

Article

A Solution for Backward Wave Oscillation in High-Order Mode Sheet Beam Slow-Wave Structures

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Abstract

This paper proposes a novel solution to suppress backward wave oscillation (BWO) in high-order mode (HOM) sheet beam (SB) slow-wave structures (SWSs) and designs an isolator between cavities based on a Bragg resonator. This method can cut-off the backward wave signal path without interrupting the operating signal path, thereby eliminating BWO while maintaining high circuit gain. Simulation results show that the S₂₁ parameter of the isolator is less than -20 dB from 175 GHz to 228 GHz. To verify the method's performance, particle-in-cell (PIC) simulation was conducted based on a HOM SB SWS—a T-slot coupled-cavity (TSCC) SWS. Results indicate that this method can effectively suppress BWO and shows significant improvement in gain and output power compared to traditional methods such as sever or lossy loading. Under operating conditions of 34.4 kV and 0.35 A, the circuit achieves a maximum output power of 527 W at 216 GHz, a maximum gain of 36.39 dB at 214.4 GHz, and a bandwidth of 3 GHz where the output power exceeds 300 W.

Keywords: terahertz TWTs; sheet beam; slow-wave structure; backward wave oscillation; high-order mode

1. Introduction

The terahertz band, characterized by high frequency, large bandwidth, high penetration, and anti-interference capabilities, holds significant research value in fields such as high-speed wireless communication, electronic countermeasures, and medical detection [1,2]. The broad application prospects of terahertz technology have driven the development of terahertz radiation sources. The traveling-wave tube (TWT), as a widely used vacuum electron device, is known for its high power, high bandwidth, and high efficiency [3–8], and is considered a highly promising terahertz radiation source [9–11].

However, as the operating frequency increases, the interaction region dimensions of traditional TWT SWSs shrink drastically, leading to significantly increased fabrication difficulty. Simultaneously, limited by the narrow beam tunnel, the beam current is limited, which severely constrains output power enhancement. To break through these bottlenecks, the SB SWS has emerged. Compared to circular beam structures, the SB offers three significant advantages: The wide dimension of the SB can be expanded, allowing it to carry a larger current, thus achieving higher output power. In addition, SWSs suitable for SB operation are mostly planar two-dimensional structures, facilitating fabrication [12,13].

Currently, in the design of G-band SB TWTs, there is an inherent design conflict between increasing power capacity and maintaining structural stability. Increasing the beam tunnel size, while enhancing current transmission capability, inevitably causes the



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fundamental mode's cut-off frequency to decrease, making the operating mode a high-order mode and introducing a significant risk of BWO, which has become a key issue restricting the development of high-performance TWTs. For example, the non-quasi-2D SWS proposed by UESTC in 2024 [14] and double-elliptical-groove waveguide SWS proposed by BVERI in 2023 [15] and staggered double vane structure in 2025 [7] have electron beam tunnel sizes of $0.72 \times 0.15 \text{ mm}^2$, $0.84 \times 0.15 \text{ mm}^2$ and $0.88 \times 0.13 \text{ mm}^2$, respectively. Other SB SWSs operating in the G-band, such as the chevron-shape double-staggered grating waveguide SWS [16], staggered grating SWS [17], sine waveguide [18], slots-loaded coupled-cavity [19], and double flat-roofed sine waveguide SWS [20] have electron beam tunnel dimensions close to this value, or even smaller. The HOM SB SWS studied in this paper—the TSCC SWS—increases the electron beam tunnel size to $1.04 \times 0.25 \text{ mm}$, and the major and minor axis dimensions of the elliptical electron beam are 0.84 mm and 0.15 mm. This results in the BWO issue of the TSCC.

Traditional methods such as lossy loading and severs suppress reflection oscillation and BWO by interrupting the operating signal path. However, the multiple interruptions to the interaction path result in a significant reduction in output power. To solve this issue, a novel isolation method is proposed in this paper, and a new type of isolator is designed to suppress backward wave oscillation. The function of the isolator is similar to sever. The S21 parameter of the isolator is less than -20 dB from 175 GHz to 228 GHz and can effectively cut-off the backward wave signal path. The isolation method with the isolator can suppress the BWO without affecting the operating signal path. As the operating signal path is not cut-off and is without energy loss, the circuit is capable of achieving high gain and high output power with a shorter length. PIC simulation results show that the circuit enables the achievement of an output power of 500 W or a gain of over 30 dB under the conditions of 50 total periods and a circuit length of no more than 50 mm, with no oscillation observed.

2. Physical Origin of Backward Wave Oscillation

Figure 1 shows a schematic diagram of TSCC. This structure is derived from a folded waveguide. Due to its dispersion characteristics being similar to those of a coupled cavity, as well as its T-shaped slot cross-section, this structure is referred to as the T-slot coupled-cavity. For example, the electron beam tunnel size of the TSCC studied in this paper is $0.25 \text{ mm} \times 1.04 \text{ mm}$, which offers a significant advantage compared to other slow-wave structures in the G band. However, the larger electron beam tunnel size also prevents it from completely cutting off electromagnetic waves with frequencies below the operating mode. This manifests in the dispersion curve as the oscillation mode appearing below the operating mode.

Figure 2 shows dispersion curve of TSCC. In the dispersion diagram, the beam voltage line (green line) intersects both the operating mode and the oscillation mode, confirming through a physical mechanism the inevitability of BWO in this structure under practical operating conditions. This phenomenon reveals that effectively suppressing BWO has become an unavoidable core challenge in the design of HOM SB SWSs when pursuing high output power.

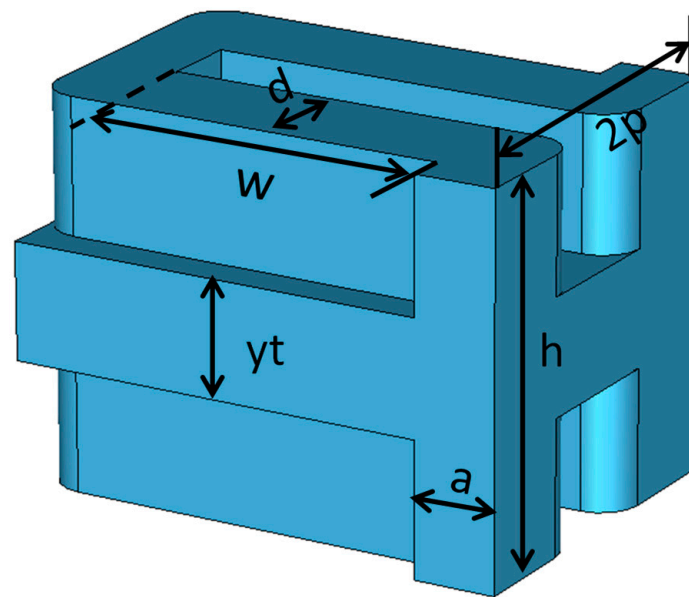


Figure 1. Schematic diagram of the TSCC.

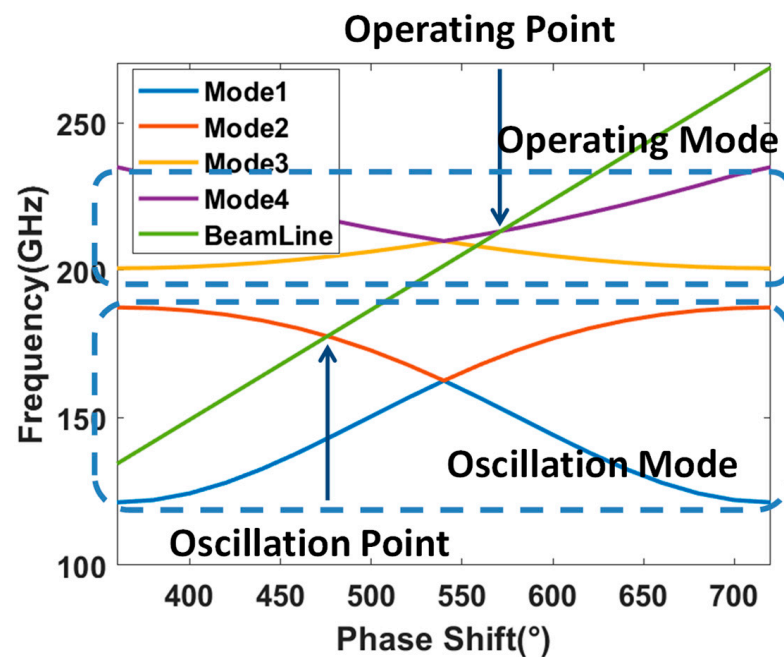


Figure 2. Dispersion curve of TSCC.

3. Proposed Isolation Method and Isolator Design

Figure 3 shows a comparison between the isolation method proposed in this paper and the traditional method. It can be seen that the traditional method employs coupling structures at both ends of the isolator, aiming to extract the operating signal transmitted in the waveguide and re-excite it in the next circuit section to prevent reflective oscillation. However, for the backward wave propagating within the beam tunnel, these two coupling structures are ineffective; instead, they cause a significant waste of operating signal energy. Therefore, based on the traditional method, this paper removes the coupling structures and connects the two circuit sections isolated by a waveguide channel. Because the operating signal and the beam are not synchronized within the isolator, a certain phase difference is introduced, which disrupts the phase condition for reflective oscillation, thus

enabling this structure to also provide the reflective oscillation suppression function of traditional structures.

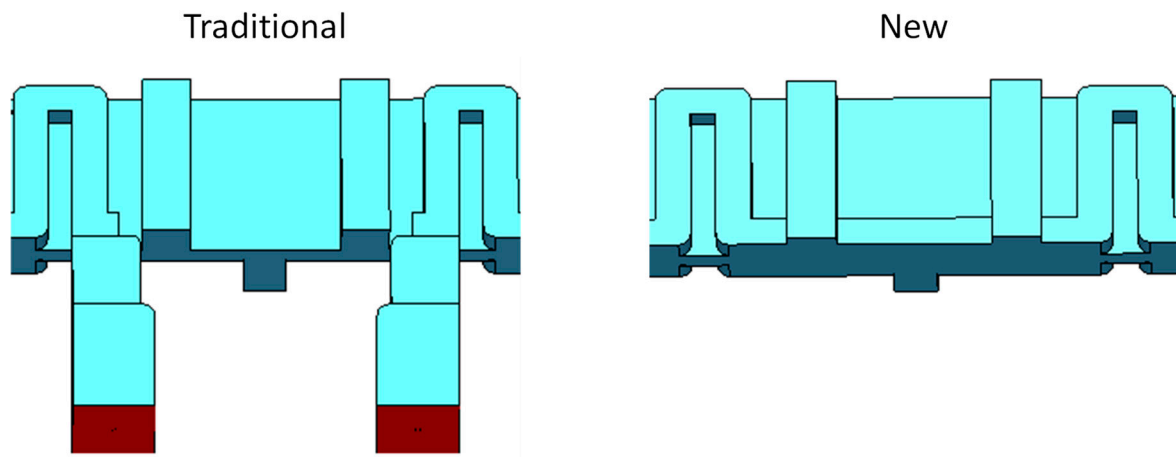


Figure 3. Schematic diagrams of the traditional isolation method and the proposed isolation method.

Figure 4 shows the structural schematic of the isolator. This isolator is modified from a Bragg resonator and consists of a beam tunnel and three staggered rectangular slots. The two rectangular slots above the beam tunnel are symmetrical about the isolator. The slot below the beam tunnel is positioned at the center of the isolator. Ports 1 and 2 are the electron beam input/output ports.

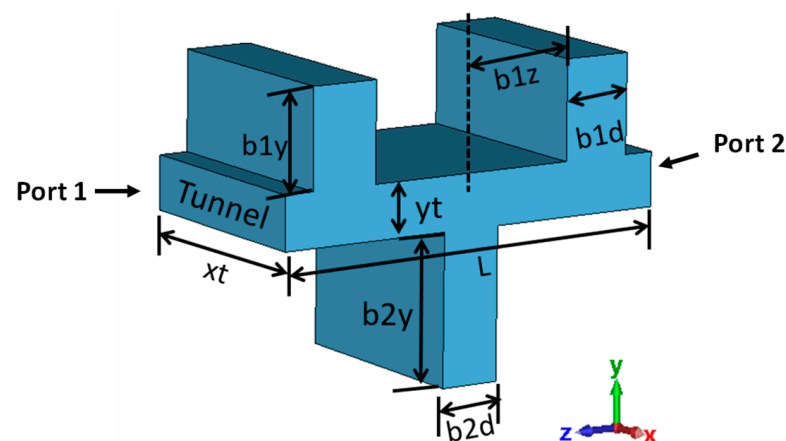


Figure 4. Schematic diagram of the isolator.

Figure 5 shows the S-parameters of the isolator at these dimensions. The S21 parameter of this isolator is less than -20 dB from 175 GHz to 228 GHz. For the frequencies corresponding to the operating point and the oscillation point, the S21 parameter is less than -30 dB, effectively isolating the backward wave while preventing the operating signal energy from leaking into the isolator. The isolator dimensions shown in Table 1 were obtained.

Figure 6 depicts the electric field distribution of the isolator at the oscillation point when the signal is input from Port 1 (the right port), which verifies the directional isolation capability. When the isolator operates at the oscillation point, the electric field intensity near Port 1 is much higher than that near the other port, indicating the effective cut-off of oscillation signals. This electric field distribution is consistent with its S21 parameter.

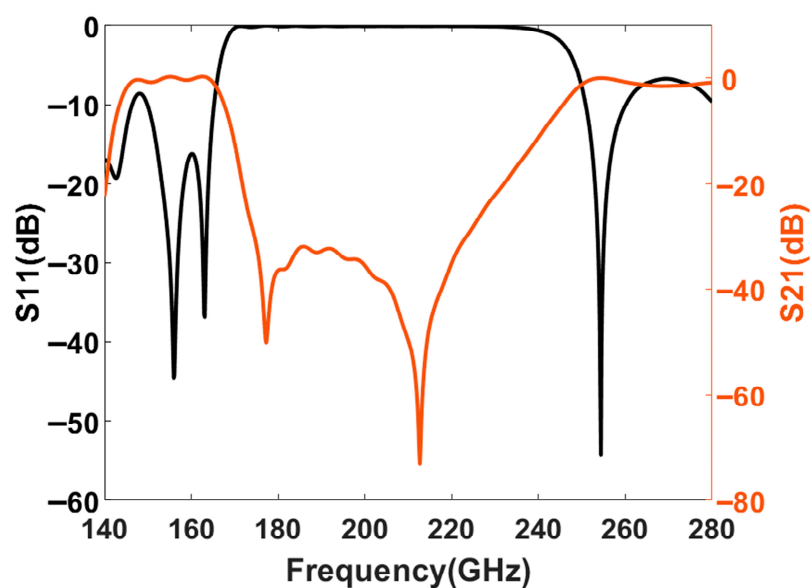


Figure 5. S-parameters of the isolator.

Table 1. Parameters of the isolator.

Parameters	Value (mm)
xt	1.04
yt	0.25
b1z	0.5
b1d	0.32
b1y	0.46
b2y	0.7
b2d	0.28
L	1.92

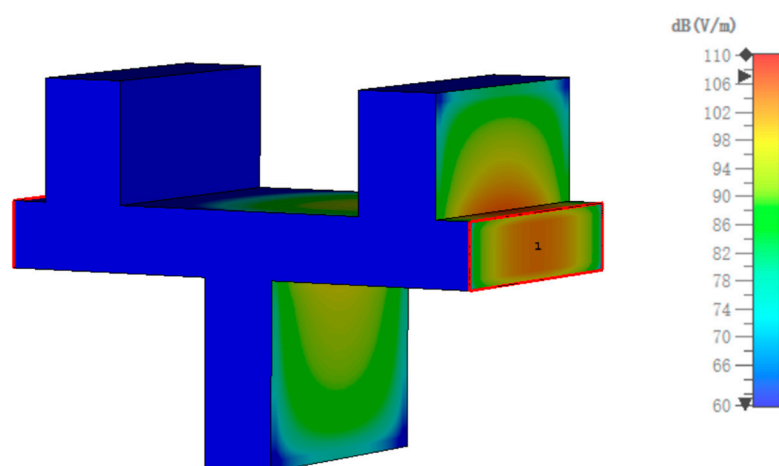


Figure 6. Electric field distribution of the isolator at the oscillation point.

Table 1 presents the ideal dimensions of the isolator. However, investigating the fabrication tolerances of the isolator is of great significance for practical manufacturing. Figure 7 shows the effect of changing the depth of the two upper rectangular slots on the S21 parameter. Variations in this parameter primarily impact the isolator's high-frequency performance. Specifically, excessive deviation from the ideal value will cause leakage of operating signals into the isolator, resulting in a reduction in output power, while having a limited impact on the suppression of BWO.

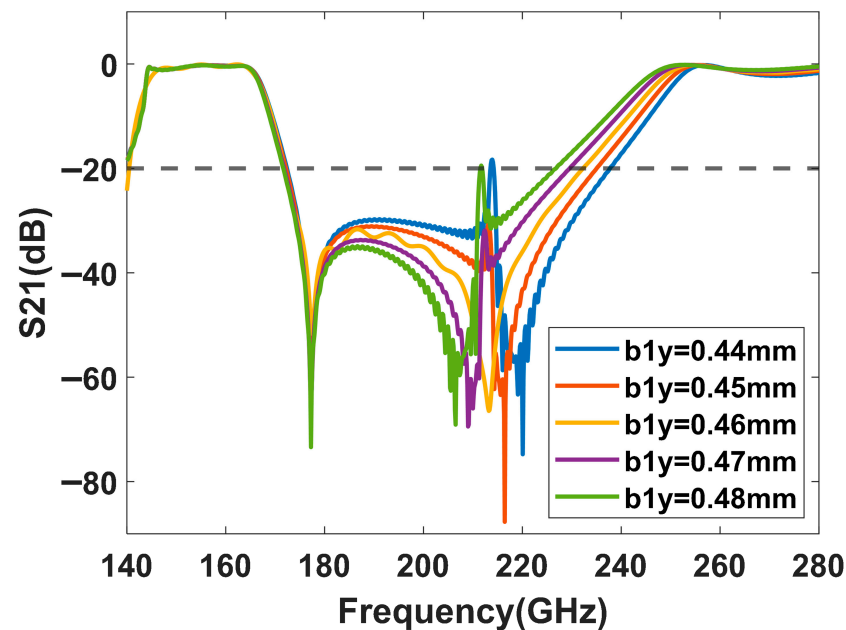


Figure 7. Variation in S21 results with different depths of the two upper rectangular slots.

Figure 8 shows the effect of changing the depth of the lower rectangular slot on the S21 parameter. Variations in this parameter affect both the high-frequency and low-frequency performance of the isolator. Specifically, when $b2y$ is less than 0.65 mm, the S21 parameter at the oscillation point will exceed -20 dB, which reduces the isolator's suppression effect on BWO.

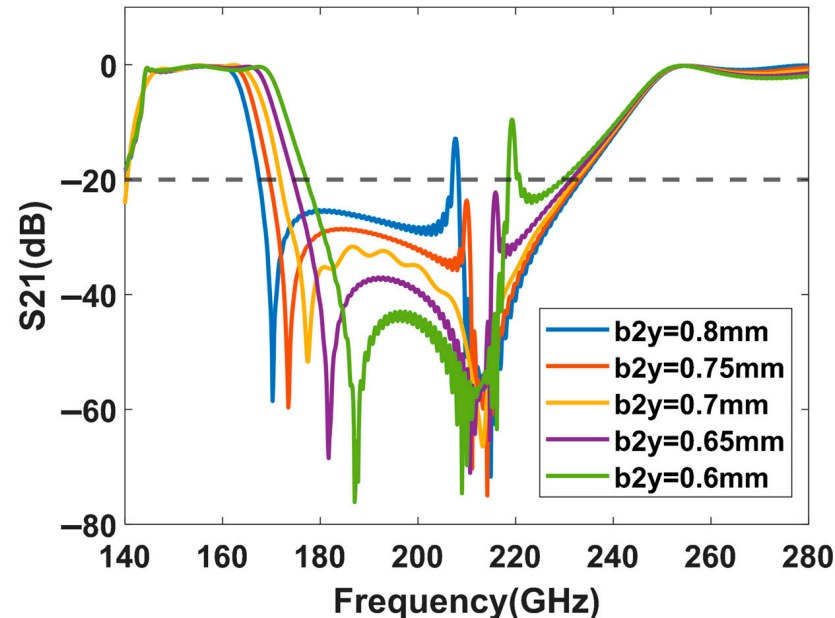


Figure 8. Variation in S21 results with different depths of the lower rectangular slot.

4. Complete Circuit Design and PIC Simulation Results

To achieve stable power amplification, the interaction circuits usually adopt a multi-section layout, with severs/attenuators placed between adjacent sections to prevent oscillations. To study the backward wave oscillation characteristics of TSCC, a single-section circuit model is designed, as shown in Figure 9. This model consists of 50 periods of TSCC. In this model, the input signal has a frequency of 216 GHz and a power of 3.5 W; the

beam current is 0.35 A and voltage is 34.4 kV; the major and minor axis dimensions of the elliptical electron beam are 0.84 mm and 0.15 mm respectively; and the background conductivity is set to 2.2×10^7 S/m. Ports 1 and 2 are the signal input/output ports, while Ports 3 and 4 are the electron beam input/output ports.

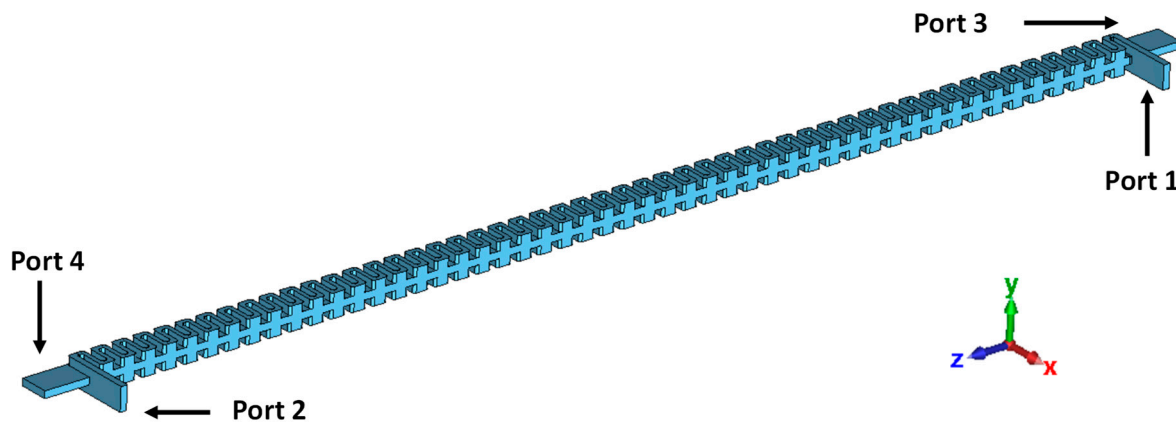


Figure 9. Single-section circuit model.

Figure 10 shows the PIC simulation results for the circuit model shown in Figure 9. (a) shows the output signal amplitude diagram for each port, and (b) shows the spectrum of the output signals after they stabilize. It can be seen that after the simulation proceeds to about 0.5 ns, the output signal power at Port 2 increases rapidly and then gradually stabilizes. However, at about 3 ns, the output power of Port 2 fluctuates, then drops quickly. Simultaneously, the output power of Ports 3 and 4 rises rapidly and then remains stable. This indicates the occurrence of backward wave oscillation, and the output signals of Ports 3 and 4 are the oscillation signals.

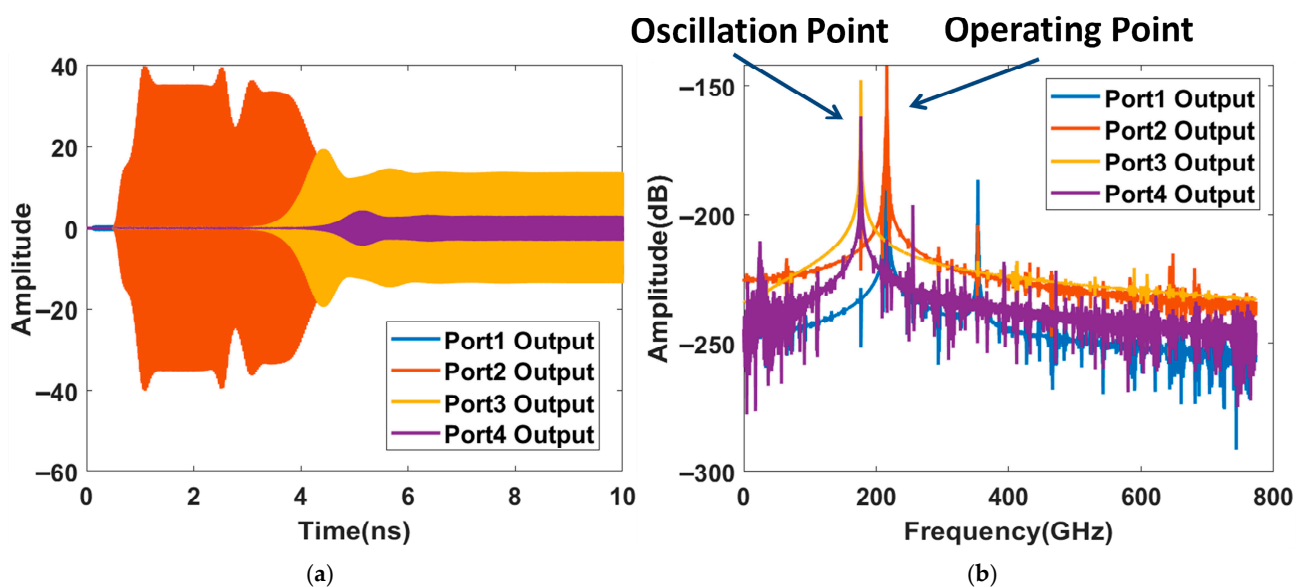


Figure 10. PIC simulation results for the single-section circuit. (a) Variation curve of output signal amplitude over time for the four ports. (b) Spectrum of output signals for the four ports.

Since the beam line intersects with both the operating mode and the oscillation mode simultaneously, these two modes can interact with the electron beam. However, the input signal frequency lies within the operating mode band, so only the operating mode interacts with the electron beam initially. When the length of a single circuit segment exceeds the

critical value, a signal at the oscillation mode frequency is excited in the circuit, leading to simultaneous interaction between both the oscillation mode and the operating mode with the electron beam, which results in the onset of BWO. Meanwhile, due to mode competition, the signal intensity of the operating mode is significantly attenuated. The oscillation mode is induced by the excessively large electron beam tunnel, which results in the observation of oscillation signals at Ports 3 and 4.

The spectrum diagram also clearly shows that the output signals of Ports 1 and 2 have only one peak at the designed operating frequency. The frequency in the output signals of Ports 3 and 4 correspond to that at the oscillation point. This confirms that the BWO problem indeed exists in this SWS.

Figure 11 shows the complete circuit model with isolators and couplers. To prevent BWO, the circuit is divided into four sections by isolators. The number of periods for each circuit section is 14, 13, 12, and 11 respectively, with the total number of periods being 50. Input and output coupling are also added to improve the circuit's transmission performance. In this model, the input signal has a frequency of 216 GHz and a power of 2.7 W; the beam current is 0.35 A and voltage is 34.4 kV; and the major and minor axis dimensions of the elliptical electron beam are 0.84 mm and 0.15 mm.

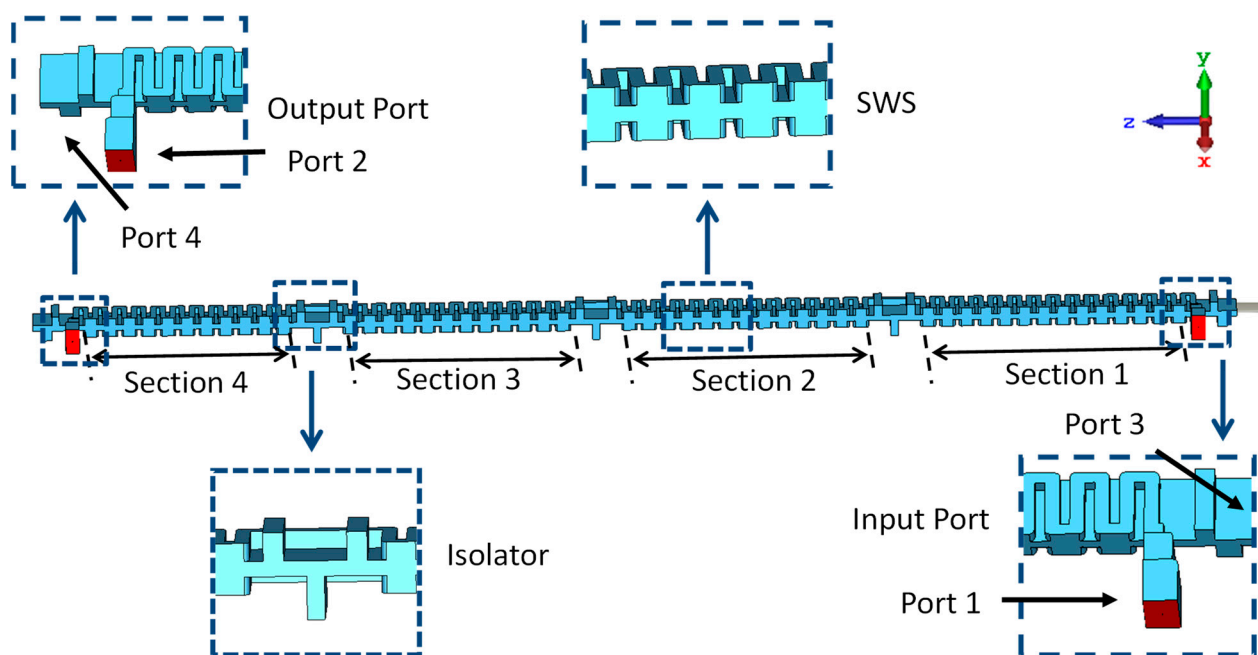


Figure 11. Complete circuit model with isolators and couplers.

Figure 12 shows the power flow distribution of the operating signal in the circuit from the PIC simulation. It can be observed that the isolator does not cut-off the power flow of the operating signal. The power flow of the operating signal transmits through the waveguide channel and gets amplified with increasing distance, as if the circuit were not interrupted.

Figure 13 shows the power flow curve of the operating signal at the center of the edge waveguide channel of the isolator from the PIC simulation to better demonstrate the effectiveness of the proposed method. It can be observed that the power flow basically increases with distance, but at specific positions the power flow remains essentially unchanged. These positions are where the isolators are located. Most of the operating signal power flows into the next circuit section through the waveguide channels at the edge of the isolator, with only a small amount leaking into the isolator itself. Furthermore, within the isolator, the operating signal in the rectangular waveguide and the electron beam in the

electron beam tunnel have different phase velocities, causing them to lose the synchronous state maintained in the SWS and generating a phase difference. This requires the electron beam and the operating signal to re-establish synchronization at the beginning of each circuit section. These two factors cause the power flow curve shown in Figure 13 to drop slightly after passing through an isolator.

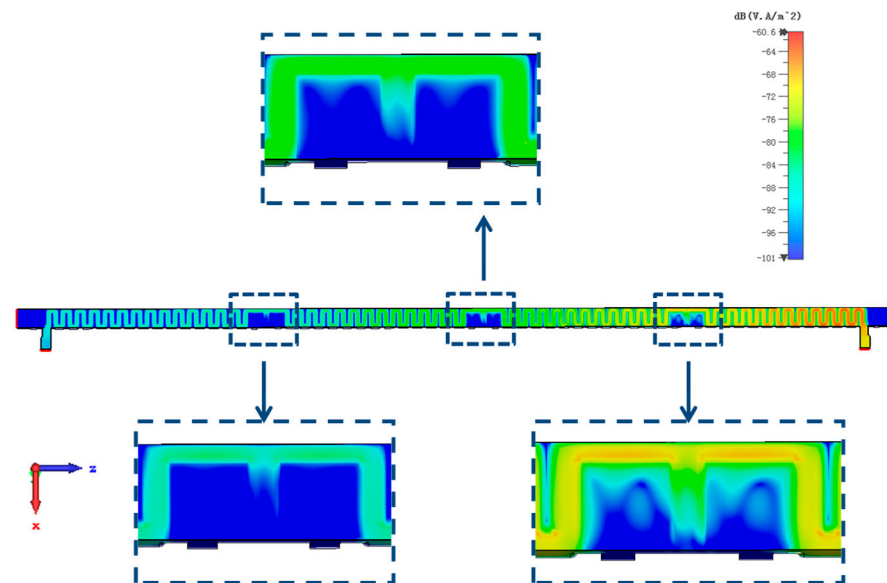


Figure 12. Power flow distribution of the operating signal in the circuit from the PIC simulation.

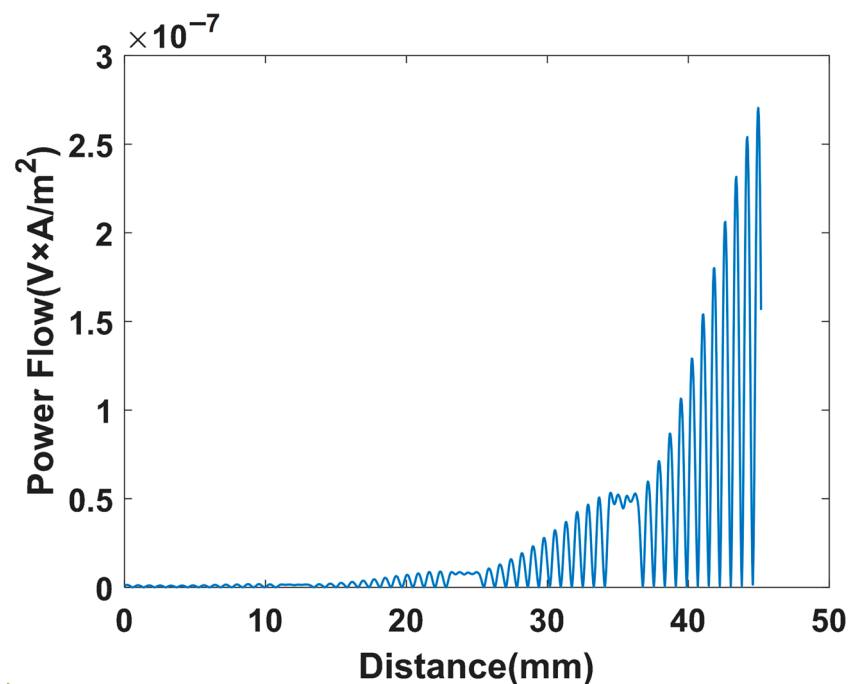


Figure 13. Power flow curve of the operating signal in the circuit from the PIC simulation.

Figure 14 shows the PIC simulation results for the circuit model shown in Figure 11. (a) shows the output signal amplitude diagram for each port, and (b) shows the spectrum of the output signals after they stabilize. After adding the isolator, the operating signal power at Port 2 remains stable, and Ports 3 and 4 have almost no output signal. Observing the spectrum, the spectrum of the Port 2 signal is relatively pure, while the spectra of Ports 3 and 4 are relatively chaotic without distinct frequency features. Therefore, BWO is effectively suppressed.

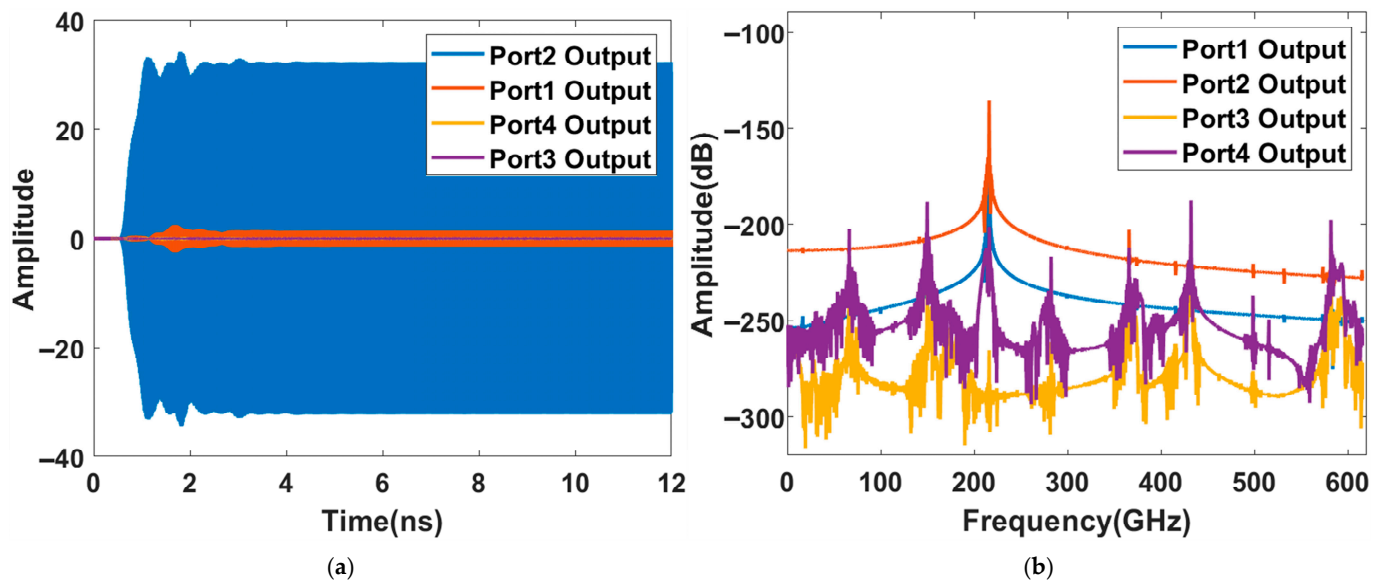


Figure 14. PIC simulation results for the circuit with the isolator. (a) Variation curve of output signal amplitude over time for the four ports. (b) Spectrum of output signals for the four ports.

Figure 15 shows the energy phase space distribution of the particles. It is evident that more electrons are retarded than accelerated, so that most of the electrons transfer some of their energy to the electromagnetic field and a small number of electrons absorb the energy from the electromagnetic field, which results in the amplification of the output signal.

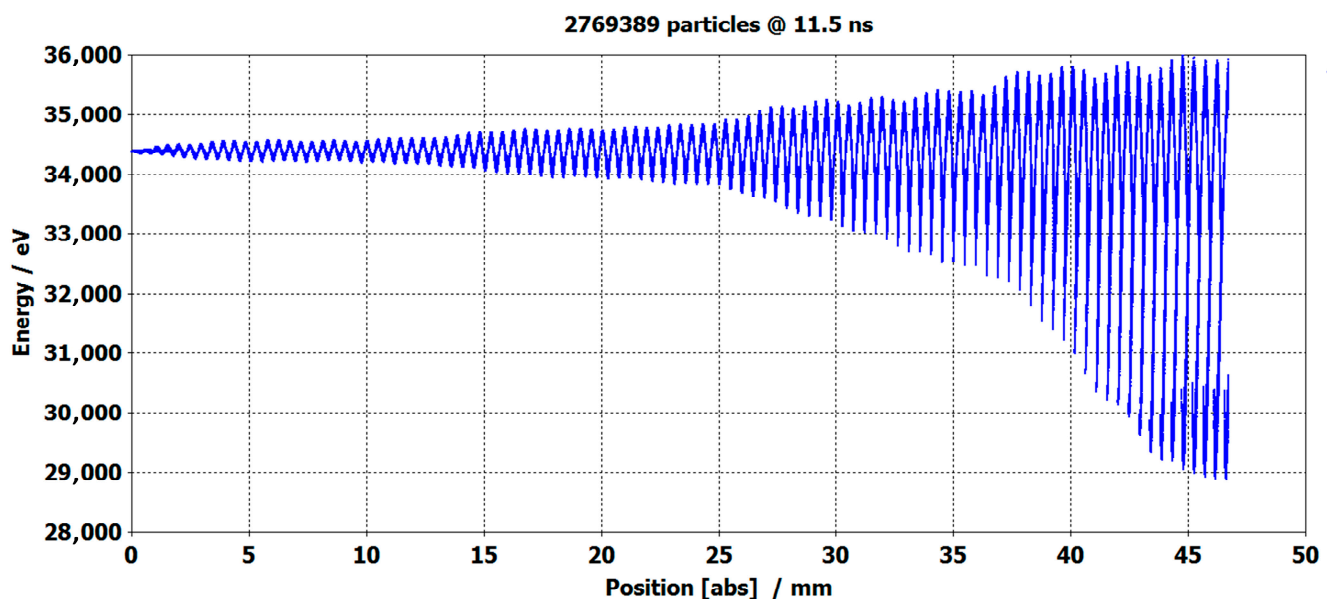


Figure 15. The energy phase space distribution of the particles from the PIC simulation.

Figure 16 shows the output power versus frequency for the traditional method and the new method under the same input signal power condition. It can be seen that when the frequency is above 214 GHz, the output power of the new method is significantly higher than that of the traditional method. This is because the new method cuts off the backward wave path without interrupting the operating signal path, avoiding the power waste associated with the traditional method, thereby effectively increasing the output power and gain.

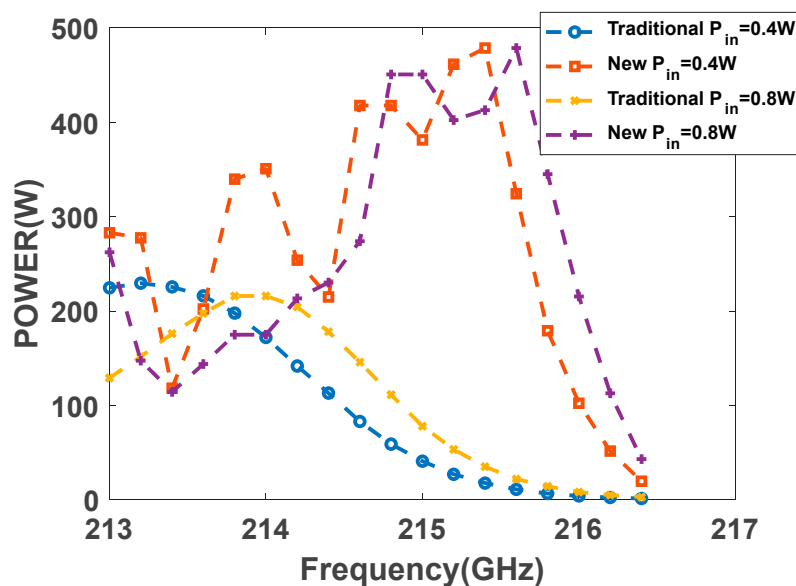


Figure 16. Output power versus frequency for the traditional method and new method.

Figure 17 shows the saturated output power and its corresponding gain at different frequencies. The maximum output power of 527 W is achieved at 216 GHz, with an input power of 2.7 W and gain of 22.87 dB; the maximum gain of 36.39 dB is achieved at 214.4 GHz, with an input power of 0.1 W and output power of 435.6 W; and the bandwidth with output power exceeding 300 W is nearly 3 GHz.

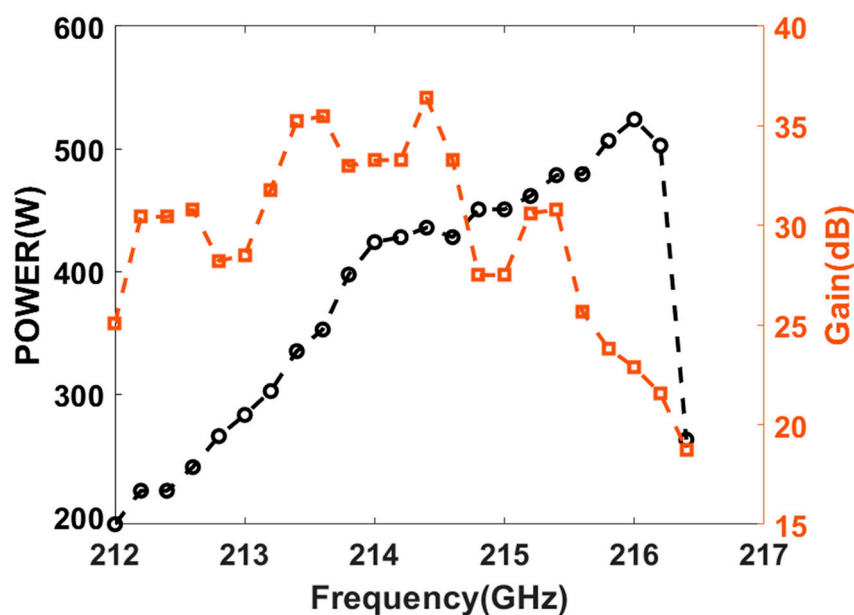


Figure 17. Saturated output power curve and its corresponding gain from the PIC simulation.

5. Conclusions

This paper presents a novel solution for suppressing backward wave oscillation in a HOM SB SWS and designs a corresponding isolator. The designed isolator has an S21 of less than -20 dB from 175 GHz to 228 GHz, which is capable of isolating the oscillation signal. The isolation method with the isolator effectively suppresses BWO by cutting off the backward wave signal path without interrupting the operating signal path, thus maintaining high output power and gain with a shorter length. PIC simulation results show that the circuit achieves a maximum output power of 527 W at 216 GHz; a maximum gain of

36.39 dB at 214.4 GHz; a bandwidth of 3 GHz with output power exceeding 300 W reaches; and a total length of the circuit under 50 mm. This solution promotes the development of high-power, compact terahertz TWTs, and facilitates the advancement of terahertz long-distance applications.

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