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Efficiency Enhancement of a Klystron-Like Relativistic Backward Wave Oscillator With Waveguide Reflection and Bunching Promotion

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ABSTRACT A klystron-like relativistic backward-wave oscillator (KL-RBWO) with transverse electron beam confinement and waveguide reflection, which works well under a magnetic-field strength below that of the cyclotron resonance, is proposed. For this device operating with a low magnetic field, effective suppression of the transverse velocity of electron beams is introduced by a local electric field near the tube head, to promote modulation uniformity of electron beams. Part of the reflected microwave from the output waveguide provides feedback enhancement to the extractor, which strengthens the local standing-wave field. Owing to a stronger electric field that can interact with the electron beam in the extractor and a higher growth of fundamental harmonic current, the efficiency of the KL-RBWO is increased to 40% when guided by a magnetic field of 0.32 T, compared with that of 30% using conventional structures.

INDEX TERMS High power microwaves, intense relativistic electron beams, relativistic backward-wave oscillator, Cherenkov radiation.

I. INTRODUCTION

Improving the conversion efficiency is a fundamental goal for most of production processes in various fields. High power microwaves (HPMs) are an intense electromagnetic field commonly generated by intense relativistic electron beams (IREBs) [1]–[4]. As one of the most promising HPM sources, relativistic backward wave oscillator (RBWO) operates based on Cherenkov radiation, and many efforts have been put forward in RBWO for efficiency improvement [5]–[10].

Gunin *et al.* introduced RBWO with a resonant reflector (RBWO-RR), in which cut-off neck is replaced by a resonant reflector to provide electron beam with pre-modulation [3]. By using non-uniform slow wave structures (SWSs), conversion efficiency of RBWO-RR exceeds 30% in X-band [6]. Xiao *et al.* proposed klystron-like RBWO (KL-RBWO) by introducing modulation cavity and extraction cavity based on RBWO-RR, significantly improving the efficiency to 50% by combining transition radiation and Cerenkov radiation [9]–[12]. Then the highest efficiencies over 70% have been demonstrated in particle-in-cell (PIC) simulations of KL-RBWO with numerous and complicated cavities [11].

However, these attempts and efforts were carried out mainly in RBWOs where IREBs are constrained with strong magnetic field. For a conventional RBWO operating at a magnetic-field strength below that of the cyclotron resonance, the beam-wave conversion efficiency obtained is generally lower than 30% [13]–[18]. In order to further promote the conversion efficiency, we propose a novel HPM generator based on KL-RBWO. Two methods are investigated in this paper. Firstly, energy modulation and electron bunching is enhanced for the transverse confinement of IREBs via anode cavity in the tube head. Secondly, we introduce feedback to the KL-RBWO via resonant cavities in the waveguide to enhance electron deceleration in the extractor [19]–[21].

The remainder of this paper is organized as follows. In section II, we will first present theoretical analysis of efficiency enhancement based on conventional KL-RBWO. Later in section III, we present effective confinement of IREBs in the RBWO with low-magnetic-field operation, by which a larger fundamental harmonic current is obtained.

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The method and results of using waveguide reflection are then presented in Section IV. Finally, a brief conclusion will be drawn in section VI.

II. STRUCTURE MODEL AND THEORETICAL ANALYSIS

FIGURE 1(a) shows a conventional KL-RBWO, which has an annular cathode, a resonant reflector (RR), non-uniform SWSs, and an extractor. The fundamental parameters of this conventional KL-RBWO are chosen to be similar to those in reference [17], except for the guiding magnetic field. The magnetic induction intensity is 0.32 T in this case, and the magnetic field in this case declines more rapidly behind the extractor.

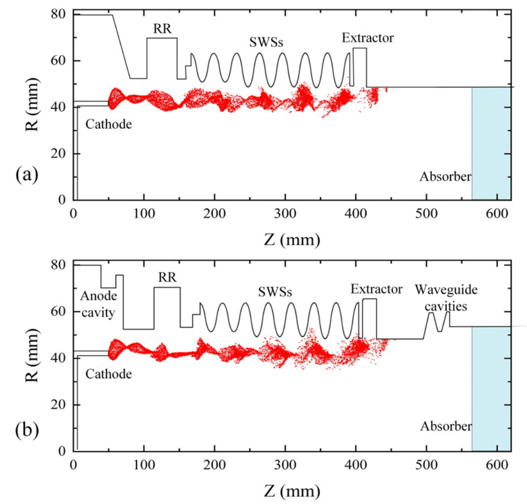

FIGURE 1. Schematic structure of (a) conventional KL-RBWO and (b) proposed KL-RBWO.

According to simulations conducted with the PIC code UNIPIC [22], when the diode voltage is 880 kV and the diode current is 13.9 kA, microwaves in a conventional KL-RBWO are generated with a total power of 3.7 GW (FIGURE 3) and a frequency of 4.35 GHz, indicating an efficiency of 30%.

Fig. 2 shows the distributions of the electron power and microwave power when the device reaches saturation. About 2.7 GW of electron power is extracted by the extractor, indicating that the energy exchange concentrates in the extractor. For this RBWO operating in the TM_{01} mode with a single-mode stage, the power generated in the extractor can be found by integrating the product of the first harmonic current and axial field [18]:

$$P = \frac{1}{T}\int_0^T \left[\int_0^d I_1(\mathrm{z,t}) \cdot E_z(\mathrm{z,t})dz\right] dt \qquad (1)$$

where d is the width of the extractor and T is the cycle of the RF field. Therefore, enhanced microwave generation should arise from a large deceleration field and a large bunching current in the extractor, as long as they match well spatiotemporally.

Compared with a conventional KL-RBWO, our proposed KL-RBWO [FIGURE 1(b)] includes two trapezoid waveguide cavities with an enlargement of radius of output waveguide to strengthen the deceleration field in the extractor. The beveled tube head is replaced by a rectangular tube head with an anode cavity to enhance the local electric field for suppression of the transverse velocity of the electron beam envelope.

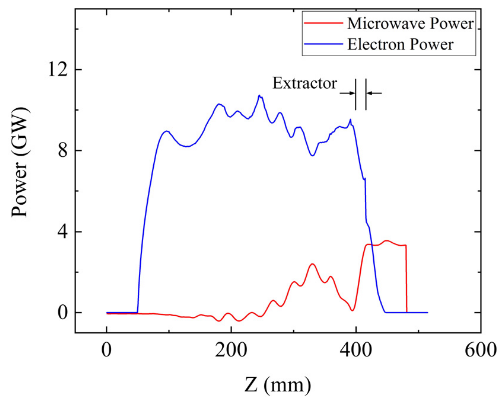

FIGURE 2. Distributions of electron and microwave power in the conventional KL-RBWO.

According to simulation results, with a diode voltage of 850 kV and a diode current of 14.7 kA, the improved device is capable of generating 5 GW of microwave power under a magnetic field of 0.32 T, with an efficiency of 40% (FIGURE 3).

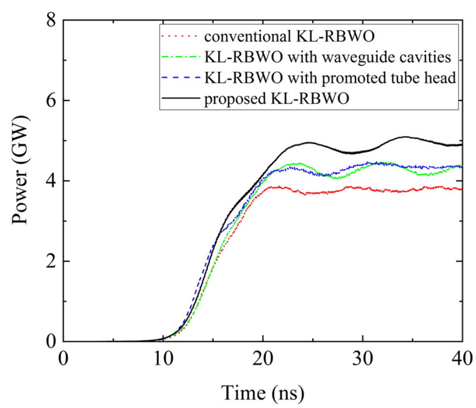

FIGURE 3. Time dependence of output microwave power obtained for the KL-RBWOs.

Additionally, microwaves with 4.3-GW powers can also be generated when the conventional KL-RBWO is provided with proper waveguide reflection, or when we replace the beveled tube head with the novel one, as shown in Fig. 3. Later, detailed analyses of the effects of the new structures introduced to the proposed KL-RBWO on device efficiency will be presented respectively in Sections III and IV.

III. BUNCHING PROMOTION VIA BEAM ENVELOPE CONFINEMENT

In KL-RBWO under low-magnetic-field-strength operation, forward IREBs propagate with large transverse velocities, forming periodical electron beam envelopes, which may cause non-uniform beam modulation and a marked decline in efficiency [23]. According to reference [24], the local electric field near the tube head can be used to suppress transverse electron velocity, in order to constrain the electrons to modulate more uniformly.

The suppression effect depends on the intensity of the local electrical field when electron motion closely matches the field well. The tube head used in the conventional KL-RBWO is beveled tube head (FIGURE 4(a)). A stronger field can be obtained in a rectangular tube head (FIGURE 4(b)), and we present rectangular tube head with anode cavity (FIGURE 4(c)) to further enhance the local radial electric field. As shown in FIGURE 5, additional anode cavity brings a larger field difference along electron transmission line between both sides of tube head, which strengthens the confinement of electron beams.

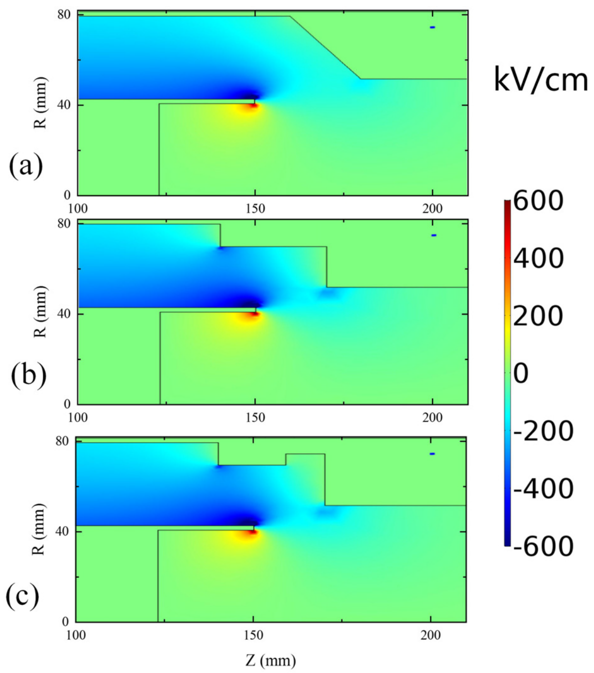

FIGURE 4. Contours of radial electric field E_r in the diodes with (a) beveled tube head, (b) rectangular tube head, and (c) rectangular tube head with anode cavity (promoted tube head).

FIGURE 6 shows the radial velocity distributions in the relativistic drift tubes employing different tube heads. It is obvious that the radial velocities of electron beam are suppressed to have a more uniform distribution in the drift tube with the promoted tube head. According to simulation results, the amplitudes of electron radial velocity averages 2.43×10^7 m/s in FIGURE 6(b) before electrons are collected, compared with that of 2.54×10^7 m/s in FIGURE 6(a).

By attaching the promoted tube head to the conventional KL-RBWO, a microwave of 4.3 GW (FIGURE 3) is generated in this device when the diode voltage is 850kV and the beam current is 14.7 kA. The device efficiency also increases

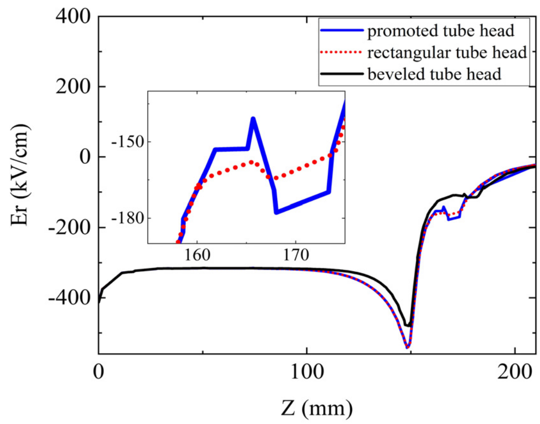

FIGURE 5. Radial electric field distributions at radius r = 46mm in the diodes with different tube heads.

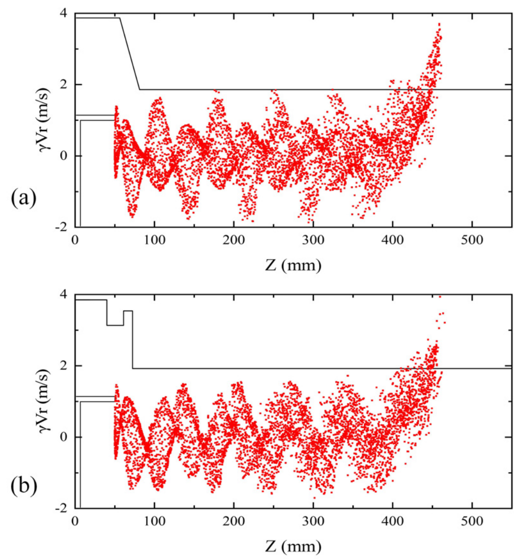

FIGURE 6. Distributions of radial electron velocities in relativistic drift tube with (a) beveled tube head and (b) promoted tube head.

from 30% to 35%. Also in the PIC simulation, the average transverse velocity of IREBs in the new device is suppressed to 4.08×10^7 m/s before oscillation begins, compared with that of 5.22×10^7 m/s in the conventional KL-RBWO. Therefore, IREBs are effectively confined transversely in the microwave device. Thanks to the effective suppression of the electron beam velocity, the peak fundamental harmonic current (FIGURE 7) grows to over 20 kA in the extractor, compared with 15 kA using a conventional beveled anode structure.

IV. FEEDBACK ENHANCEMENT VIA WAVEGUIDE REFLECTION

To provide additional feedback from the forward microwave in the output port, Two trapezoid cavities are built up and the radius of output waveguide is enlarged. As the resonant reflector reflects most of the backward-wave power, and the extractor provides partial feedback for the oscillator,

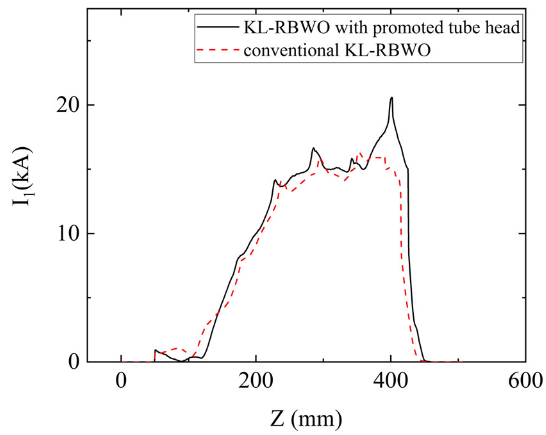

FIGURE 7. Fundamental harmonic current distributions in the KL-RBWOs using different tube heads.

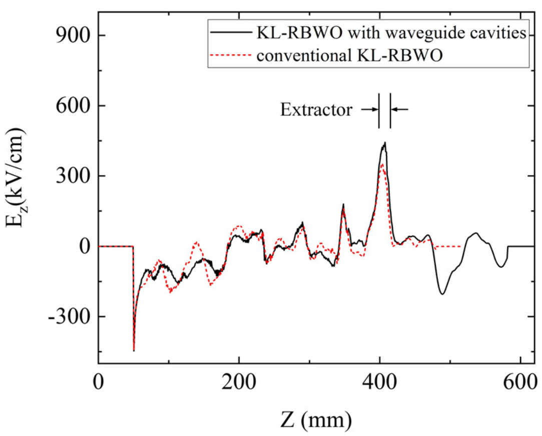

FIGURE 8. Axial electric field distributions for the KL-RBWOs with and without waveguide reflection.

the waveguide cavities (shown in FIGURE 1(b)) provide a distributional feedback to the KL-RBWO [19]–[21]. The conversion efficiency also increases from 30% to 35% with proper waveguide reflection provided to the extractor.

The enhancement of deceleration field is a kind of constructive resonance due to reflection. We calculate the the external Q-factors (Q_e) of TM_{01} mode at working frequency using CST Studio Suite. Here, Q_e describes the resonant characteristics and is defined as follows [25], [26]:

$$Q_e = \omega_0 \tau_g / 2 \tag{2}$$

where ω_0 is the working frequency, and τ_g is the group delay. According to simulation result, the inherent factor of the extractor increases from 18.01 to 19.51 due to the waveguide cavities.

The axial electric field distribution along the beam transmission line at radius r = 43 mm is shown in FIGURE 8. A clear increase in the peak deceleration field from 350 kV/cm to 430 kV/cm is observed in the extractor, which is responsible for the increase in power extraction from the modulated electrons.

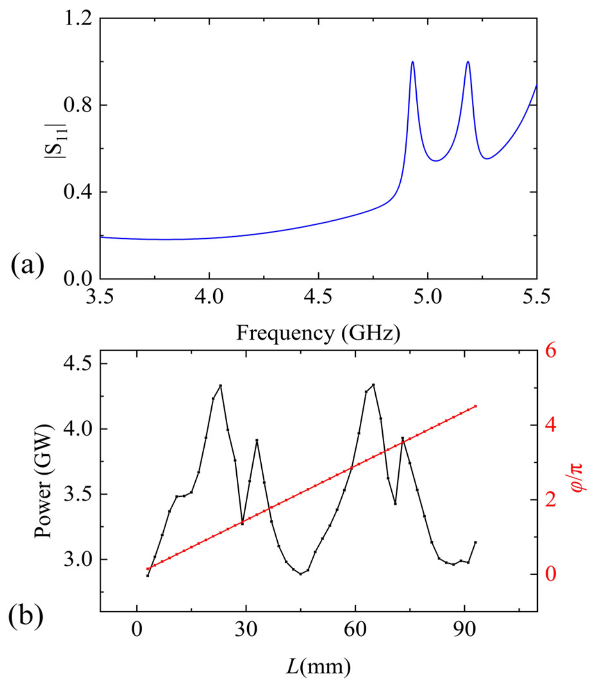

FIGURE 9. (a) Reflection characteristic of the waveguide cavities (b) Variation of feedback phase and output power with drifting length between extractor and waveguide reflector.

Reflection characteristic of the waveguide cavities is shown in FIGURE 9(a), it is observed that about 4.7% of forward microwave is reflected back to the extractor. For the TM_{01} mode microwave with a frequency of 4.35 GHz drifting in the drift section with a radius of 48 mm, the transverse wavenumber T_1 is 50.1 m^{-1} and the longitudinal wave number β is 76.10 m^{-1}. Here, the feedback phase is defined as $\varphi = 2\beta L$, where L is the drift length between the extractor and waveguide cavities. Clearly, the output power varies periodically with feedback phase, as illustrated in FIGURE 9(b).

V. CONCLUSION

An improved HPM device with low-magnetic-field operation is proposed based on a KL-RBWO. A remarkable enhancement in efficiency originates from the combination of two methods: a strong electric field that interacts with IREBs, owing to feedback enhancement; and a large bunching current due to the effective suppression of the transverse electron beam velocity. PIC simulations show that when the diode voltage is 850 kV and the beam current is 14.7 kA, about 5 GW of power is obtained at a microwave frequency of 4.35 GHz under a magnetic field of 0.32T, corresponding to a beam-wave interaction efficiency of 40%, compared with 30% in the conventional KL-RBWO. The theoretical and simulation results preliminarily verify its feasibility, and further studies are to follow.

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