W-Band Traveling Wave Tube Amplifier Based on Planar Slow Wave Structure

G. Ulisse and V. Krozer, *Senior Member, IEEE*

***Abstract*— A novel planar slow wave structure (SWS) for traveling wave tube (TWT) is proposed. The major advantage of the planar architecture is its easy realization with respect to the typical 3-D SWSs. The particle in cell simulations of the TWT show an achievable gain up to 36.4 dB and a maximum output power of 17.4 W for an operating frequency of 92 GHz. The planar structure can be realized using the standard photolithographic techniques, which improve the reproducibility and performance.**

***Index Terms*— Traveling wave tube, vacuum electronics, vacuum electronic devices, W-band amplifier, planar slow-wave structure, metamaterial, travelling-wave amplifier, 5G communications.**

I. Introduction

NOWADAYS vacuum tubes are employed for a number of specialized applications such as satellite communications, radar, and medical apparatus [1], where the need for high signal power at microwaves and millimeter-waves can't be provided by solid-state devices. In this context a strong research is still ongoing in the optimization of those devices in particular in relation with the electron gun, the slow wave structure (SWS) and the in-out coupling, in order to achieve better performing vacuum electronic devices in terms of efficiency, power and bandwidth. Another aspect for current research is miniaturization and ease of fabrication of vacuum electronic devices, which could lower the device costs.

New applications, such as high-data-rate communications, high-resolution radar, and active imaging in the millimeter-wave and submillimeter-wave bands, demand for availability of compact high-power sources at frequencies beyond W-band, and will be the driving force for vacuum electronics research in the near future [2]. In particular, vacuum electronics could play a fundamental role in 5G mobile communications since the solid state devices cannot provide sufficient transmit power at millimeter-wave frequencies. In fact the 5G architecture will be based also on wireless access network (WAN) at millimeter wave bands (30–300 GHz), where large available bandwidth offers high speed indoor/hotspot communication [3]. Traveling wave tubes (TWT) could be a perfect solution to achieve long distance wireless connection with high data rate beyond 1 km in distance for point–to–multipoint communications [4].

The main obstacle in the realization of a TWT device in the upper W-band frequency range and beyond are the small dimensions of the SWS and the high precision of alignment between the SWS and the electron beam[5]–[7].

The helix TWT amplifiers are one of the most widely used amplifiers thanks to their low operating voltage, wide operating bandwidth, and high efficiency. Like most vacuum electron devices, the size of the helix TWT reduces with the increasing the operating frequency, which limits the use of helix TWT up to a maximum operating frequency of 70 GHz. Also helix structures are essentially 3D structures, which are very difficult to manufacture with high repeated precision. In addition, the packing of the helix into the waveguide and alignment with the electron beam represent major challenges for helices with diameters well below 1 mm.

For the reasons stated above alternative architectures have been studied and developed in order to realize vacuum tube amplifiers operating over 100 GHz [8], [9]. The complexity of such structures requires the applications of state-of-the-art fabrication technologies such as LIGA or SU-8 processes. The fabrication technologies for slow-wave structures for THz vacuum tubes have to assure extremely high accuracy, tolerance control, high-aspect ratio capability, and repeatability due to the many periods employed in TWT.

In order to simplify the realization of the TWT, new architectures were proposed in the last years based on 2D slow wave structures, such as meander lines [10], [11]. Nowadays, only few examples of 2D slow-wave structures were reported in the literature and none of them was based on metamaterials concepts. The 2D slow-wave structure TWT still have issues to be solved before they can be fabricated as prototype devices. In the studied devices an electron sheet beam operating at low voltage, lower than 5 kV, was used requiring excessively high magnetic focusing field, which is very difficult to be realized with known magnetic materials compatible with vacuum tube fabrication. The use of a cylindrical electron beam can significantly simplify the fabrication of TWT devices thanks to their simpler and more mature technology. The cylindrical beam can be generated by a Pierce gun and focused by a standard magnetic focusing system resulting in a simpler and affordable TWT amplifier.

In this work, we propose a new TWT amplifier, working at 92 GHz, based on a planar slow-wave structure based on metamaterial concept that operates with a cylindrical electron beam and a magnetic focusing of only 0.35 T.

Manuscript received October 19, 2016; revised November 1, 2016; accepted November 7, 2016. Date of publication November 11, 2016; date of current version December 27, 2016. This work was supported by the Horizon 2020 research and innovation program (TWEETHER) under Grant 644678. The review of this letter was arranged by Editor H. Mimura.

The authors are with Goethe University of Frankfurt am Main, 60438 Frankfurt, Germany (e-mail: ulisse@physik.uni-frankfurt.de).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LED.2016.2627602

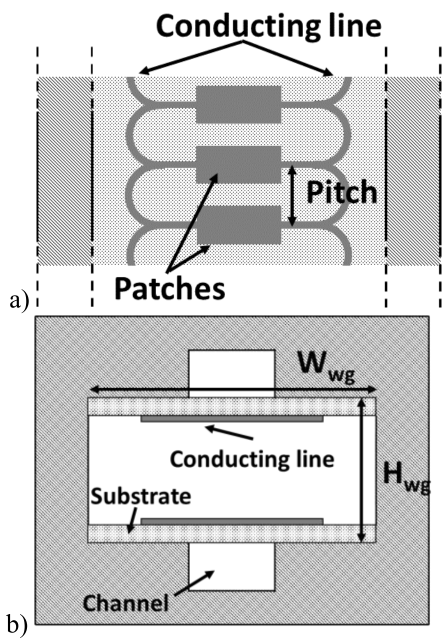

Fig. 1. Schematic of the planar slow wave structure. a) top view; b) front cross section.

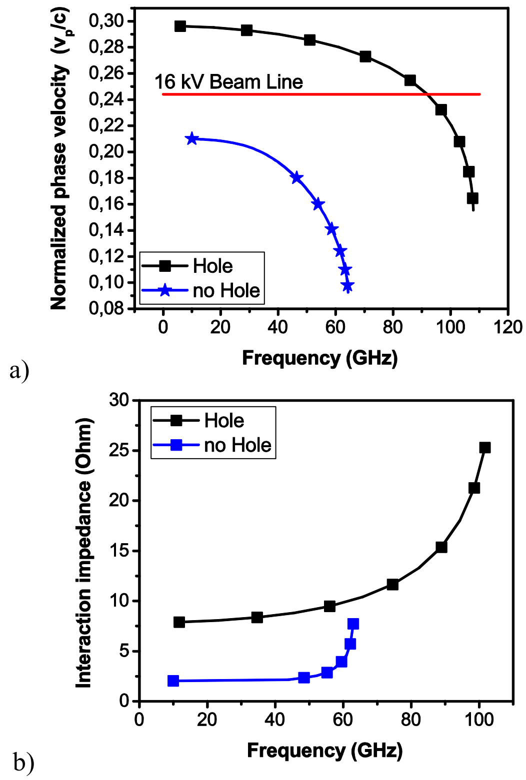

Fig. 2. a) Comparison of the a) phase velocity, b) interaction impedance, of the planar slow wave structure inserted in a waveguide with and without rectangular hole.

II. Planar Slow Wave Structure

The proposed slow wave structure originates from a ring-shaped microstrip meander-line realized on a diamond substrate as shown in Fig. 1a. Two diamond substrates, with a thickness of 20 μm, are then placed into a metallic shield. The metallic shield is a rectangular waveguide with two rectangular channels under the dielectric substrates (see Fig. 1b). The metallic lines have a pitch (p) of 0.2 mm, a width of 20 μm and a thickness of 3 μm. The slow-wave structure on the top of the waveguide is shifted by p/2, along the axial direction with respect to the line on the bottom wall of the waveguide. The shift of p/2 between the top and bottom line is fundamental since a misalignment can strongly reduce the interaction impedance and consequently the gain of the TWT. The waveguide has a width (W_{wg}) of 0.9 mm and a height (H_{wg}) of 0.25 mm. The rectangular channel under the substrates has dimension of 0.15 $\times$ 0.4 mm (See Fig. 1b). The overall slow wave structure constitutes 300 pitch periods. The 300 periods were chosen since over that length there is saturation of the gain and no further amplification can be achieved.

A cylindrical electron beam travels along the central axis of the slow wave structure. The diameter of the electron beam is 0.16 mm. It should be emphasized that no tunnel is foreseen for the electron beam, which simplifies the alignment, since there is no lateral confinement, and operation of the travelling tube device.

III. Results and Discussion

Eigenmode solver was used to determine the cold parameters simulating a single period of the structure. Periodic boundary conditions were applied on the longitudinal direction of the waveguide. Imposing a value of the phase shift on the periodic boundary enables to calculate the eigenfrequency and the interaction impedance [12]. The interaction impedance is computed in the center of the structure along the electron beam axes. Both for the eigenmode and particle in cell calculations we used the CST simulation tool.

Since the structure is complex it's not possible to find an analytical model to easily predict the cold parameters. As first step we fixed the beam voltage and consequently the phase velocity that the electromagnetic wave must have at 92 GHz. A range of possible values for the pitch was calculated considering the following formula $p = (\lambda_e \cdot \theta_n)/2$ where λ_e is the electronic wavelength and θ_n is the normalized phase shift [12]. With a beam voltage of 16 kV at 92 GHz we have $\lambda_e = 0.815$ mm, as a consequence the pitch can be approximately varied from 0.1 mm to 0.4 mm. Parametric simulation varying the geometrical parameters was then performed to optimize the interaction impedance.

In order to increase the operating voltage and the interaction impedance a rectangular channel is considered along the waveguide under the diamond substrate as shown in Fig. 1b.

In Fig. 2 the phase velocity and the interaction impedance with and without the channel in the waveguide are compared. As shown the implementation of the channel inside the waveguide walls permits to tune the phase velocity and consequently the beam voltage. The increase of the operating beam voltage up to 16 kV permits to strongly reduce the magnetic field to 0.35 T. In the works presented in literature on planar slow wave TWT magnetic fields over 0.7 T up

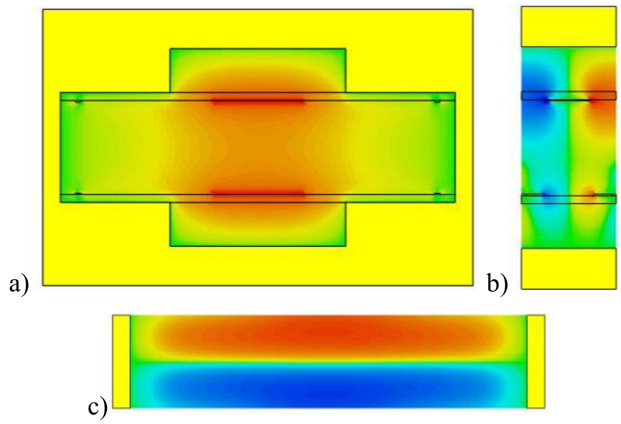

Fig. 3. Normalized axial component of the electric field a) front view, b) lateral view, c) top view.

to 1.4 T [13] were considered, the higher value being at the maximum achievable for known magnetic materials.

As shown in Fig. 2b also the interaction impedance increases adding an air channel underneath the substrate. An interaction impedance of 16.8 Ω was achieved at 92 GHz, which is considerably improved compared to typical values achieved with 3D slow wave structures operating in the same frequency range, such as for example folded waveguide [14]. The patches added along the SWS, as shown in Fig 1a, help to further increase the interaction impedance, in fact the addition of the rectangular patches can improve the interaction impedance by a factor of 2.2 at 92 GHz.

In Fig. 3 we report the normalized axial component of the electric field along the cross sections of the single element of the SWS. It is possible to see that the electric field is mainly concentrated in the middle of the structure and this show how the interaction with a circular beam can be almost optimal.

Once optimized cold parameters have been found, particle in cell (PIC) simulations were performed in order to determine the gain and the bandwidth of the amplifier.

The considered electron beam current is 60 mA that can be easily achieved with a cathode current density of 1 A/cm^2. This current density can be easily achieved with standard thermionic cathodes. The electron beam voltage is assumed to be 16 kV.

In the PIC simulations the waveguide and the metallic striplines are made of copper with a conductivity of $2.25 \cdot 10^7$ S/m according to results previously reported in literature [11]. These values are half of the theoretical conductivity values. The main parameters used in the PIC simulations are summarized in Table 1.

The gain and the bandwidth were calculated considering an input power of 4 mW that can be easily provided with a solid-state signal synthesizer. A maximum gain of 36.4 dB was achieved for 300 periods at 92 GHz with 3 dB bandwidth of 2 GHz. Furthermore, as shown in Fig. 4, gain higher than 30 dB between 88.5 GHz and 93 GHz can be realized.

A maximum output power of more than 17 W at 92 GHz was achieved assuming an input power of 4 mW. The relative efficiency of the TWT amplifier is 1.8 %, which has to be improved in further work.

TABLE I
MAIN PARAMTERS USED IN PIC SIMULATIONS

Parameter	Value
Electron Energy	16 keV
Beam Current	60 mA
Magnetic Field	0.35 T
Beam Diameter	0.16 mm
Input Power	4 mW
Copper conductivity	$2.25 \cdot 10^7$ S/m

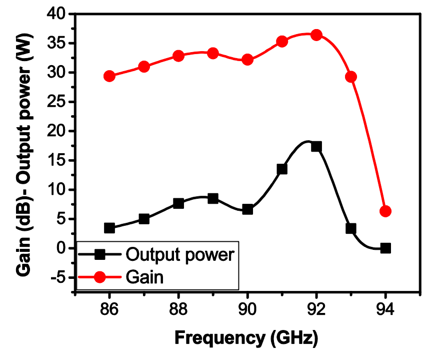

Fig. 4. (Black line, square symbol) Output power, (Red line, circle symbol) gain. Input power 4 mW.

A critical point in this device could be the thermal dissipation of the stripline. Anyway the thermal conductivity of the diamond (800-1000 W/mK) is typically higher than copper (~ 400 W/mK). So we expect that the diamond will quickly dissipate the heat produced from the RF signal. Furthermore the dissipated power in the stripline is several order of magnitude smaller than the output signal so the thermal heating of the conductive line can be neglected.

IV. CONCLUSION

A novel planar slow wave structure for traveling wave tube is proposed and a TWT amplifier using this structure has been designed. Particle in cell simulations show a maximum gain of 36.4 dB and a 30 dB gain across 5GHz bandwidth. An output power of 17.4 W at a frequency of 92 GHz has been found, which is the highest output power reported for a TWT amplifier using planar 2D slow-wave structures. The new TWT architecture can be an important step in the miniaturization and reduction of costs in the realization of W-band TWTs.

REFERENCES

[1] J. Qiu, B. Levush, J. Pasour, A. Katz, C. Armstrong, D. Whaley, J. Tucek, K. Kreischer, and D. Gallagher, "Vacuum tube amplifiers," *IEEE Microw. Mag.*, vol. 10, no. 7, pp. 38–51, Dec. 2009, doi: 10.1109/MMM.2009.934517.

[2] C. Paoloni, R. Letizia, R. Zimmerman, F. Andr, S. Kohler, V. Krozer, G. Ulisse, F. Magne, A. Ramirez, M. Rocchi, M. Marilier, and R. Vilar, "W-band twts for new generation high capacity wireless networks," in *Proc. IEEE Int. Vac. Electron. Conf. (IVEC)*, Apr. 2016, pp. 1–2, doi: 10.1109/IVEC.2016.7561865.

[3] S. E. Alavi, M. R. K. Soltanian, I. S. Amiri, M. Khalily, A. S. M. Supa'at, and H. Ahmad, "Towards 5G: A photonic based millimeter wave signal generation for applying in 5G access fronthaul," *Sci. Rep.*, vol. 6, p. 19891, Jan. 2016, doi: 10.1038/srep19891.

[4] C. Paoloni, F. Magne, F. Andre, V. Krozer, R. Letizia, M. Marilier, A. Ramirez, M. Rocchi, R. Vilar, and R. Zimmerman, "Millimeter wave wireless system based on point to multipoint transmissions," in *Proc. Eur. Conf. Netw. Commun. (EuCNC)*, 2016, pp. 106–110, doi: 10.1109/EuCNC.2016.7561014.

[5] A. S. Gilmour, *Klystrons, Traveling Wave Tubes, Magnetrons, Crossed-Field Amplifiers, and Gyrotrons*. Norwood, MA, USA: Artech House, 2011.

[6] C. Paoloni, M. Mineo, A. Di Carlo, A. Durand, V. Krozer, M. Kotiranta, F. Bouamrane, T. Bouvet, and S. Megtert, "1-THz cascade backward wave amplifier," in *Proc. IVEC*, 2012, pp. 237–238, doi: 10.1109/IVEC.2012.6262146.

[7] C. Paoloni, A. Di Carlo, F. Bouamrane, T. Bouvet, A. Durand, M. Kotiranta, V. Krozer, S. Megtert, M. Mineo, and V. Zhurbenko, "Design and realization aspects of 1-THz cascade backward wave amplifier based on double corrugated waveguide," *IEEE Trans. Electron Devices*, vol. 60, no. 3, pp. 1236–1243, Mar. 2013, doi: 10.1109/TED.2013.2240686.

[8] M. Mineo and C. Paoloni, "Corrugated rectangular waveguide tunable backward wave oscillator for terahertz applications," *IEEE Trans. Electron Devices*, vol. 57, no. 6, pp. 1481–1484, Jun. 2010, doi: 10.1109/TED.2010.2045678.

[9] M. Kotiranta, V. Krozer, and V. Zhurbenko, "Square helix TWT for THz frequencies," in *Proc. 35th Int. Conf. Infr., Millim., Terahertz Waves*, 2010, pp. 1–2, doi: 10.1109/ICIMW.2010.5612585.

[10] C. Ding, Y. Wei, L. Zhang, G. Guo, Y. Wang, M. Zhang, Z. Lu, Y. Gong, W. Wang, D. Li, and J. Feng, "Beam-wave interaction study on a novel Ka-band ring-shaped microstrip meander-line slow wave structure," in *Proc. 39th Int. Conf. Infr., Millim., Terahertz Waves (IRMMW-THz)*, 2014, pp. 1–2, doi: 10.1109/IRMMW-THz.2014.6956271.

[11] F. Shen, Y. Wei, X. Xu, Y. Liu, M. Huang, T. Tang, Z. Duan, and Y. Gong, "Symmetric double V-shaped microstrip meander-line slow-wave structure for W-band traveling-wave tube," *IEEE Trans. Electron Devices*, vol. 59, no. 5, pp. 1551–1557, May 2012, doi: 10.1109/TED.2012.2188635.

[12] M. Mineo and C. Paoloni, "Double-corrugated rectangular waveguide slow-wave structure for terahertz vacuum devices," *IEEE Trans. Electron Devices*, vol. 57, no. 11, pp. 3169–3175, Nov. 2010, doi: 10.1109/TED.2010.2071876.

[13] F. Shen, Y. Wei, H. Yin, Y. Gong, X. Xu, S. Wang, W. Wang, and J. Feng, "A novel V-shaped microstrip meander-line slow-wave structure for W-band MMPM," *IEEE Trans. Plasma Sci.*, vol. 40, no. 2, pp. 463–469, Feb. 2012, doi: 10.1109/TPS.2011.2175252.

[14] J. He, Y. Wei, Y. Gong, W. Wang, and G. S. Park, "Investigation on a W-band ridge-loaded folded waveguide TWT," *IEEE Trans. Plasma Sci.*, vol. 39, no. 8, pp. 1660–1664, Aug. 2011, doi: 10.1109/TPS.2011.2157176.