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Research on Large-Signal Simulation of Helix-Loaded Azimuthally Periodic Circular Waveguide for 140-GHz TWT

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Keywords: Traveling wave tube, dispersion characteristics, beam-wave interaction, 3-D particle-in-cell simulations, millimeter-wave amplifier

Abstract: To address the issues of low output power and focusing difficulties encountered by conventional helix traveling wave tube (TWT) in the short millimeter wave band, a novel helix-loaded azimuthally periodic circular waveguide TWT (HLAP-CW TWT) is proposed in this paper. The novel structure consists of helixes that are arranged periodically about the axis of the conventional circular waveguide. And the N helixes share a single electron beam with a large current value in axial. In this paper, the specific design scheme for the HLAP-CW TWT of 140 GHz is proposed. The dispersion characteristics of the HLAP-CW are studied by HFSS in order to determine the operation voltage of the beam-wave interaction. Furthermore, the 3-D particle-in-cell (PIC) simulations are carried out with the electron beam voltage U=3758V and the electron beam current I=0.25A. In the operation frequency range from 120GHz to 154GHz, the output powers of the HLAP-CW TWT all exceeds 55W with the input power maintained 50mW. The maximum corresponding gain and the highest beam-wave interaction efficiency are 25.98dB and 8.43%, respectively. Therefore, the HLAP-CW TWT is a millimeter-wave amplifier with a wide bandwidth and a large output power, which provides a new solution of the current challenges faced by millimeter-wave TWT.

1. Introduction

The helix is one of the most important slow-wave structures for traveling-wave tube (TWT) due to its outstanding combined performance in bandwidth, power capacity and gain characteristics [1]-[3]. However, because of the electron beam going normally through the inner space of helix, the dimension of the beam tunnel is thus limited and reduces sharply with frequency increase, which leads to a small beam current and consequently decreasing output power. The disadvantage of a dielectric-lined waveguide is the low interaction impedance, which has discouraged acceptance for millimeter-wave TWT interaction circuits[4]-[5]. In addition, the manufacture and assembly become more difficult with shorter working wavelength. Thus, in an effort to alleviate the above disadvantages, a novel SWSs for miniaturization of high-power millimeter-wave TWTs is now proposed.

The novel helix-loaded azimuthally periodic circular waveguide (HLAP-CW) consists of helixes that are arranged periodically about the axis of the conventional circular waveguide, as shown in Fig.1, which is now proposed for potential applications in high power broad band TWTs working at W band and higher frequency. It inherits the unique properties of the conventional helix structure by inherently wide bandwidth, low dispersion and relatively high interaction efficiency, and N-helixes may interact with one electron beam having larger current for high output power; furthermore, the microelectro-mechanical systems (MEMS) technologies[6]-[10] will alleviate the machining difficulties, which is helpful for a miniaturized radiation sources in millimeter and submillimeter-wave regimes. Therefore, the HLAP-CW may be enabling SWS for miniaturized broad band high power millimeter-wave TWTs.

In this paper, the dispersion characteristics of the HLAP-CW are studied by HFSS in order to determine the operation voltage of the beam-wave interaction. In Section III, the non-linear beam-wave interaction properties of the HLAP-CW TWT are investigated here based on the particle-in-cell code in the CST PIC-solver. And the relationships between the HLAP-CW non-linear characteristics and the electron beam parameters are also derived. A brief summary and conclusions are given in Section IV.

2. Electronmagnetic characteristics of HLAP-CW

The structural diagram of the HLAP-CW is shown in Fig. 1. The dispersion characteristics of the HLAP-CW TWT are illustrated in Fig. 2, which is solved by 3-D electromagnetic simulation software HFSS. It is clear that the dispersion curve and the voltage curve matches well from 120GHz to 160GHz, which indicates that the beam-wave interaction can be carried out effectively in wide operation frequency range. And the corresponding structure parameters are given in Fig. 3.

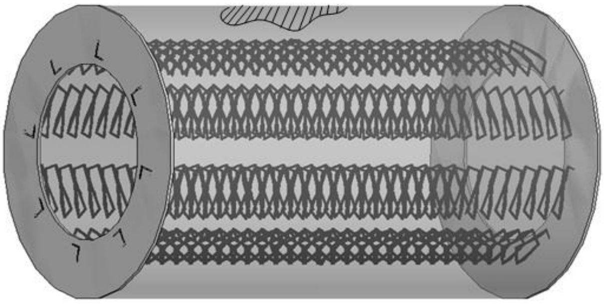

Figure 1: Schematic of HLAP-CW

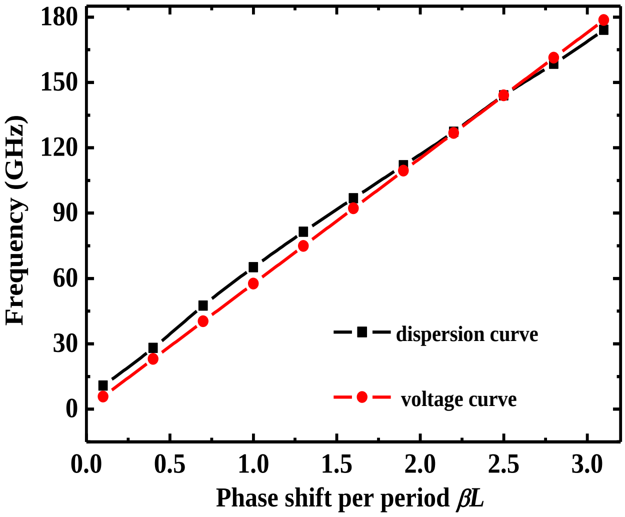

Figure 2: Dispersion curve of HLAP-CW

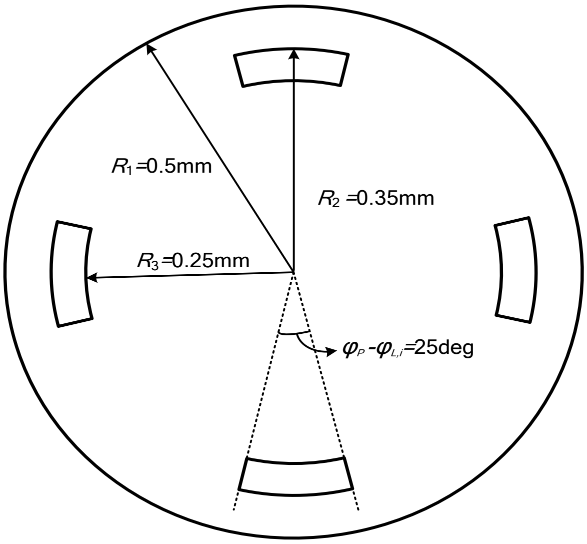

Figure 3: Structure dimension of HLAP-CW

Figure 4 shows the transmission characteristic of the HLAP-CW TWT with 63 periods of slow-wave structure. In our calculation, the conductivity of the material of the operation circuit is set as 2.2×10^7S/m after considering the machining technology and the surface roughness. In operation frequency range from 120GHz to 160 GHz, we can get the transmission losses of the novel structure is greater than -0.2dB, and the transmission parameter S_{11} is less than -20dB.

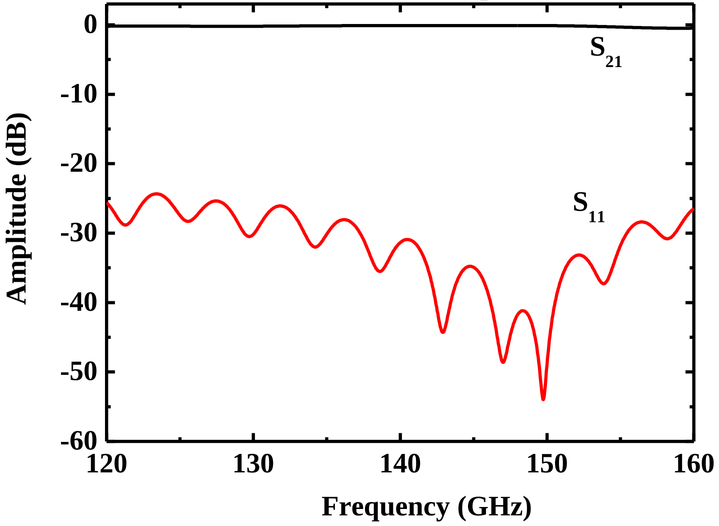

Figure 4: Transmission characteristic of HLAP-CW

3. Non-linear beam-wave interaction characteristics of HLAP-CW

Furthermore, the 3-D particle-in-cell (PIC) simulations are carried out with the electron beam voltage U=3758V based on the normalized phase velocity curve in Section II. Fig. 5 shows the 3D beam-wave interaction model of the HLAP-CW TWT, and the concrete parameters in CST PIC-solver are set in Table 1. Here, the calculation platform is a personal computer with Intel i7-2600 3.4G CPU and 4G memory. The CPU time is approximately 58 hours for a single frequency within 2ns calculation.

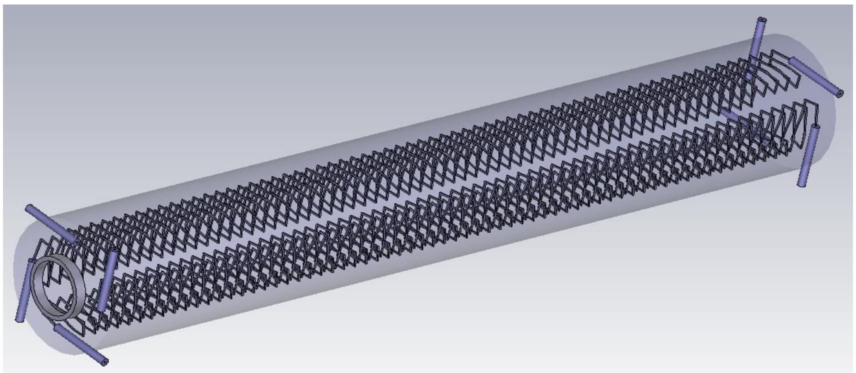

Figure 5: 3D beam-wave interaction model of the HLAP-CW TWT

Table 1: Parameters setting in CST PIC-Solver

Parameters	value
U_0	3758V
I_0	0.25A
Magnetic field	1.2T
Time	2ns
Conductivity of materials	$\sigma = 2.2\times10^7$S/m
Particle number	730176
Gridding number	1547440

The output power for several operation frequencies are plotted with the input power maintained 50mW in Fig. 6. In the operation frequency range from 120GHz to 154GHz, the output powers of the HLAP-CW TWT all exceeds 55W, and the corresponding gain and the beam-wave interaction efficiency are obtained in Fig. 7.

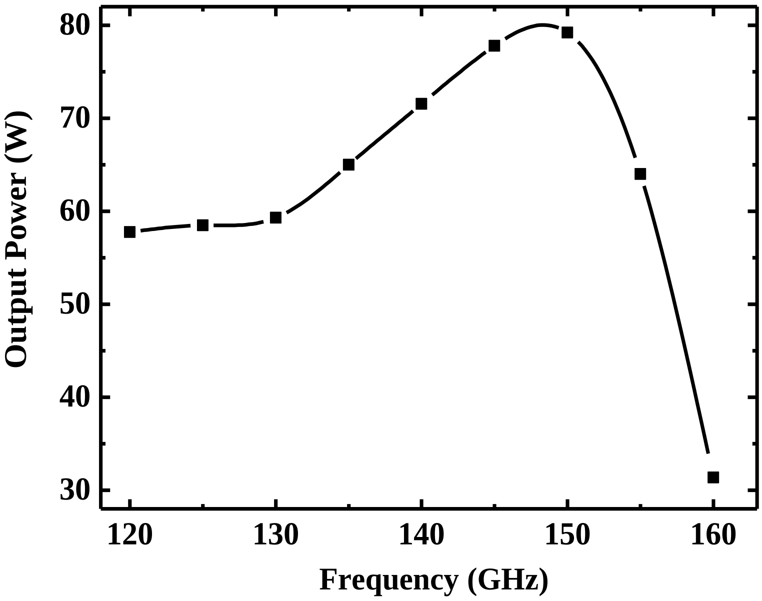

Figure 6: Amplitude-frequency characteristics

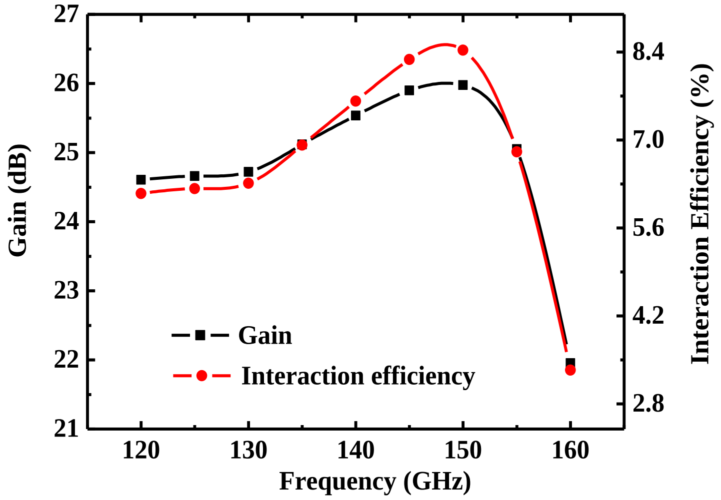

Figure 7: Gain and interaction efficiency

Fig. 8 shows the particle-in-cell simulation results of 140 GHz. We can see that the output power is upon 65W, which becomes stable after 1.05-ns interaction. The electron bunch phenomenon in beam-wave interaction and the phase space figure of the electron are plotted in Fig. 9 and Fig. 10, respectively.

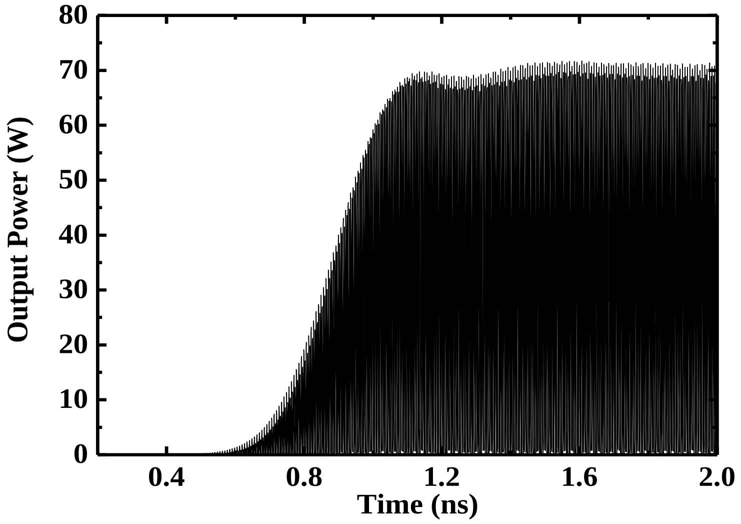

Figure 8: Output power of HLAP-CW TWT in 140GHz

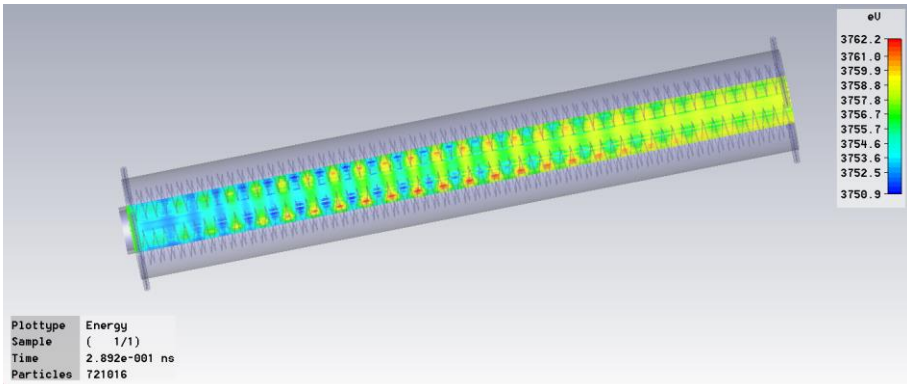

Figure 9: Electron bunch phenomenon in beam-wave interaction

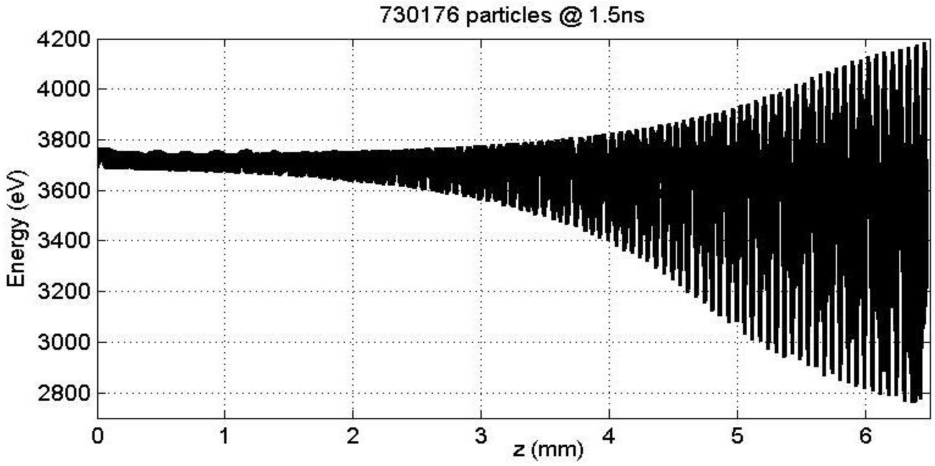

Figure 10: Phase space of the electron

The effects of the input power on the beam-wave interaction properties of the HLAP-CW TWT are investigated in Fig. 11. It is clear that the output power increases as the input power increase in small-signal region, and then they changes the non-linear growth trend in saturation region. The result shows that the saturated output power of the HLAP-CW TWT is 144W in 140GHz when the saturated input power is 200mW.

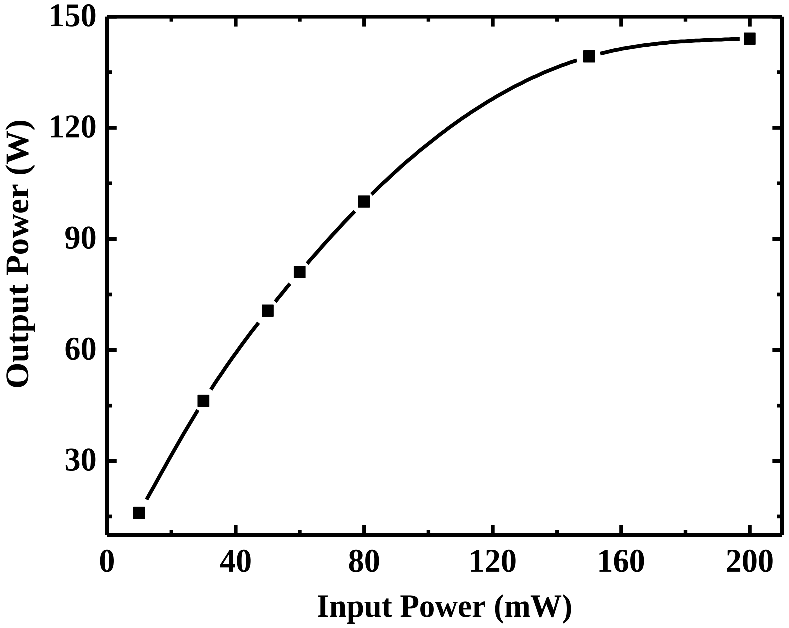

Figure 11: Input/output amplitude conversion performance

In Fig. 12, the dependence of output power on the electron beam current I_0 is studied in 140GHz. It is obvious that the saturated input power, gain and the electron efficiency are 422W, 33.2dB and 12.1% with I_0=0.93A, respectively.

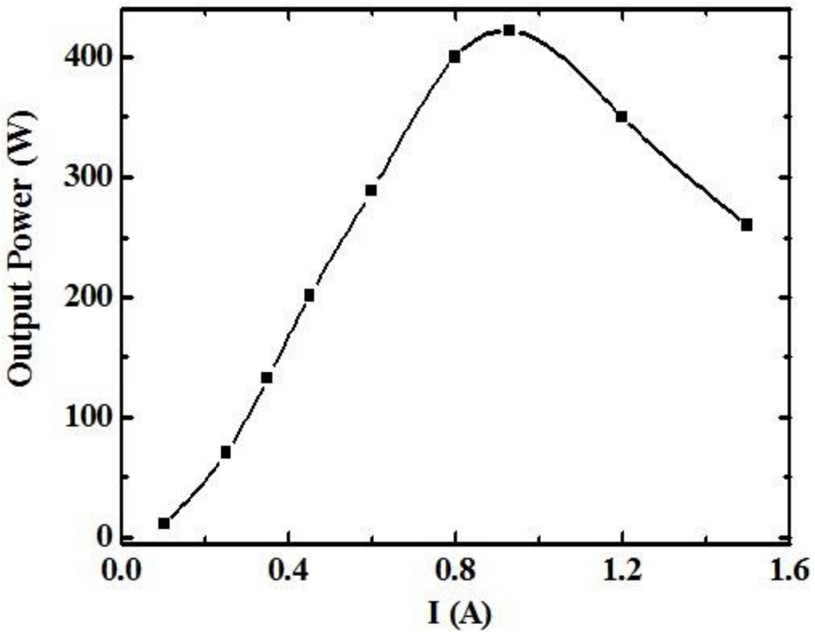

Figure 12: The dependence of output power on I0

4. Conclusion

In this paper a novel linear-beam TWT circuit structure, the helix-loaded azimuthally periodic circular waveguide (HLAP-CW), has been investigated. The dispersion characteristics of the HLAP-CW are validated by HFSS in order to determine the operation voltage of the beam-wave interaction. It is clear that the dispersion curve and the voltage curve matches well from 120GHz to 160GHz, which indicates that the beam-wave interaction can be carried out effectively in wide operation frequency range. Furthermore, the 3-D particle-in-cell (PIC) simulations are carried out with the electron beam voltage U=3758V based on the normalized phase velocity curve. In the operation frequency range from 120GHz to 154GHz, the output powers of the HLAP-CW TWT all exceeds 55W, and the corresponding gain and the beam-wave interaction efficiency are 25.98dB and 8.43%, respectively. The HLAP-CW TWT has a wide bandwidth and a large output power in millimeter-wave band, which provides a new solution of the current challenges faced by millimeter-wave TWT.

Acknowledgements

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