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2019

Shao, W., Xu, D., Wang, Z., Gong, H., Lu, Z., Duan, Z., . . . Aditya, S. (2019). Stacked dual beam electron optical system for THz integrated wideband traveling wave tube. *Physics of Plasmas*, 26(6), 063106-. doi:10.1063/1.5096331

<https://hdl.handle.net/10356/87450>

<https://doi.org/10.1063/1.5096331>

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Cite as: Phys. Plasmas **26**, 063106 (2019); doi: [10.1063/1.5096331](https://doi.org/10.1063/1.5096331)

Submitted: 16 March 2019 · Accepted: 27 May 2019 ·

Published Online: 12 June 2019

View Online

Export Citation

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Wei Shao,¹ Duo Xu,¹ Zhanliang Wang,¹ Huarong gong,¹ Zhigang Lu,¹ Zhaoyun Duan,¹ Yanyu Wei,¹ Yubin Gong,¹ and Sheel Aditya²

AFFILIATIONS

¹National Key Laboratory of Science and Technology on Vacuum Electronics, School of Electronic Science and Technology, University of Electronic Science and Technology of China, Chengdu 610054, China

²Satellite Research Centre, Nanyang Technological University, Singapore 639798

ABSTRACT

In this paper, a stacked dual beam electron gun and the associated electron optical system are proposed. The stacked dual beam electron gun includes two compact focusing electrodes which help to achieve dual sheet beams. As an application of this dual beam electron gun, a 340 GHz integrated dual beam traveling wave tube (TWT) based on the staggered dual vane slow-wave structure (SWS) is also put forward. In order to reduce the length of the TWT, a novel input/output coupler is introduced. The overall transmission characteristics of the SWS structure together with the input/output couplers show a wide bandwidth covering a frequency range of 306 GHz to 360 GHz. Based on the parameters obtained for the integrated TWT, a stacked dual-beam electron gun with dual focusing electrodes is designed to achieve a beam current of 43 mA, a beam voltage of 21.4 kV, and a cross-sectional size of each beam of 0.3 mm × 0.08 mm. A uniform magnetic field of 0.52 T is utilized to focus the dual electron beams, and a beam transmission efficiency of 97.1% is achieved over a length of 50 mm. Finally, particle in cell simulation results show that the integrated dual-beam TWT can generate an output power of 5 W over the frequency range of 315 GHz to 350 GHz, with the maximum output power of 24.5 W at 330 GHz.

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I. INTRODUCTION

Recently, vacuum electron devices (VEDs) in the THz wave band have attracted a lot of attention. Owing to their characteristics of high power and high efficiency, these devices have potential applications in satellite communication, high-resolution radars, electronic counter-measures, and bio-imaging.^{1,2}

The VED family includes traveling wave tubes, gyrotrons, magnetrons, klystrons, etc. Among these, traveling wave tubes have the advantages of high power, wide bandwidths, and high efficiency. Since the first traveling wave tube was proposed by Kompfner in 1943,³ the family of traveling wave tubes (TWTs) has been growing and different types of TWTs, such as helix TWT, coupled-cavity TWT, folded waveguide TWT, and staggered double vane TWT, have been widely studied.^{4–6}

However, the size of the TWT decreases with the increase in the operating frequency. In particular, in the THz wave band, the size becomes very small, with a corresponding drop in the output power. Power combining is one of the solutions which can improve the output power of the tube. Power combining may be achieved through the combination of separate TWTs or through an integrated TWT. The slow wave structures (SWSs) of the separate power-combining TWTs

are separated from each other and may need multiple magnetic focusing systems. The following is an example of separate power-combining TWTs. In 2013, Northrop Grumman Corporation proposed a 220 GHz folded waveguide TWT with a linear array of five circular electron beamlets propagating through five separate serpentine waveguide SWSs; the short pulse test results showed an output power of 56 W at 214 GHz with a bandwidth of 5 GHz.⁷

Power combining through an integrated TWT is based on the specific structural characteristics of some SWSs. The advantages of power combining through an integrated TWT when compared with the separate TWT power combining technique are that the integration can reduce the size of the whole structure and one just needs a single magnetic focusing system which is more convenient for the assembly. Power combining based on the staggered dual vane structure was carried out in Ref. 8, and a high-power 220 GHz TWT driven by dual electron beams was obtained with an output power of more than 100 W in the frequency range of 200 GHz to 234 GHz with an input power of 50 mW. In 2013, a three-beam TWT with an overmoded staggered dual vane SWS was designed;⁹ the analytical gain calculation indicated that the circuit can amplify the TM₃₁ mode with a gain of 15–20 dB/beam at 64–84 GHz using three 10 kV and 150 mA elliptical

FIG. 1. The sketch of the stacked dual-beam electron gun.

beams. A G-band TWT with a dual gap-groove folded-waveguide was proposed in Ref. 10, and the beam-wave interaction results indicated that the TWT can generate an output power of 278 W with the beam voltage of 21.6 kV and the current of 70 mA.

Each of the electron beams in the beam array used in power combining can have either a circular cross section or an elliptical cross section. The latter cross section corresponds to a sheet beam. In the case of the circular electron beams, considering beam propagation in the z -direction, the array can be oriented along the x - or the y directions and the orientation does not impact the design of the focusing electrodes.^{11,12} But for the sheet electron beams, the design of the focusing electrodes depends on whether the sheet beams are arranged in line along their width or are stacked one above the other along their height. The research about the in-line sheet electron beams has achieved some significant progress in recent years.^{13,14} But there are few reports about the stacked sheet beams. This paper is focusing on the forming, magnetic focusing, and beam-wave interaction of the stacked beams. Compared to the in-line beams, the stacked beams can make the structure compact. Moreover, combination of stacked beams and in-line beams can form a two-dimensional array that can further improve the output power of the integrated TWT.

In this paper, a stacked dual beam electron optical system with dual focusing electrodes is presented and applied to an integrated TWT. The concept of the novel stacked dual beam electron gun is described in Sec. II. A 340 GHz staggered dual vane SWS with a novel input/output coupler is presented in Sec. III. Based on the parameters obtained for the SWS, a dual-beam electron gun is designed, and the simulation results for forming, focusing, and transmission of the stacked dual sheet beams are described in Sec. IV. Beam-wave

interaction simulation results are given in Sec. V. Some useful conclusions are drawn in Sec. VI.

II. CONCEPT OF THE STACKED DUAL-BEAM ELECTRON GUN

The sketch of the stacked dual-beam electron gun is shown in Fig. 1. For a traditional single sheet beam electron gun, the focusing electrode is placed symmetrically around the cathode, leading to an electric field which is also symmetric along the x - and y -directions. The target size of the sheet beam can be achieved by adjusting the location, shape, and potential of the focusing electrode. If one uses a similar arrangement to generate stacked dual beams from two cathodes, the fields for each cathode will become asymmetric; the upper beam will suffer a downward focusing force, and the lower beam will suffer an upward focusing force, causing the two beams to collide. Therefore, it is necessary to find a way to make each beam experience a focusing force which is symmetric with respect to the center of each cathode. This paper utilizes the following novel method to solve this problem.

As shown in Fig. 1, the focusing electrode has a large flare angle along the y -direction, thus having relatively less influence on the focusing of the beams. There are three additional thin strips attached to the focusing electrode and oriented along the x -direction. The strips are placed such that the upper and the middle strips are symmetric about the upper cathode and the lower and the middle strips are symmetric about the lower cathode. The width of the beams (dimension along the x -direction) is controlled with the focusing force generated by the flare angle of the focusing electrode along the x -direction. The height of the beams (dimension along the y -direction) is mainly controlled by the three strips, not the flare angle along the y -direction. The reason for using three strips is that they enable easier control of the electric field as compared to just one strip put at the center of the focusing electrode. Three strips can form symmetric fields with respect to the central xz -plane of both beams. By varying the position, thickness, and length of the strips, the focusing electric fields can be more conveniently adjusted to control the beams more precisely. These three strips are called the secondary focusing electrode in this paper.

For the arrangement shown in Fig. 1, the electric field distribution between the anode and the cathode is shown in Fig. 2. It can be observed that each electron beam experiences identical fields which, in addition, are symmetric with respect to the central xz -plane of both beams.

FIG. 2. The electric field distribution in the yz -plane between the cathode and the anode. (a) Overall field distribution. (b) Zoomed-in field of the region within the red dashed circle in (a).

FIG. 3. A sketch of the staggered vane dual beam SWS. (a) Improved structure proposed in this paper; (b) the staggered vane dual beam structure of Type A proposed in Ref. 8.

TABLE I. The optimized parameters of the unit period SWS.

Parameters	Value (mm)
w	0.5
p	0.31
g	0.09
h	0.18
t	0.12
h_1	0.4

To demonstrate an integrated TWT using the stacked dual beams generated by the proposed electron gun, a staggered dual vane SWS is put forward in Sec. III.

III. STAGGERED DUAL VANE SLOW-WAVE STRUCTURE

The slow wave structure (SWS) as the core component of a TWT influences the performance of the tube greatly. This section describes a 340 GHz staggered dual vane SWS with a novel input/output coupler.

A. Dispersion characteristics of the structure

A sketch of the stacked dual sheet beam SWS is shown in Fig. 3(a). The SWS is an improved version compared to the structure proposed in Ref. 8 and shown in Fig. 3(b). The optimized geometrical parameters of the structure are given in Table I: vane height h , vane thickness g , vane width w , vane period p , beam tunnel height t , and middle vane height h_1 .

The eigenmode of the structure is calculated by CST, and the field distribution is shown in Fig. 4(a). Figure 4(b) shows the Brillouin curve, and it can be seen that the frequency range is around 340 GHz, meeting the design requirement.

The operating voltage U_0 of the structure can be derived from the following equations:

$$v_p = \beta c = c \sqrt{1 - \frac{1}{(1 + \gamma)^2}}, \quad (1)$$

$$\gamma = \frac{U_0}{m_e c^2 / e}, \quad (2)$$

FIG. 4. (a) The distribution of the electric field in the yz-plane. (b) The Brillouin curve and the beam line for 21.4 kV.

FIG. 5. The SWS structure together with the input/output couplers.

where v_p is the phase velocity, β is the phase constant, c is the velocity of light, γ is the relativistic factor, and m_e and e are the mass and the charge of the electron, respectively.

The phase velocity and the phase constant at 340 GHz can be obtained from the dispersion curve shown in Fig. 4(b) so that the theoretical value of operating voltage can be calculated. The beam line of 21.4 kV is plotted in the same figure, and it is tangential to the dispersion curve over a wide frequency range, implying that the structure has a relatively wide bandwidth.

B. Transmission characteristics of the structure

Figure 5 shows the SWS together with the input/output couplers. A single-section SWS with 150 periods is selected. Here, the scheme of input/output coupling is different from the scheme proposed in Ref. 15. To shorten the length of the tube and to reduce the complexity of assembly with the magnetic circuit, the input/output couplers do not require the transition structure and the ridge-loaded taper structure described in Ref. 15. This novel design of input/output couplers can shorten the length of the coupling structure as compared to that in Ref. 15.

As can be seen in Fig. 5, both ends of the SWS consist of short-circuited rectangular end-waveguides. Each of the end-waveguides is further connected to a rectangular coupling waveguide as shown. Each of the two coupling waveguides connects to the input/output waveguide

FIG. 6. The transmission characteristics of the SWS with the input/output waveguide.

ports through a 90° twist. As shown in Sec. II, the field distribution indicates that the E_z components of the electric field in the upper and lower parts of the SWS are out of phase and thus are suitable to match the TE₂₀ mode in the input/output waveguide ports. The size of the standard rectangular waveguide in this paper is selected as 0.71 mm × 0.36 mm.

An optimization of the input/output coupling structure and the SWS is carried out, and the transmission characteristics of the entire high-frequency structure are obtained. These characteristics are presented in Fig. 6 for the SWS dimensions listed in Table I. Port 1 in Fig. 6 refers to the input port, and port 2 refers to the output port. The remaining ports refer to the beam tunnel ports. The conductor loss is considered in simulation,¹⁶ and a conductivity of 1.43×10^7 S/m is used for the material of the high-frequency structure. The reflection coefficient S_{11} is less than -15 dB in the frequency range of 306 GHz to 360 GHz. The transmission coefficient S_{21} varies between -17 dB and -20 dB in this frequency range.

IV. FORMING AND FOCUSING OF THE STACKED DUAL BEAMS

Based on the dimensional parameters of the SWS obtained in Sec. III, a stacked dual-beam electron gun is designed. The separation

FIG. 7. The trajectory of the dual electron beams in the electron gun.

FIG. 8. The cathode emission current of the gun.

FIG. 9. The envelope of the beams along x and y directions.

FIG. 10. 2-D particle distribution at the cross-sectional planes: (a) at the cathode surface and (b) at the beam waist $z = 5.5$ mm.

between the central xz -planes of the two sheet beams is 0.52 mm. Since the size of each beam tunnel is $0.5 \text{ mm} \times 0.12 \text{ mm}$, the cross-section of each sheet beam is selected as $0.3 \text{ mm} \times 0.08 \text{ mm}$. The beam current of each beam is selected to be 43 mA which corresponds to a modest current density of 180 A/cm^2 . The voltage of the cathode and focusing electrode is set as -21.4 kV relative to the anode. The cathode is considered to have two rectangular emission surfaces of size $0.4 \text{ mm} \times 0.2 \text{ mm}$. The simulated beam trajectories are presented in Fig. 7. The electron beams are compressed with different ratios in the x and y directions. The beam waists along both directions occur almost at the same z position, which simplifies the design of the focusing system.

As shown in Fig. 8, the cathode emission currents for both beams converge to 43 mA with thirty iterations. The envelopes of the electron beams along x and y directions in the absence of the focusing magnetic field are plotted in Fig. 9. As can be seen, the beam waists of both electron beams occur at about $z = 5.5 \text{ mm}$. It can also be observed that beyond the beam waists, the beams

FIG. 11. The envelopes of the beams with the ideal 0.5 T uniform magnetic field.

diverge. Figures 10(a) and 10(b) show the two-dimensional particle distribution in the xy -plane at the cathode surface and at $z = 5.5$ mm (beam waist), respectively. The size of the beams at the beam waist is $0.3 \text{ mm} \times 0.08 \text{ mm}$, which meets the design goal. With these, a dual sheet beam electron gun with a beam current of 43 mA, a beam voltage of 21.4 kV, and a cross-sectional size of each beam of $0.3 \text{ mm} \times 0.08 \text{ mm}$ is obtained.

The focusing magnetic field arrangements such as the PCM (periodic cusped magnet field), PPM (periodic permanent magnet field), and Wiggler magnet field can generate the needed magnetic field for a single beam. But to focus well the stacked dual beams in this paper, one needs the uniform magnetic field arrangement because of its uniformity along x and y directions.¹⁷ In the simulation of the beam transmission, we assume a 0.5 T uniform magnetic field, and the details of the beam waists obtained earlier are exported to the simulator. The envelopes of the two beams so obtained are plotted in Fig. 11. For almost 50 mm, the electron beams do not strike the walls of the

beam tunnel, indicating that 100% beam transmission efficiency can be realized with the ideal uniform field.

Based on these considerations, as shown in Fig. 12, a hemi-ladder permanent magnet structure is selected to generate the focusing magnetic field.¹⁸ The magnetization directions of magnetic blocks are also shown in Fig. 12, and the sizes of the blocks are $180 \text{ mm} \times 71 \text{ mm} \times 60 \text{ mm}$, $180 \text{ mm} \times 56 \text{ mm} \times 20 \text{ mm}$, and $180 \text{ mm} \times 34 \text{ mm} \times 20 \text{ mm}$. After some optimization, a magnetic flux density of about 0.52 T,^{19,20} which is uniform over a length of more than 50 mm, is obtained and is shown in Fig. 13. In the simulation of beam transmission, the beam waist of the beam is put at the middle of the rising edge of the magnet field. The corresponding envelopes of the beams are shown in Fig. 14, and it can be seen that a small part of the beams strikes the beam tunnels close to the end of the SWS. Thus, a beam transmission efficiency of about 97.1% is achieved over a distance of 50 mm.

The results presented so far do not consider the velocity/energy spread in the beam. Since the electron gun considered here is a high

FIG. 12. The profile of the magnetic circuit in the yz -plane and magnetization directions.¹⁸

FIG. 13. The axial magnetic flux density of the structure.

FIG. 14. The envelopes of the beams with the designed focusing magnetic field.

voltage and low current electron gun, the effects caused by the velocity or energy spread are expected to be relatively small.^{21,22} To confirm this, we consider the Maxwell-Boltzmann thermal velocity distribution in the CST simulation, with the cathode temperature set as 1400 K.²³ For an oxide-coated cathode, the average initial thermal energy of the electrons is taken to be about 0.08 eV and the maximum energy is taken as 0.1 eV.²¹ Figures 15 and 16 show the comparison of the results with/without thermal velocity distribution; it can be seen that the thermal velocity distribution has very little influence on the beam trajectory.

In a similar manner, the beam transmission with the designed focusing magnetic field is also considered together with the initial thermal energy spread of the electrons. It is seen that the beam transmission efficiency is about 97% over a distance of 50 mm which is the same as that without considering the initial velocity spread.

V. BEAM-WAVE INTERACTION OF THE STACKED DUAL BEAMS

In this section, the beam-wave interaction for the staggered dual vane TWT with dual beams is carried out.²⁴ Beam-wave interaction indicates the performance of the TWT and the usefulness of the dual-beam electron gun.

A 10 mW sinusoidal CW signal is applied as the excitation source of the tube. The other parameters of the electron gun, SWS, magnetic field, and conductivity of copper remain the same as described in Sec. III and IV. The results of average output power and gain vs frequency are plotted in Fig. 17. The output power is greater than 5 W in the frequency range of 315 GHz to 350 GHz with the maximum output power of 24.5 W at 330 GHz. The maximum small signal gain is 34 dB with the 3-dB gain frequency range of 315 GHz to 345 GHz.

FIG. 15. The x-direction envelope of the upper beam with/without thermal velocity distribution.

FIG. 16. The y-direction envelope of the upper beam with/without thermal velocity distribution.

FIG. 17. The average output power and gain vs frequency.

VI. CONCLUSIONS

In this paper, a novel stacked dual-beam electron gun has been proposed and its application has been shown in a 340 GHz integrated TWT based on a staggered dual vane slow-wave structure (SWS). The SWS incorporates a novel input/output waveguide coupler. The simulated transmission characteristics of the SWS along with the input/output couplers indicate that the structure has a good performance over a wide bandwidth of 54 GHz. The dual beam electron gun and the associated electron optical system including the magnetic circuit have been designed to operate with the dual vane SWS. With a uniform magnetic field of 0.52 T, a beam transmission efficiency of 97.1% has been indicated. The output power of this integrated dual-beam TWT has been estimated to be more than 5 W power in the frequency range of 315 GHz to 350 GHz.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (Grant No. 61531010).

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