (slow) EM wave. It is then possible to choose the beam width and the direction of the guide magnetic field in such a way that in a certain layer of the beam electrons will form compact bunches already in the catcher section of the device.

Electron bunching in the layers close and remote to the surface of the comb is shown in Figs. 3 and 4, respectively. In the both figures we depict the distance, $x_i - \upsilon_{-1}t$ (in the frame moving with the velocity of the "$n \approx -1$" operating spatial harmo-

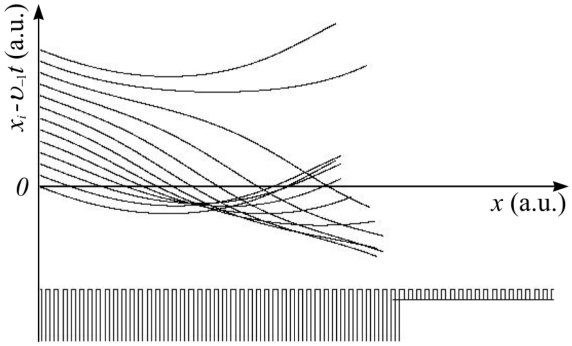

Fig. 3. Electron bunching in the layer close to the surface of the comb. All electrons of this layer are dumped on the surface of the buncher comb. Inclined to the surface of the comb guide magnetic field is optimally adjusted to achieve maximal generated power (1.5 W) in the buncher section.

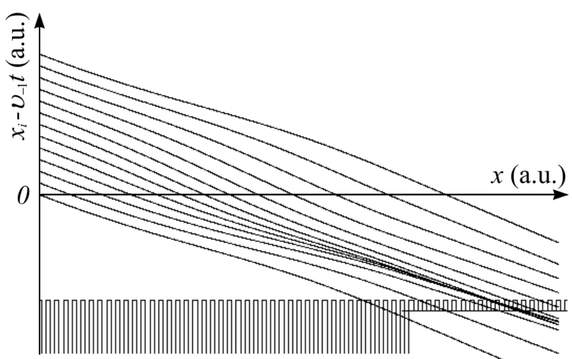

Fig. 4. Electron bunching of the layer entering the interaction region of the 1.5 W 3 mm wavelength (X-band) buncher section on the distance $0.38L_1$ far from the comb surface for the same direction of the guide magnetic field as in Fig. 3.

nics), between 12 electrons equally spaced in the entrance time to the interaction region on one period, $T_b = 2\pi/\omega_b$, of the generated output microwave signal.

We implemented these conditions experimentally. Fig. 5 shows a sketch isometric drawing of the clinotron-multiplier. The first comb contains 42 resonator slots of spatial period $L_1 = 0.27$ mm, while the second comb is comprised of 24 resonator slots of spatial period $L_2 = 0.1$ mm. There is a cylindrical cavity on the left of the housing, which is used for

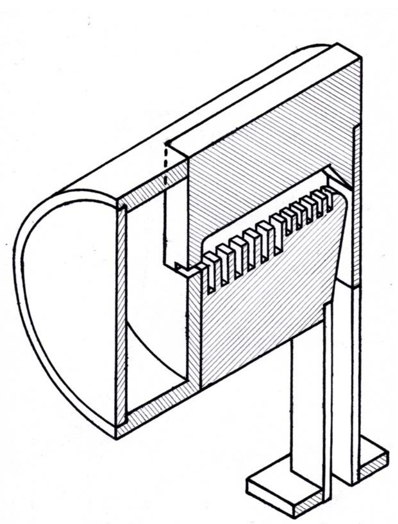

Fig. 5. Sketch sectioned isometric drawing of the clinotron-multiplier. Comb spatial periods are exaggerated for the sake of visualization.

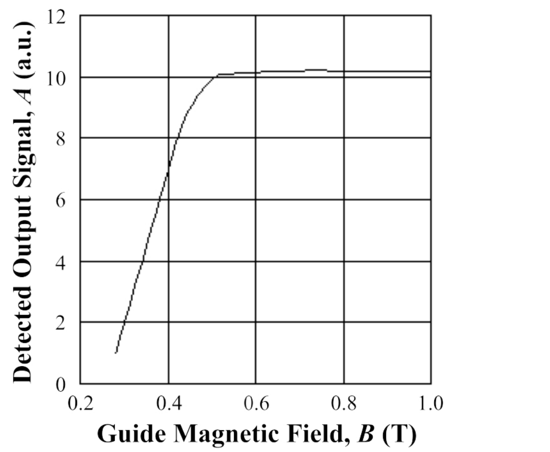

Fig. 6. Dependence of the detected output signal amplitude (a.u.) on the guide magnetic field induction.

placing of the electron gun assembly. The electron gun of diode-type with plane electrodes forms the electron beam of cross-section 2.5×0.14 mm^2; width of the anode hole is 0.6 mm. Both combs are water cooled; the cooling is not shown in the sketch drawing. Output waveguide (with the dimensions 0.7×0.35 mm^2) transmits only sub-mm signal.

In our experiment the beam voltage is 4.8 kV, current is 140 mA, the wavelength in the buncher section is 2.8 mm with generated power $1.2 \div 1.3$ W, while the wavelength of the sub-mm waveband in the catcher section is 0,935 mm with output power about 10 mW. Zone of generation of the multiplied sub-mm signal constituted 50 V in voltage range and 360 MHz in frequency range. In the device under investigation, guide magnetic field induction is $0.3 \div 0.5$ T (see Fig. 6), whereas for a BWO of similar waveband it is about 1.0 T.

III. Summary

Experimental investigation of the proposed clinotron-multiplier showed the principal possibility of moving upward in frequency into the short-wavelength part of the sub-millimetre waveband. The device setup was a simplest and not optimal one, thus, leaving room for substantial further output power enhancement. A characteristic feature of clinotron-multiplier oscillators is their operation in a narrow range of voltages / small frequency tuning range, which, perhaps, could be extended by mechanical tuning the dispersion curve of the buncher section.

References

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