Nonlinear Investigation of Beam-wave Interaction in E Band Folded Waveguide TWT

Jun HE$^{1,*}$, Dan ZHU$^2$ and Ming-guang HUANG$^1$

$^1$The Key Laboratory of High Power Microwave Sources and Technology, Institute of Electronics, Chinese Academy of Sciences, Beijing 100190, China

$^2$The Aerospace Science and Technology Group 804, Shanghai 201109, China

*Corresponding author

Keywords: Millimeter-wave traveling-wave tube, Folded waveguide, Beam-wave interaction, High power.

Abstract. A E-band folded waveguide traveling-wave tube (FWTWT) is modelled, and the nonlinear interaction between the electron beam and electromagnetic field is investigated by utilizing a 3-D particle-in-cell (PIC) code, MAGIC3D. The process of the interaction for millimeter wave TWT are presented, including the longitudinal momentum of the electron, the averaged radiation power, and the influence of input power on output power. The radiation power and gain of the FWTWT at 85GHz are 88.5W and 27.5dB. The output power of the FWTWT changes only 1 dB across the 6-GHz bandwidth ranging from 82GHz to 88GHz, which is attractive for many applications, e.g. 5G communication networks, satellite communication, electronic counter measures.

Introduction

E-band (60 – 90 GHz) transceivers are expected to play a key role in future 5G communication networks [1]. Folded waveguide traveling wave tube (FWTWT) [2] is excellent candidate for applications in millimeter wave regimes. Folded waveguide structure draws a widely attention to develop a compact millimeter and submillimeter wave radiation source, and some important experimental results have been obtained [3][4].

In this paper, with the aim to provides a quantitative analysis of the interaction and demonstrate the increase of output power and gain, our study focuses on the nonlinear interaction between the electron beam and electromagnetic field in a E-band FWTWT. Section II builds a beam-wave interaction model of E-band FWTWT with the help of MAGIC3D [5]. Numerical simulation results and discussions are also presented in this Section. A brief summary is given in Section III.

Beam-wave Interaction Model

The nonlinear interaction dynamics between the electron beam and electromagnetic field in the FWSWS are simulated using the 3-D PIC code, MAGIC. As a finite difference, time domain code, MAGIC provides self consistent interaction between charged particles and electromagnetic fields by solving the Maxwell’s time-dependent equations with Lorentz force equation.

![Figure 1. Three-dimensional view of the model of the FWTWT.](image-url)
The 3-D view of the model of FWTWT is shown in Figure 1. To eliminate regenerative oscillations along the circuit and increase the stable gain, an attenuator is included in the novel FWTWT and the interaction circuit is partitioned into two gain sections. The attenuator design contains a continuous taper to provide a good match and a long section for sufficient attenuation. The length of TWT is determined by optimum output power and gain.

The beam voltage of this FWTWT is 17.3 kV and other main parameters for simulation are listed in Table 1. The beam current is set to be 0.10 A for the consideration of effective beam transportation along pretty small tunnel. The electron beam is well-distributed across a radius of 0.22 mm and the filling factor is 60%.

| Parameter                                | Value     |
|------------------------------------------|-----------|
| Beam Voltage                             | 17.3 kV   |
| Beam Current                             | 0.10 A    |
| Number of Period in First Section         | 50        |
| Number of Period in Attenuation Area      | 10        |
| Number of Period in Second Section        | 93        |

3-D PIC Simulation Results

Figure 2 shows the longitudinal momentum of the particle versus circuit length where working frequency is 85 GHz and input power is 167 mW. With the increase of interaction distance, there are more decelerated electrons than the accelerated ones, which indicate the beam losing more energy than gaining and converting its kinetic energy to the electromagnetic wave energy.

Figure 3 plots an averaged electromagnetic power versus the axial distance. It is observed that the radiation power increases slightly in the first section and decays dramatically at the position of attenuator. Due to the modulated electron beam, the power growth continues to increase until the power is significantly amplified to 88.5 W at the end of the circuit.

Figure 4 shows the Field Ez versus simulation time. Figure 5 shows Fourier transformation of electric fields at the output port. Notice that the FFT indicates the presence of a single frequency, 85 GHz, in the frequency range of 10-200 GHz. It is concluded from Figure 4 and Figure 5 that the FWTWT is free from oscillation.

Figure 6 gives the influence of varying input power on the performance of output power at 83, 84 and 85 GHz. Within the same beam parameters, the output powers of these three frequencies saturate at different input powers, that is 100.9, 120.5 and 167 mW, respectively.

![Figure 2. The longitudinal momentum of the particle versus the axial distance.](image)

![Figure 3. The averaged radiation power as a function of the axial distance.](image)
Figure 4. The Field Ez as a function of the simulation time.

Figure 5. Fourier transformation of electric field at output port.

Figure 6. The influence of input power on the output power.

Figure 7 shows the output power and gain versus frequency. The radiation power and gain of the FWTWT at 85GHz are 88.5W and 27.5dB. It should be noted in Figure 7 that, the output power of the FWTWT changes only 1 dB across the 6-GHz bandwidth ranging from 82GHz to 88GHz, which is attractive for many applications, e.g. 5G communication networks, satellite communication, electronic counter measures.

Figure 7. The variation of output power and gain with frequency for the FWTWT.
Conclusion
In this paper, the performance of a E-band FWTWT is investigated by PIC simulation. The nonlinear beam-wave interaction in this circuit is calculated in both time and spatial domain with the help of MAGIC. Simulation results indicate that the E band FWTWT may produce 88.5W saturated radiation power and 27.5dB gain. This numerical nonlinear investigation provides a quantitative analysis of the beam-wave interaction and, most important, demonstrate an available way to obtain high output power at E-band.

The section headings are in boldface capital and lowercase letters. Second level headings are typed as part of the succeeding paragraph (like the subsection heading of this paragraph).

Acknowledgement
This research was financially supported by the National Natural Science Foundation of China under Grant NO.61401430.

References
[1] T. Stander, “A review of key development areas in low-cost packaging and integration of future E-band mm-wave transceivers”, in IEEE Africon, 2015, pp 234-238.
[2] G. Dohler, D. Gagne, D. Gallagher, and R. Moats, “Serpentine waveguide TWT”, in IEDM Tech. Dig., 1987, pp. 485-488
[3] S.T. Han, J.I. Kim, K.H. Jang, J.K. So, S.S. Chang, N.M. Ryskin and G.S. Park, “Experimental investigation of millimeter wave folded-waveguide TWT”, in Proc. Int. Vacuum Electronics Conf., May 2003, pp. 322-323.
[4] S. Bhattacharjee, J.H. Booske, C.L. Kory, D.W. van der Weide, S. Limbach, S. Gallagher, J.D. Welter, M.R. Lopez, R.M. Gilgenbach, R.L. Ives, M.E. Read, R. Divan, and D.C. Mancini, “Folded waveguide traveling-wave tube sources for terahertz radiation,” IEEE Trans. Plasma Sci., vol. 32, no.3, pp. 1002-1014, June 2004.
[5] Magic User’s Manual, ATK Mission Res. Inc., Newington, VA, 2004.