Design of a Novel Folded Waveguide for 60-GHz Traveling-Wave Tubes *

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The 60-GHz traveling-wave tube (TWT) prevails nowadays as the amplifier for the satellite communication and electronic countermeasures. The folded waveguide (FW) is a promising all-metal slow-wave structure (SWS) for the 60-GHz TWT with advantages of robust performance, fine heat dissipation, considerable power and bandwidth. A novel FW periodically loaded with rectangular grooves is analyzed for the purpose of gaining higher power and gain. The rf characteristics are investigated by numerical simulation, and the nonlinear large-signal performance of such a TWT is analyzed by a 3D particle-in-cell code MAGIC. Compared with normal circuits, relatively higher continuous-wave power (40–56 W) and similar bandwidth (5 GHz) are predicted by simulation. Meanwhile, the designed operation voltage is 10.5 kV, which keeps the low-voltage advantage of the popular helix TWT competitor. The novel FW will favor the design of a broadband and high-power 60-GHz TWT.

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Traveling wave tubes (TWTs) have significant application in space communication, electronic countermeasures, radar, and remote sensing as millimeter-wave amplifier devices with advantages of stability, reliability, high power and broad bandwidth.[1−3] Due to the growing demand, a 60-GHz TWT prevails nowadays in the near-field security communication, satellite communication and countermeasures.[4] As the core part where the electron beam and electromagnetic (EM) wave interact for energy transmission, the slow-wave structure (SWS) determines the performance of a TWT.[5] Among the typical SWSs, the helix has a broad bandwidth and limited power, while the coupled cavity produces high power with narrow bandwidth. The helix is widely used in communication and electronic countermeasure for the broad band, and coupled cavity prevails in radar for large pulse power. In lower frequency, we usually choose a helix TWT to meet the broadband application. However, the helix thread is very small when it comes to the V band, which restricts the power capacity and heat dissipation. The reliability is also challenged in the vibration environment or when the helix current increases unexpectedly in applications. The folded waveguide (FW) has advantages over the helix and coupled cavity for the simple structure, low-cost and precise fabrication, simple input and output transitions. Furthermore, as a promising all-metal SWS, FW not only has a considerable bandwidth, but also improves the power capacity, robust performance and heat dissipation, which is helpful in improving reliability and environmental suitability.[6−11] It can meet requirements of many application areas.

The normal FW, as shown in Fig. 1, usually has a considerable bandwidth, while the unsatisfying interaction impedance restricts the ability for higher power.[8−10] Meanwhile, the gain is low per period, thus the circuit length cannot be shortened if enough gain is needed. Therefore, exploring other novel structures becomes necessary so as to qualify the small package and high-power application, such as microwave power module. Liao *et al.*[11] and He *et al.*[12] developed some novel structures such as rectangular-groove-loaded FW and double-groove-loaded FW that can notably increase interaction impedance. However, they bring in strong dispersion at the same time. In this Letter, we present a novel FW that provides considerably higher interaction impedance with just slightly stronger dispersion. We also intentionally lower the operation voltage to about 10 kV in design so as to keep the low-voltage advantage of the popular helix TWT competitor. Lower voltage will reduce the design difficulty and increases the reliability, especially in aviation application with low-air-pressure

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environment. For the same reason, lower voltage will also benefit the design of the matched miniature power supply.

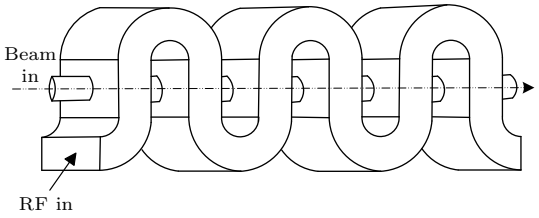

Fig. 1. Three-dimensional diagram of the normal folded waveguide.

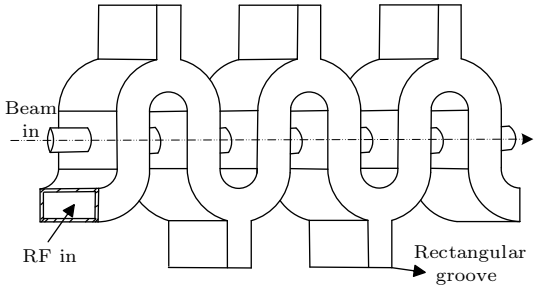

Fig. 2. Three-dimensional diagram of the novel folded waveguide.

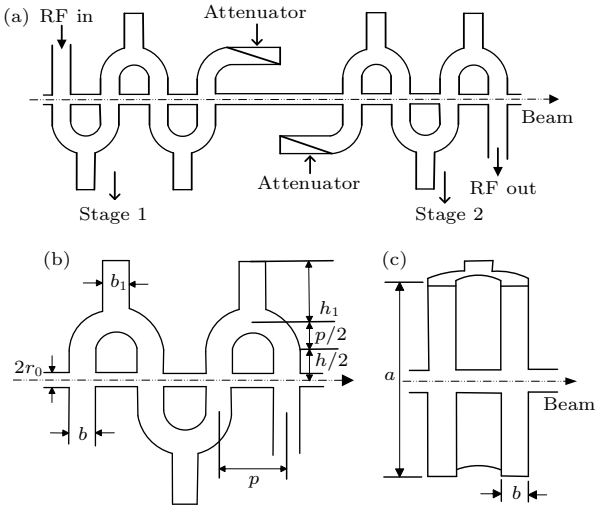

Fig. 3. (a) Sketch of the novel FW SWS, (b) and (c) size sketches.

As shown in Fig. 2, the novel FW is formed by periodically adding rectangular grooves to the E-plane bends of a normal FW. As shown in Fig. 3, the novel FW SWS has two stages, both of which include an attenuator to restrain self-excitation oscillation.

The geometrical parameters are labeled in Fig. 3. The axial period is p, the outer and inner radiuses of the bends are $p/2+b/2$ and $p/2-b/2$, respectively, h is the height of the straight guide, and r_0 is the radius of the beam tunnel. We prefer b_1 to be less than b and h_1 to be less than $2b$ so as to restrain dispersion. Based on our experience, balanced performance comes when b_1 is near 85% of b and h_1 is about 140% of b, and the optimized sizes of groove can be obtained by simulation. In this structure, if we choose a suitable size of the groove for designed working band, the EM wave reflected in the groove region will strengthen the electric field, which can promote interaction impedance and subsequently increase the output power.

A 3D electromagnetic code HFSS is adopted to calculate and compare the radio-frequency characteristics between the novel and normal FW. We make 59.5 GHz as the central frequency for an example in this work. However, in our study, the central frequency can be easily shifted by adjusting geometrical parameters according to applications.

Since weak dispersion means broader bandwidth and larger interaction impedance means higher power, the simulation focuses on the two important characteristics. The parameters for simulation are as follows (in millimeters): (i) novel circuit ($a = 2.96$, $b = 0.52$, $p = 0.68$, $h = 0.68$, $b_1 = 0.44$, $h_1 = 0.72$, and $r_0 = 0.26$) and (ii) normal circuit ($a = 2.96$, $b = 0.52$, $p = 0.68$, $h = 0.89$, and $r_0 = 0.26$). Optimized sizes of h_1 and b_1 are chosen here by simulation to prove that the novel circuit has a higher interaction impedance with similar dispersion property of the normal circuit.

Figure 4 shows the comparison of radio-frequency characteristics between the two FWs. Although the dispersion property of the novel FW is slightly inferior to the normal FW, with which we have already made a 5-GHz-bandwidth TWT, the interaction impedance is considerably greater. Therefore, we can predict that the novel FW TWT has advantages over the normal one with higher power and similar band performance. Furthermore, in our investigation, the novel FW also has advantages in other frequency bands by scaled design from the size of the 60-GHz circuit.

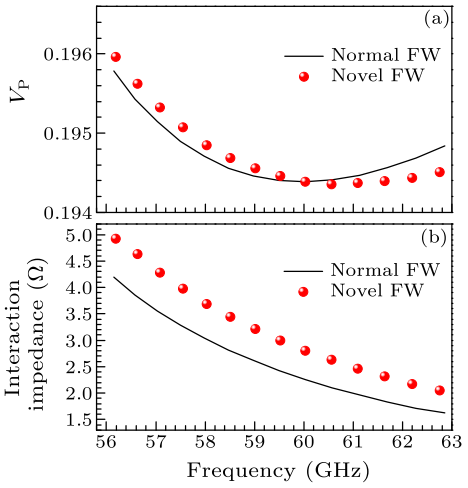

Fig. 4. Comparisons of (a) dispersion property and (b) on-axis interaction impedance. Hereafter V_P represents the phase velocity in units of the velocity of light in a vacuum.

Figure 5 shows the influences of the grooves' sizes

on dispersion property and interaction impedance. As the length h_1 or width b_1 increases, the dispersion property becomes worse while the interaction impedance first increases and then halts or decreases. Since longer h_1 or b_1 will bring stronger dispersion but not always higher interaction impedance, optimized sizes of groove are needed to keep a broad bandwidth and to obtain a higher power.

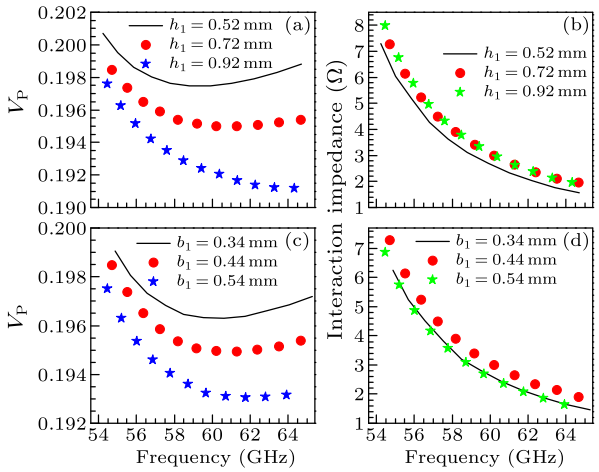

Fig. 5. (a) Dispersion versus groove's length h_1, (b) interaction impedance versus groove's length h_1, (c) dispersion versus groove's width b_1, (d) interaction impedance versus groove's width b_1.

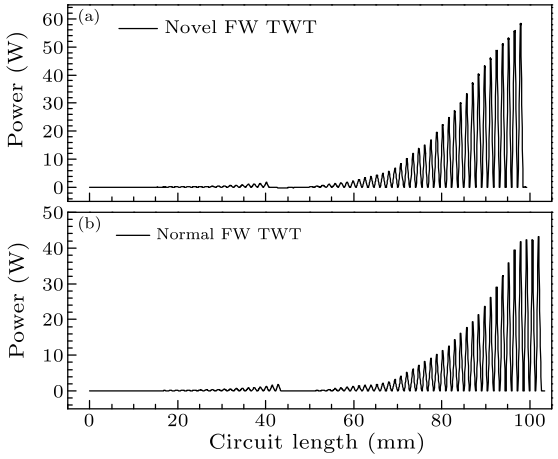

Fig. 6. Power variation versus axial circuit length at 60 GHz: (a) novel FW, (b) normal FW.

A 3D particle-in-cell code MAGIC is adopted to make performance comparison. With MAGIC, we can easily observe the variation of the electron beam's velocity, power flux, electric-field density, input and output powers of the TWT, and so on.[13]

The nonlinear large-signal beam-wave interaction of both the novel and normal FW TWT are compared by MAGIC. We carry out the particle-in-cell simulation with lossy waveguide whose material is copper. We adopt fine meshes to guarantee the accuracy of calculating results, such as output power and circuit attenuation due to the lossy metal. Concentrated attenuators are also applied, as shown in Fig. 3. The results are obtained firstly by adjusting geometrical parameters of the two circuits so that they have the same phase velocity at the central frequency as the one shown in Fig. 4, and then by choosing the same beam voltage (10.5 kV) according to the beam-wave synchronism condition, together with the same beam current (75 mA), input power (45 mW), and axial focusing magnetic field (0.3 T) so as to make a fair comparison.

Figure 6 shows the growing power versus the axial circuit length. We can obtain a direct view that the novel FW TWT produces near 60-W power whereas the normal FW TWT produces the power below 45 W, both have a circuit length about 100 mm. The result is obtained with the input frequency at 60 GHz. The novel one has advantages for the higher power and gain.

Figure 7 depicts the output power as a function of driving frequencies. The novel FW TWT produces considerably higher power through the designed 5-GHz bandwidth, proving coherence with the radio-frequency characteristics. Based on the experience from the design of a normal FW TWT, we can state that the novel FW TWT is capable of providing above 30-W continuous-wave power and 5-GHz bandwidth.

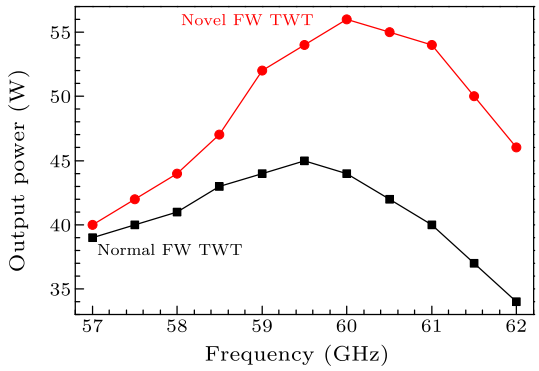

Fig. 7. Output power versus the input frequency.

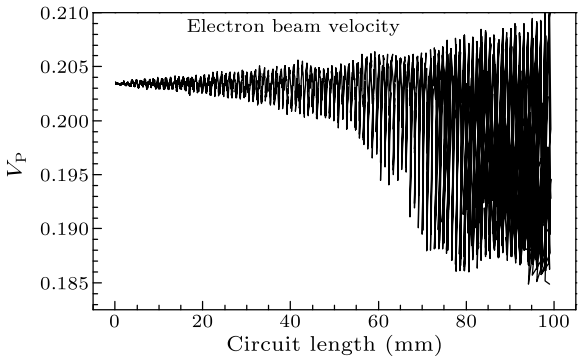

Fig. 8. Axial electrons' velocity modulation versus the circuit length.

Figure 8 depicts the electron beam's velocity varia-

tion versus the axial circuit length. The electron beam is axially modulated by the input EM wave at stage 1, then the bunched beam stimulates a new EM wave and interacts with it at stage 2. Most of the beam velocity reduces at the end of the circuit by converting its kinetic energy to the amplified microwave.

In summary, a novel FW for a 60-GHz TWT has been presented. It is formed by periodically adding rectangular grooves to the bends of a normal FW. The normal and novel FWs are compared with respect to the rf characteristics and large-signal beam-wave interaction. The novel FW has relatively higher interaction impedance and similar dispersion property to the normal FW. In large-signal simulation, the novel FW TWT also produces considerably higher continuous-wave power (40–56 W) through the designed 5-GHz bandwidth with 10.5-kV operation voltages. The novel FW promises a higher power, broadband and miniature TWT.

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