CHIN. PHYS. LETT. Vol. 26, No. 11 (2009) 114207

Analysis of a Novel Ka-band Folded Waveguide Amplifier for Traveling-Wave Tubes *

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(Received 10 July 2009)

A novel Ka-band folded waveguide (FW) amplifier for traveling wave tubes (TWT) is investigated. The dispersion curve and interaction impedance are obtained and compared to the normal FW circuit by numerical simulation. The interaction impedance is higher than a normal circuit through the whole band. We also study the beam-wave interaction in this novel circuit, and the nonlinear large-signal performance is analyzed by a 3-D particle-in-cell code MAGIC3D. A much higher continuous-wave (CW) output power with a considerably shorter circuit compared to a normal circuit is predicted by our simulation. Moreover, the novel FW even has a broader 3-dB bandwidth. It therefore will be useful in designing a miniature but high-power and broadband millimeter-wave TWT.

PACS: 42.60.Da, 07.57.Hm, 41.20.Jb

Traveling wave tubes (TWTs) have significant applications in radar, space communication, electronic counter measure and other domains as the millimeter-wave radiation sources have advantages of stability, reliability, broad band and considerable power.[1,2] The slow-wave circuit, as the key part which amplifies the power of the microwave in TWTs, decides the performance.[3] Among the typical slow-wave amplifiers, the folded waveguide (FW) has advantages over helix and coupled-cavity with a moderate bandwidth and power capability in the millimeter-wave frequency range, it also prevails for the simple structure, low-cost and precise fabrication, robust performance, simple input and output transitions.[4,5]

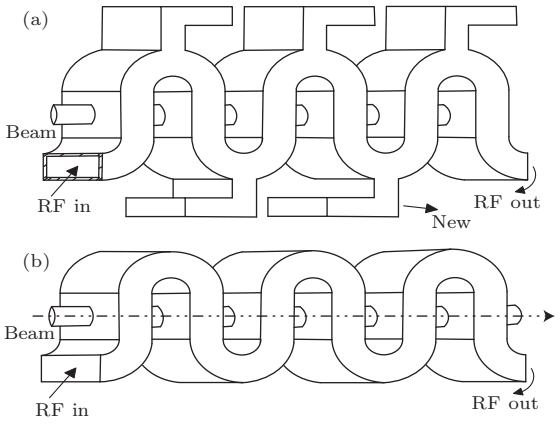

Fig. 1. Three-dimensional diagrams: (a) the novel folded waveguide, (b) the normal folded waveguide.

Higher power and broader band are required with technology moving forward, but the low interaction impedance of the normal FW in Fig. 1 restricts the amplification of microwave power.[6,7] Meanwhile, the gain is low per period, so the circuit length is considerably long if enough gain is needed. The miniature circuit is a trend as well, if we want to obtain a higher power within a shorter circuit, finding other novel structures becomes necessary.

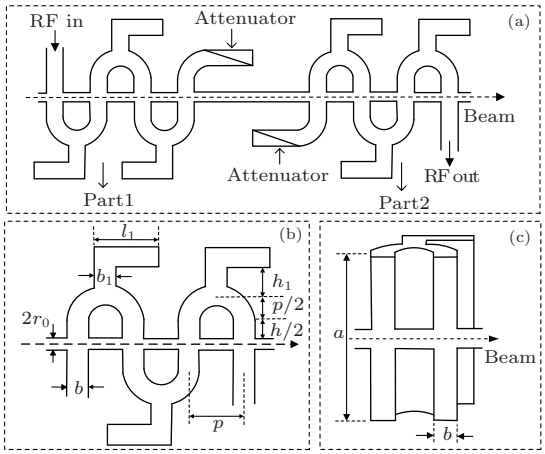

Fig. 2. Sketch of the novel folded waveguide.

As shown in Fig. 2, the novel FW is formed by adding right-angle rectangular grooves periodically to the bends of the normal E-plane FW. We conceive of this method to change the distribution of the electric field intending to promote the interaction impedance

*Supported by the National Natural Science Foundation of China under Grant No 60532010, and the Talent Fund of Chinese Educational Administration under Grant No NCET-05-0800.

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and subsequently increase output power. The circuit has two parts (in Fig. 1) that include an attenuator to restrain self-excitation oscillation. As shown in Fig. 2, the axial period is p, the outer and inner radius of the bends are $p/2 + b/2$ and $p/2 - b/2$ respectively, h is the height of the straight guide, b_1 can be less than $p + b$ but we prefer it to be near or less than b, l_1 should be less than $2p$, h_1 should be short to keep a small cross-sectional area which is propitious for focusing the electron beam with axial focusing magnetic field.

Dispersion and interaction impedance, as the most important radio-frequency characteristics of a slow-wave amplifier, predict the bandwidth and power gain. We adopt a three-dimensional electromagnetic simulation code HFSS to compare the normal and novel FW. Attenuation is also concerned. We focus on a domain with a center frequency at 35 GHz in Ka band in this study.

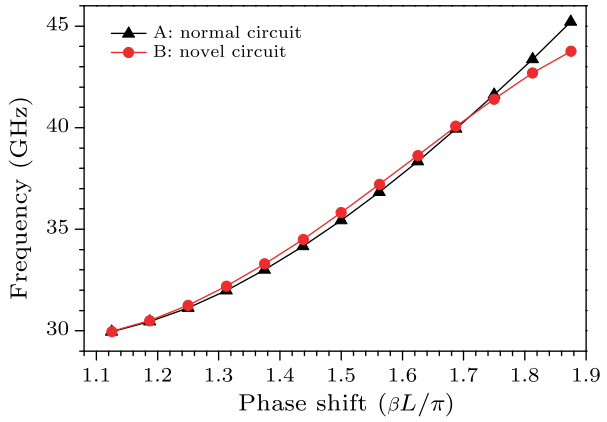

Fig. 3. Dispersion curve.

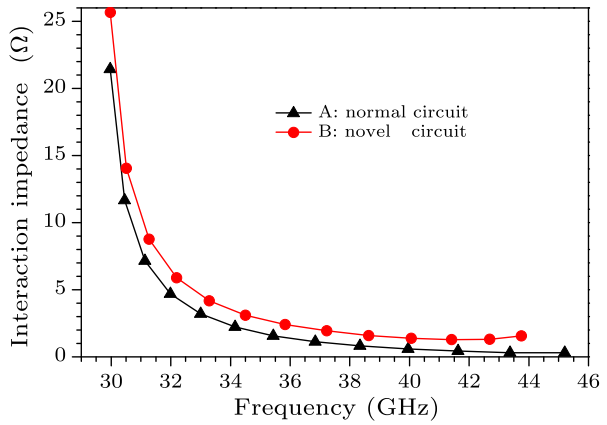

Fig. 4. On-axis interaction impedance.

Figures 3 and 4 show the comparison of the dispersion curve and interaction impedance between the novel and normal FW. The dispersion curves are very close from 30 to 41 GHz but the interaction impedance of the novel FW is considerably higher than the normal one, especially at higher frequencies in the band, which means it can support beam-wave interaction better in a wider frequency domain where the normal FW cannot support it because of the low and insufficient interaction impedance. Attenuation at 35 GHz is also investigated by testing the S-parameter with HFSS. We assume that the material is copper (conductivity 5.8×10^7 S/m) for both FWs and obtain that attenuation is 0.013 dB/mm in the normal FW and 0.017 dB/mm in the novel FW. While the total length of the novel circuit (134 mm) is shorter than the normal circuit (174 mm) when they both work at the saturation region revealed through the later MAGIC simulation, so the total attenuation for the novel circuit is 2.28 dB, which is barely larger than the normal circuit (2.26 dB). The above three properties predict that the novel FW circuit will produce higher power in a wider bandwidth.

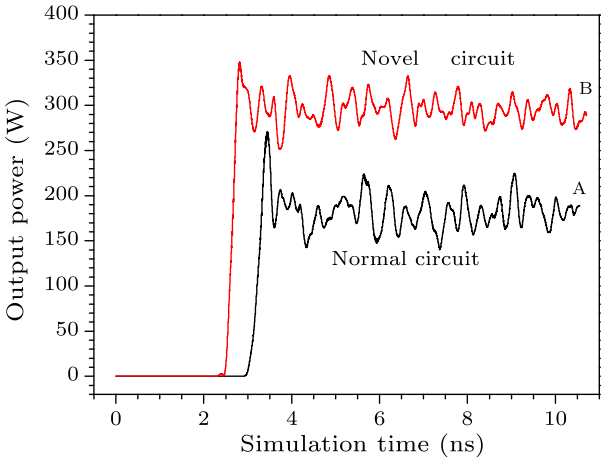

Fig. 5. Output power versus simulation time.

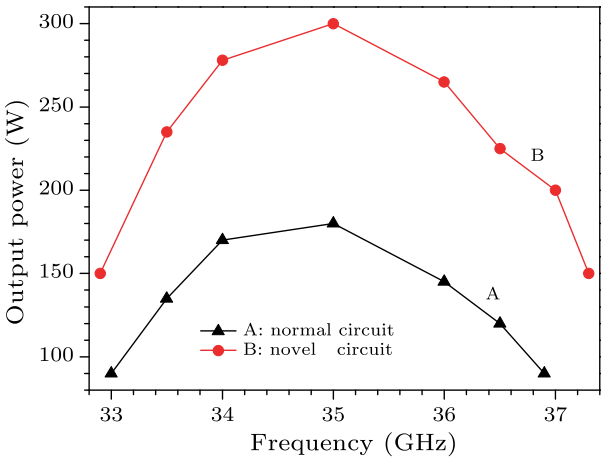

Fig. 6. Output power versus frequency.

Compared to radio-frequency characteristics, the nonlinear large-signal beam-wave interaction shows us the performance closer to practical application with the electronic beam involved, such as operating bandwidth, power gain and electronic efficiency.[8] It is tested by a 3-D particle-in-cell code MAGIC3D that solves Maxwell's equation with a Lorentz parti-

cle equation to obtain a self-consistent solution in time and 3-D space.[9]

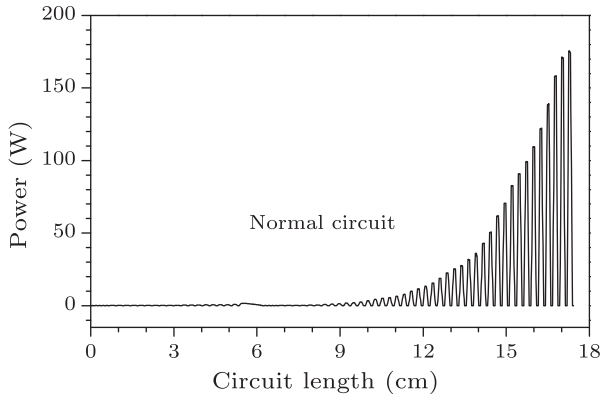

Fig. 7. Radiation power versus the axial distance (normal FW).

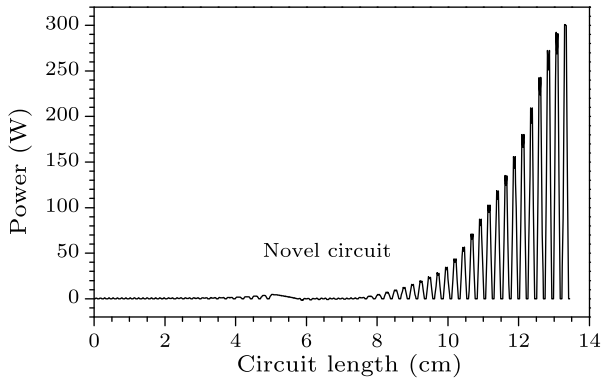

Fig. 8. Radiation power versus the axial distance (novel FW).

We use copper as the conductor of the normal and novel FW circuits in MAGIC simulation, the mesh is quite small to guarantee the accuracy of calculating attenuation and other results. Figure 5 shows the output power versus the simulation time. As time goes by, output power from the novel FW becomes stable around 300 W while only 180 W from the normal FW at 35 GHz. The results which have already included attenuation by setting up an initial condition called surface loss in operation are obtained under the same input power (0.1 W) and beam current (0.3 A). The beam voltage is very close as well, 11.2 kV for the novel FW and 11.15 kV for the normal one according to the phase velocity of their working slow-wave. We can easily realize in calculation that the novel FW circuit has advantages for producing a much higher power with higher efficiency. Figure 6 depicts the output power as a function of driving frequencies. The novel FW not only produces higher power through the whole band, but also has a wider 3-dB bandwidth compared to the normal FW, proving coherence with radio-frequency characteristics. The novel FW circuit supports a 3-dB bandwidth up to about 4.4 GHz, which is very promising when designing a broadband millimeter-wave TWT.

Figures 7 and 8 show the radiation power measured at one side of the FW bends as a function of the axial circuit length. We can have a direct view that around 300 W saturated power exists at the end of the 13.4-cm-long novel circuit while about 180 W at the end of the 17.4-cm-long normal circuit. Thus the novel FW circuit also has the advantage of giving out higher saturated power in a shorter circuit. This is very useful in decreasing its volume and adapting to the trend of miniature TWT.

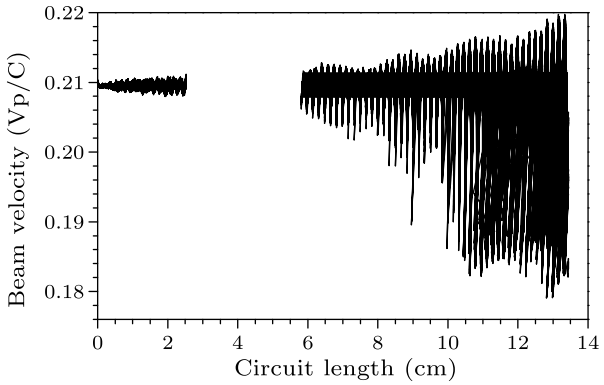

Fig. 9. Axial beam velocity modulation.

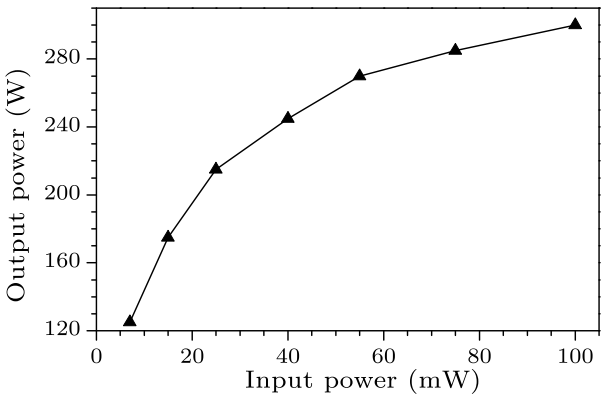

Fig. 10. Output power versus input power.

Figure 9 depicts the beam velocity modulation along the axial circuit distance obtained from MAGIC3D simulation. The electron beam is axially modulated by the input microwave in part 1. Then the bunched beam motivates the microwave again and interacts with it in part 2, most of the beam velocity reduces at the end of the circuit because its kinetic energy converts to the amplified microwave. Figure 10 shows the output power as a function of input power. The gain decreases as input power increases. We can see that output power adds only 30 W when input power goes up from 55 mW to 100 mW and about to be saturated as the trend. It is suggested there is no need for continually increasing the input power to get more output if our requirement is already satisfied, because low input is easier to achieve and the performance of the circuit is more stable away from the saturated area in practical applications.

Figure 11 shows the frequency spectrum obtained from the Fourier transformation of the time-varying electric field measured within the novel FW circuit. There is a single frequency at 35 GHz indicating that the circuit is not affected by higher modes and is free from oscillation.

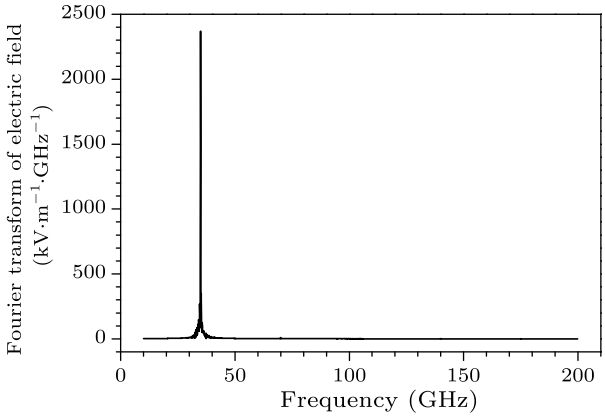

Fig. 11. Frequency spectrum obtained within the circuit.

In summary, we have reported a novel folded-waveguide TWT amplifier and studied its radio-frequency characteristics and nonlinear large-signal beam-wave interaction. It predicts a 300 W cw output power by average at 35 GHz with a 4.4 GHz 3-dB bandwidth, with performance much better than the normal folded waveguide that produces only a 180 W output and a 3.9 GHz 3-dB bandwidth. The novel folded waveguide is shorter as well. It therefore has advantages over the normal folded waveguide for higher power, broader band and smaller volume, which is very promising for designing a novel millimeter wave TWT with high performance.

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