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RESEARCH ARTICLE

Improved Power Capacity in a Low-Magnetic Field and High-Efficiency Transit-Time Oscillator by a Double-Gap Extractor

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ABSTRACT With an increase in the input power of a low-magnetic field and high-efficiency transit-time oscillator, the deceleration electric field in the single-gap extractor increases sharply to output a higher-power microwave, resulting in radio frequency breakdown on the surface of the single-gap extractor. Thus, a double-gap extractor with an operating mode of π mode is introduced to reduce the electric field in this type of device. The double-gap extractor can extract electron energy in two stages and lengthen the deceleration distance. Therefore, the electron beam loses less energy at the same deceleration distance in the double-gap extractor, and a weaker deceleration electric field is generated in the double-gap extractor. Additionally, the modulation electric field in the device with a double-gap extractor is stronger for modulating electrons and can further increase the fundamental harmonic current, resulting in higher extraction efficiency. In simulations, the output power is 6.3 GW and the maximum electric field strength is 1.06 MV/cm in the initial model with a single-gap extractor. When the single-gap extractor is replaced by the double-gap extractor, the output power increases to 6.5 GW with a conversion efficiency of 40% and a guiding magnetic field of 0.6 T. The maximum electric field strength decreases to 817 kV/cm, indicating an enhancement in the power capacity of the device.

INDEX TERMS High-power microwaves, transit-time oscillator, improved power capacity, deceleration electric field.

I. INTRODUCTION

High-power microwaves (HPMs) refer to electromagnetic waves with power exceeding 100 MW and wavelengths ranging from 1 mm to 1 m. They are typically generated through the interaction between intense relativistic electron beams (IREBs) and microwaves in vacuum tubes [1], [2], [3], [4], [5], [6], [7]. Driven by scientific and industrial applications, C-band HPM sources have been rapidly developed in recent years. Under a strong confining magnetic field, C-band high-power microwave sources have made significant progress in high-efficiency and high-power [8], [9], [10], [11], [12]. For example, an output microwave with a power of 4.4 GW was obtained in experiments with a guiding magnetic field of 2.2 T [8]. However, a strong guiding magnetic field increases the volume, weight, and energy consumption of an HPM system. Low-magnetic field HPM sources with small volumes, weights, and energy consumption have wide application prospects [13], [14], [15], [16].

According to the theory in Reference [17], the transverse kinetic energy of electrons is increased by strong traveling wave fields under a low magnetic field, which is detrimental to the high beam-wave conversion efficiency. Therefore, low-magnetic field and high-efficiency HPM sources usually extract the energy of electron beams by standing wave fields, which is regarded as transit radiation [6], [18], [19], [20], [21]. To achieve efficient beam-wave interaction under a low magnetic field, concentrated energy extraction of electrons is usually adopted in transit radiation devices. Therefore, the deceleration electric field is very high,

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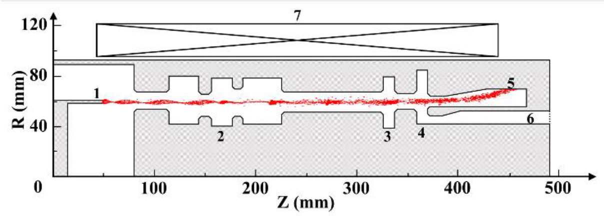

FIGURE 1. Structure of the low-magnetic field and high-efficiency TTO: 1 the annular cathode, 2 the first buncher, 3 the second buncher, 4 the single-gap extractor, 5 the electron collector, 6 the output waveguide, 7 the guiding magnetic field.

and the power capacity of the transit radiation devices is usually low. An output microwave with higher power leads to a stronger deceleration electric field, which is prone to radio frequency (RF) breakdown.

In this paper, we describe our efforts to improve the power capacity in a C-band transit-time oscillator (TTO), resulting in an output microwave power of 6.5 GW, a conversion efficiency of 40%, a low guiding magnetic field of 0.6 T, and maximum electric field strength of 817 kV/cm. The remainder of this paper is organized as follows. In Section II, we designed a higher-power TTO with a single-gap extractor based on previous research and found that the maximum electric field strength was very high. Therefore, in Section III, we attempt to reduce the deceleration electric field and improve power capacity by adopting a double-gap extractor. Finally, the conclusions are summarized in Section IV.

II. LOW-MAGNETIC FIELD AND HIGH-EFFICIENCY TTO WITH A SINGLE-GAP EXTRACTOR

In reference [21], we simulated and experimentally studied a low-magnetic field and high-efficiency transit-time oscillator with two bunchers. In this device, a second buncher is introduced to further modulate the electron beam and improve the conversion efficiency under a low guiding magnetic field. When the diode voltage, diode current, and guiding magnetic field were 600 kV, 15 kA, and 0.5 T respectively, a microwave with a power of 3.65 GW and a frequency of 4.31 GHz was obtained. The conversion efficiency was over 40%. To increase the output power of this device, we design a structure similar to that in reference [21] (as demonstrated in FIGURE 1). To bunch the electron beam and obtain high beam-wave conversion efficiency in a higher-power device, the radius of the annular beam is increased to 60 mm for reducing the space charge force between electrons, resulting in a small beam ripple (as shown in FIGURE 1). As shown in FIGURE 2, a microwave with a power of 6.3 GW is obtained in the simulations and the efficiency is 38.8% when the diode voltage, diode current (I_0), and guiding magnetic field are 800 kV, 20.3 kA, and 0.6 T respectively.

FIGURE 3 shows the electron power flows in devices with and without a second buncher. The electron power flow refers to the axial variation of the electron power, which can indicate the beam-wave interaction. It can be seen that the electron power decreases and then increases to the original value in the

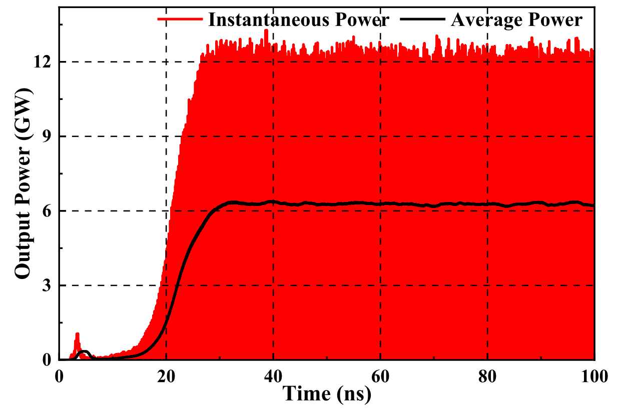

FIGURE 2. Variation of the output microwave power over time in the TTO with a single-gap extractor.

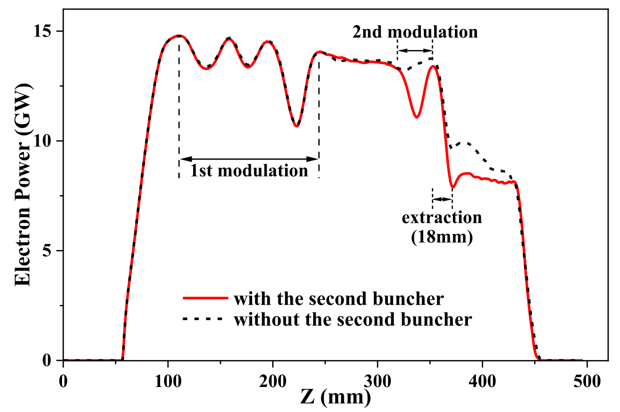

FIGURE 3. Electron power axial distribution for the TTO with and without the second buncher.

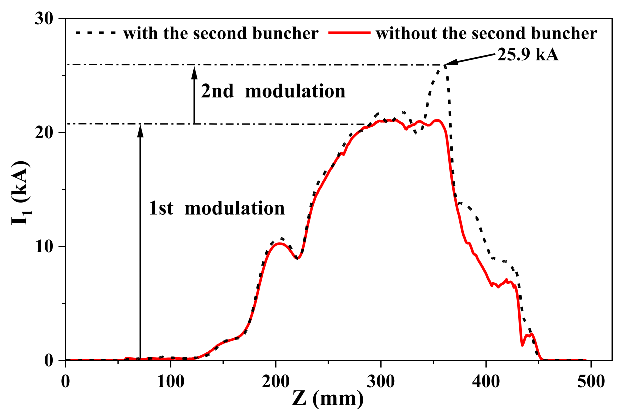

FIGURE 4. Fundamental harmonic current axial distribution for the TTO with and without the second buncher.

first buncher, indicating that the electron beam is modulated for the first time. In the second buncher, it decreases and increases with the same rule, marking the second modulation of the electron beam. Finally, in the single-gap extractor, the electron power drops sharply because of the intense beam-wave interaction, and the deceleration distance of the electrons is 18 mm.

The axial distributions of the fundamental harmonic current (I_1) with and without the second buncher are shown in FIGURE 4. The fundamental harmonic current increases

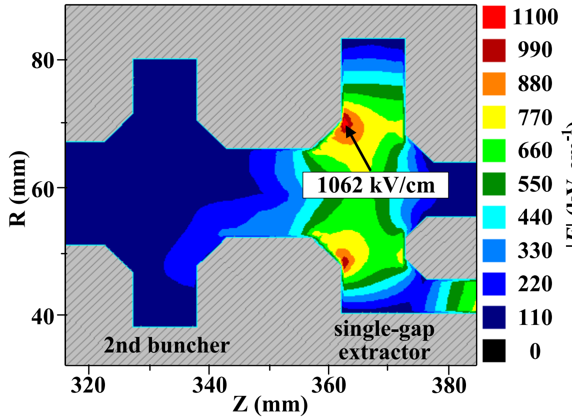

FIGURE 5. The electric field strength distribution in the single-gap extractor of the high-power TTO.

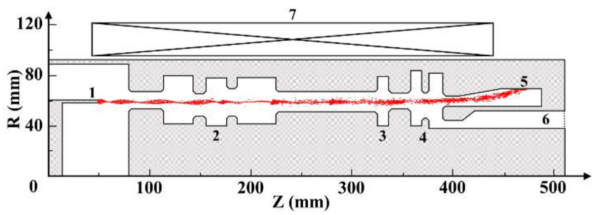

FIGURE 6. Structure of the TTO with a double-gap extractor: 1 the annular cathode, 2 the first buncher, 3 the second buncher, 4 the double-gap extractor, 5 the electron collector, 6 the output waveguide, 7 the guiding magnetic field.

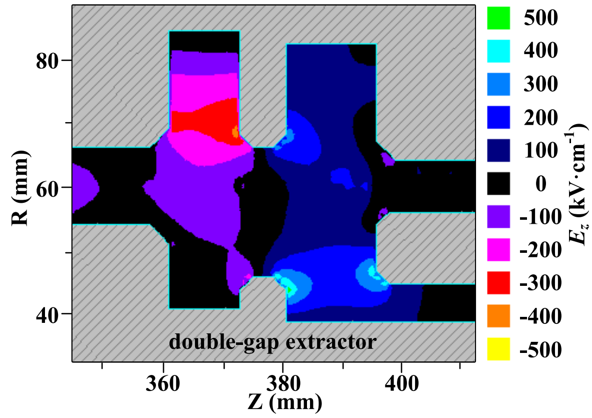

FIGURE 7. Axial electric field distribution in the double-gap extractor.

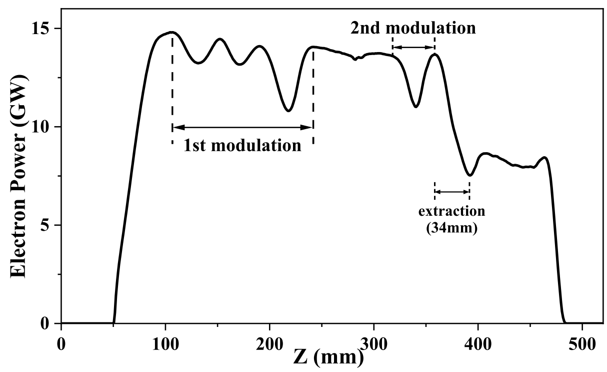

FIGURE 8. Electron power axial distribution for the TTO with a double-gap extractor.

to 20.7 kA after the first modulation, corresponding to the first modulation in FIGURE 3. After introducing the second buncher, the fundamental harmonic current increases for the second time and reaches a maximum of 25.9 kA in front of the single-gap extractor, which is related to the second modulation in FIGURE 3. The modulation depth (I_1/I_0) increases by 25.6% after the second modulation. Combining the results in FIGURE 3 and FIGURE 4, the second buncher modulates the electron beam for the second time and further increases the electron modulation depth, contributing to a higher beam-wave conversion efficiency at a higher power level and a low magnetic field.

Deduced from FIGURE 3, the sharp energy extraction of the electron beam in the single-gap extractor is the main source of the 6.3-GW output microwave. To output a microwave with such high power, a strong standing wave field is established in the narrow single-gap extractor, with a Q factor of 15.9 at the working frequency. Therefore, the maximum field strength on the extractor surface is as high as 1.06 MV/cm (FIGURE 5), exceeding the breakdown threshold in vacuum (1 MV/cm) [22]. The necessity of reducing the surface electric field strength in the device is clear, particularly in the extractor.

III. HIGH POWER CAPACITY TTO WITH A DOUBLE-GAP EXTRACTOR

To reduce the maximum field strength on the surface of the extractor, a double-gap extractor is adopted to replace the single-gap extractor in the initial structure. Based on the trial-and-revision procedure, the device is optimized for high efficiency and low deceleration electric field, and the final structure is shown in FIGURE 6. The Q factor of the double-gap extractor is 14.2 at the working frequency of 4.32 GHz, slightly lower than that of the single-gap extractor, so the double-gap extractor can output more microwaves with lower energy storage. The operating mode of the double-gap extractor is π mode (as shown in FIGURE 7) so that the concentrated energy extraction of the single-gap extractor becomes a two-stage energy extraction of the double-gap extractor, and the deceleration distance of the electrons increases. In addition, the fundamental harmonic current of TTO with a double-gap extractor is greater, leading to an increase in conversion efficiency. According to reference [6], the microwave power generated in the extractor can be calculated by:

$$P = \frac{1}{T}\int_0^T [\int_0^d I1(z,t)\cdot Ez(z,t)dz]dt \quad (1)$$

where T is the period of the RF electric field and d is the width of the extractor. If the power of the output microwave remains unchanged, increasing d and I_1 can effectively reduce the deceleration electric field, thereby reducing the maximum field strength on the extractor surface.

FIGURE 8 shows the electron power flow in the TTO with a double-gap extractor, which is similar to that in FIGURE 3.

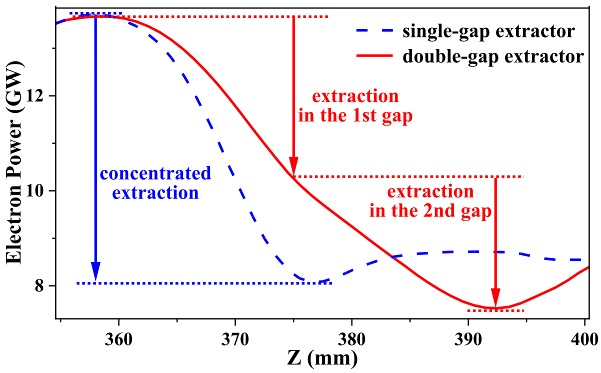

FIGURE 9. Electron power axial distribution for the single-gap extractor and the double-gap extractor.

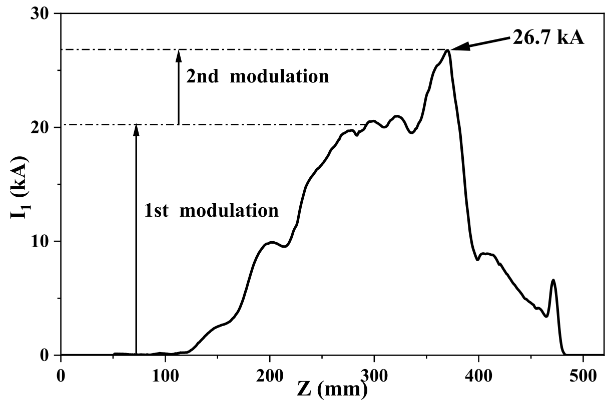

FIGURE 10. Fundamental harmonic current axial distribution for the TTO with a double-gap extractor.

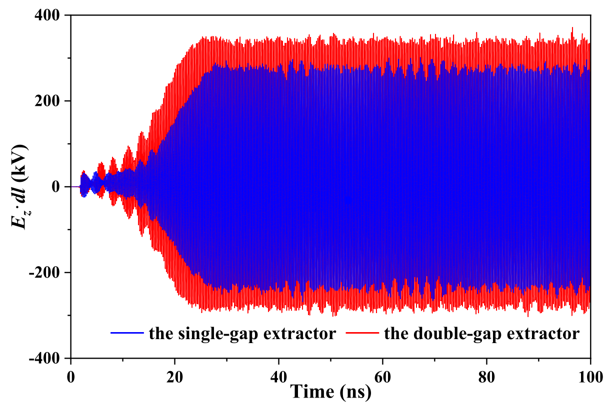

FIGURE 11. The modulation voltage in the second buncher.

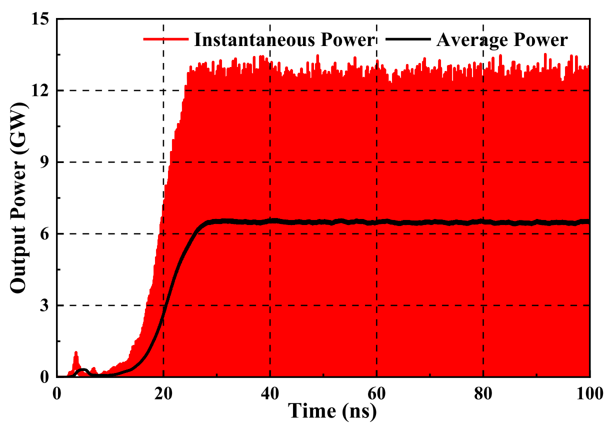

FIGURE 12. Variation of the output microwave power over time in the TTO with a double-gap extractor.

It illustrates two modulations of the electron beam in the first buncher and second buncher, thereby achieving deep bunching of the electrons and efficient beam-wave interaction. Owing to the two-stage energy extraction of the double-gap extractor, the deceleration distance of the electrons increases to 34 mm, which is almost twice that of the single-gap extractor in FIGURE 3. The electron beam power decreases by almost as much as that in the single-gap extractor. FIGURE 9 compares the electron power flows of the single-gap extractor and the double-gap extractor in the devices. The electron energy extracted by each gap of the double-gap extractor is less than that extracted by the single-gap extractor, and the deceleration electric field of each gap is smaller than that of the single-gap extractor. Therefore, the double-gap extractor can output almost the same microwave power with a smaller deceleration electric field.

As shown in FIGURE 10, the fundamental harmonic current increases twice and reaches a maximum of 26.7 kA in front of the extractor, which indicates that the electron beam is modulated twice. The change rule of the fundamental harmonic current resembles that shown in FIGURE 4, but the maximum value is larger. Compared with the single-gap extractor, the second buncher in the device with a double-gap extractor has a greater modulation voltage (FIGURE 11). Therefore, the electron beam is modulated more strongly by the RF field, and the maximum fundamental harmonic current is larger, leading to efficient extraction of electron energy and an improvement in power capacity.

Therefore, the deceleration electric field in the double-gap extractor can be effectively reduced by increasing the electronic deceleration distance and fundamental harmonic current. Compared with the single-gap extractor with an output microwave of 6.3 GW (FIGURE 2) and a maximum surface field strength of 1.06 MV/cm (FIGURE 6), the double-gap extractor can yield a power of 6.5-GW (FIGURE 12) with a maximum electric field strength of only 817 kV/cm (FIGURE 13), significantly improving the power capacity in the low-magnetic field and high-efficiency TTO.

The output power, conversion efficiency, and maximum electric field strength of the TTO with a single-gap extractor and the TTO with a double-gap extractor are compared in FIGURE 14. Within the voltage range of 545-655 kV, these two devices can output microwaves with power greater than 5 GW, and the conversion efficiencies are higher than 35%. For TTO with a double-gap extractor, the conversion efficiency gradually declines when the voltage is higher or lower than the optimal value of 800 kV. As the double-gap extractor structure is more complex, a higher or lower voltage results in a mismatch between the fundamental harmonic current and deceleration electric field, which is unfavorable for efficient beam-wave interaction. For TTO with a

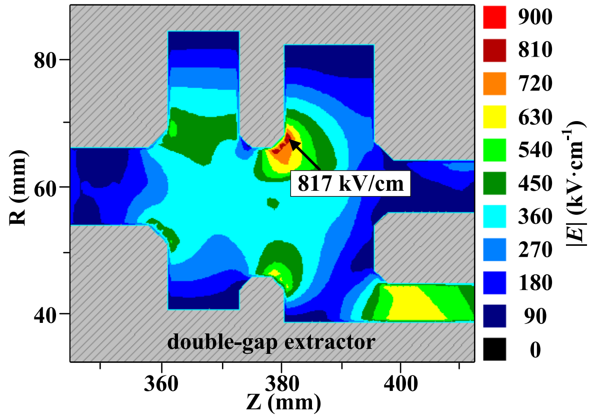

FIGURE 13. The electric field strength distribution in the double-gap extractor of the high-power TTO.

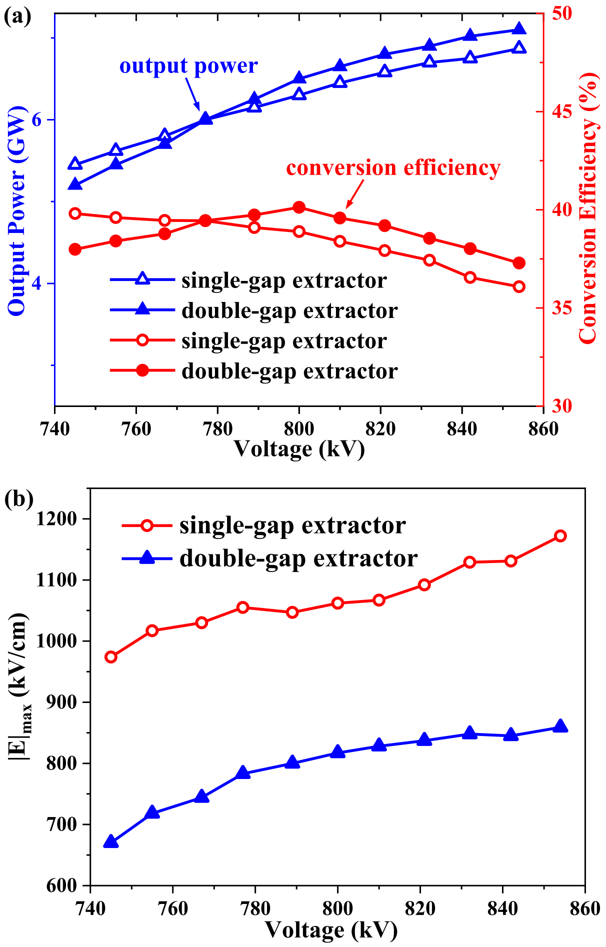

FIGURE 14. Comparison of output power and conversion efficiency (a) and maximum electric field strength (b) for the TTO with a single-gap extractor and the TTO with a double-gap extractor.

single-gap extractor, the conversion efficiency decreases with an increase in voltage because a single-gap extractor with a simple structure has a poor ability to extract electron energy. A higher voltage is not conducive to the efficient extraction of electron energy. In the entire voltage range, the maximum field strength of the double-gap extractor is always smaller than that of the single-gap extractor, indicating a higher power capacity of the double-gap extractor. In particular, when the voltage is 545 kV, the output power of the TTO with a double-gap extractor is greater than 5 GW, and the maximum electric field strength is only 670 kV/cm, which enables long-pulse operation [9], [12].

IV. CONCLUSION

A double-gap extractor is adopted to enhance the power capacity of the TTO with a low magnetic field, high output power, and high conversion efficiency. The double-gap extractor has a longer deceleration distance for the electron beam. This implies that a weaker deceleration electric field can extract the same electron energy. In addition, the electron beam is bunched by a stronger microwave and the fundamental harmonic current is greater. Thus, the conversion efficiency and power capacity can be improved. In the simulations, when an 800-kV, 20.3-kA electron beam is constrained by a magnetic field of 0.6 T, the output microwave power is 6.5 GW with a beam-wave conversion efficiency of 40%. The maximum electric field strength on the device surface is 817 kV/cm. Compared with the device with a single-gap extractor, the device with a double-gap extractor can output microwaves with a higher power while having a lower maximum field strength, which is favorable for obtaining longer pulse width and higher repetition frequency in further HPM experiments. The results indicate a significant improvement in the power capacity of a C-band low-magnetic field, high-efficiency, and high-power TTO.

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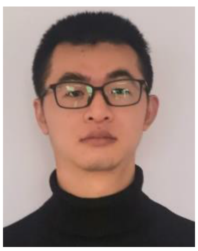

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