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COMPARISON OF THz BACKWARD WAVE OSCILLATORS BASED ON CORRUGATED WAVEGUIDES

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Abstract—The backward wave oscillator is a promising and powerful source at THz frequencies. The rectangular corrugated waveguide is an effective solution as slow wave structure to design backward-wave oscillators (BWOs), suitable to be fabricated by photolithographic high-aspect ratio processes. However, assembling and vacuum pumping are a critical issue. In this paper, a corrugated waveguide with the width of the corrugation narrower than the waveguide width will be investigated as slow wave structure for BWOs. A relevant improvement from the point of view of the assembling, together with even better performance will be demonstrated. Two backward wave oscillators, at 1 THz central frequency, designed with conventional and narrow corrugated waveguide will be compared in terms of output power and frequency band of tuning.

1. INTRODUCTION

The huge potential of applications at THz frequencies is well known due to a large number of theoretical and experimental studies [1–3]. Unfortunately, it has not yet exploited due to the lack of sources with performance, dimensions, weight and price appealing for the market. The effort to fill the power gap between microwave and optics is demonstrated by the number of research teams active in the field, working on solid state, optical or vacuum electron devices at THz frequencies. Vacuum electron tubes are certainly the most promising solution in the low THz range (0.1–1.5 THz) when relative high power is required [4, 5]. The backward wave oscillator (BWO) is a very simple device [6, 7]. Its working mechanism is based on the interaction

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of the electron beam with the first negative space harmonic of the RF field. The phase velocity has the same direction of the electron velocity, whilst the group velocity is in the opposite direction. Its main characteristics, such as a relatively simple realization, a wide tuning range, the electronic tuning, the stability in frequency, were proved in the past. The BWO is actually the only THz vacuum power source commercially available [8], even if limited to a few mW of output power.

Three-dimensional simulators, electromagnetic and particle-in-cell, and the new high aspect-ratio photolithographic fabrication processes [9, 10], give the opportunity to greatly improve BWOs performance at THz frequencies. Folded waveguide and corrugated waveguide were preferred as interaction structures for the device. The first realization of a backward wave oscillator was the Carcinotron (1985) that showed about 2 mW at 850 GHz [11]. A 650 GHz folded waveguide source demonstrated 59 mW [12]. BWOs based on corrugated waveguide and sheet beam were designed with relevant output power and tunability [13, 14]. The rectangular corrugated waveguide was demonstrated suitable for the realization of backward wave oscillators and to support a sheet electron beam. The advantage of a sheet electron beam is to provide a relative high current with a low current density. However, the magnetic focusing is still a challenging issue.

Even if corrugated waveguides are suitable to be fabricated by photolithographic technique, the required high aspect-ratio or the assembling imperfections due to the sealing of the closing wall, could be critical and affect the final performance. The vacuum pumping is surely another issue to consider. To overcome these problems, a corrugated waveguide with the corrugation narrower than the waveguide width is investigated. The advantages from the manufacturing point of view are remarkable. The interacting field is concentrated around the corrugation and far from the lateral walls. The sealing and eventual fabrication defects do not sensitively affect the field propagation. Further, the vacuum pumping is highly eased, due to the hollow nature of the structure.

The purpose of this paper is to demonstrate that THz BWOs, using the narrow corrugated waveguide as slow wave structure (SWS), can achieve similar or even better performance than the ones using the conventional wide corrugated waveguide. A comparison of the performance of two 1-THz BWOs, one designed with a conventional wide corrugated waveguide and the other with a narrow corrugated waveguide, is proposed.

2. BACKWARD WAVE OSCILLATOR DESIGN

Two backward wave oscillators were designed at about 1 THz adopting two different corrugated waveguides as slow wave structure: the wide corrugated waveguide, shown in Fig. 2(a), and the narrow corrugated waveguide, a rectangular waveguide with the corrugation narrower than the waveguide width, shown in Fig. 2(b) [15]. The schematic is shown in Fig. 3. The design goals for both the BWOs were: 20% frequency tuning range at 1 THz central frequency, by a beam-voltage sweep from 8 kV to 16 kV, and an output power higher than 100 mW. The electron beam current was fixed at 8mA and the beam cross-section dimensions were fixed at 80 μm width and 20 μm thickness (a moderate 4 : 1 ratio) [16, 17]. The beam axis was placed at a distance $\delta = 15\,\mu\mathrm{m}$ from the corrugations for avoiding collisions with the metal surfaces. A focusing magnetic field of 1 T was applied to keep the electron beam confined. Copper losses ($\sigma = 5.8 \cdot 10^7 \cdot \Omega^{-1} \cdot \mathrm{m}^{-1}$) were considered. The different distributions of the z-component electric field are shown in Fig. 2 as well. In case of the narrow corrugated waveguide, the E_z field almost completely surrounds the corrugation and is located far from the lateral walls. This assures very low sensitivity to possible assembly defects.

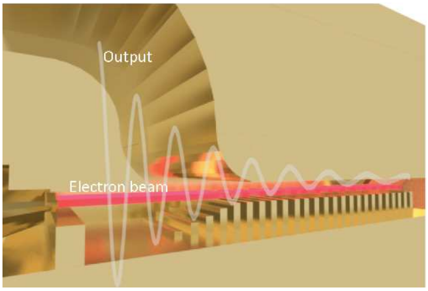
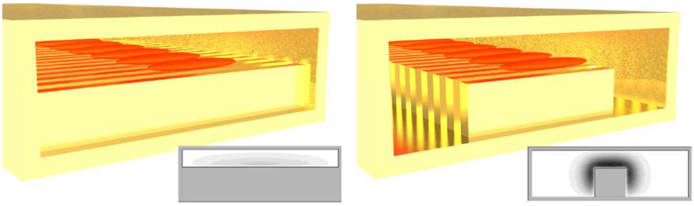


Figure 1. Backward wave oscillator.



(a) (b)

Figure 2. Rendering and electric field distribution of the wide corrugated waveguide (a) and the narrow corrugated waveguide (b).

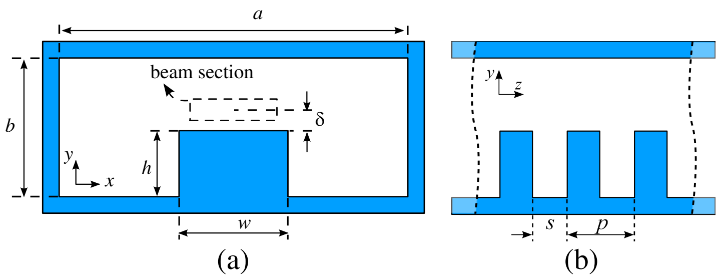


Figure 3. Schematic of the corrugated waveguide, (a) front view, (b) side view.

To make the BWOs comparable, the two SWSs were designed to have the same dispersion behavior. It was first designed a narrow corrugated waveguide by three-dimensional electromagnetic code [18]. The height of the corrugation h (that mainly determines the upper cut-off frequency) and the period p (that mainly determines the phase velocity of waves and consequently the beam voltage for synchronism) were optimized to get the required performance. The width w of the corrugation has to be wider than the electron beam width to guarantee an efficient interaction. The dimensions a and b of the rectangular waveguide were chosen to ease the output coupling.

Once the dimensions of the narrow corrugated waveguide were established, a wide corrugated waveguide, characterized by the same dispersion curve, was accurately designed by the analytical model in [19]. The height b of the waveguide was kept fixed at 127 μm, whilst the width was varied to match the lower-cut-off frequency of the narrow corrugated waveguide. Then, the height of the corrugations h and the space between the corrugations s were adjusted to get the same upper cut-off frequency and the same slope of the dispersion curve of the narrow corrugated waveguide. The dimensions of the two corrugated waveguides are listed in Table 1. The comparison of the cold parameters as a function of the beam voltage is shown in Fig. 4. The dispersion curves are practically the same for both the corrugated waveguides, but the narrow corrugated waveguide has lower losses and higher interaction impedance (computed on the beam axis).

The interaction length for both the BWOs is fixed at 150 periods. The dimensions of the output waveguide are fixed at 240 μm width and 127 μm height for both the corrugated waveguides, and it is vertically offset to the SWS axis to allow the electron beam flow (Fig. 1). The output couplers were designed to match the rectangular waveguide port with very low insertion loss (better than 0.5 dB) in the frequency tuning range. The matching between the output rectangular waveguide and

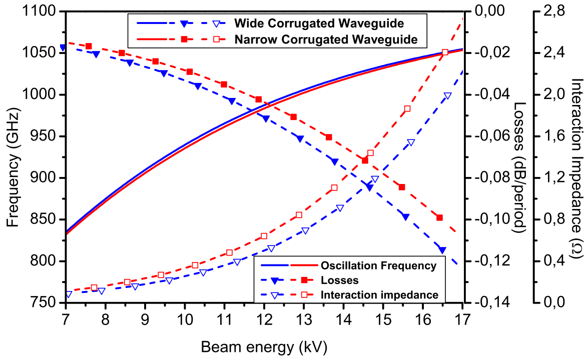


Figure 4. Comparison of the cold parameters.

Table 1. Corrugated waveguide dimensions (μm).

Parameter	Wide Corrugated Waveguide	Narrow Corrugated Waveguide
p	50	50
s	30	25
w	318	100
h	61	55
a	318	240
b	127	127

the SWS is obtained by a linear widening of the width of the waveguide enclosure and by a vertical tapering of the corrugations (15 periods).

An evaluation of the sensitivity of the cold parameters of the wide corrugated waveguide to possible fabrication defects was performed. The fabrication is typically performed by assembling the corrugated waveguide, realized by photolithography, with a proper closing surface. The corrugation can be realized in two different directions: y-direction, where the closing surface is the top wall, and x-direction, where the closing surface is the lateral wall. The y-direction realization could suffers from a misalignment of the top plane with the corrugation (Defect 1) Fig. 5(a). A possible defect in x-direction realization (Defect 2) is a not perfect contact between the closing lateral wall and the corrugation that creates an air gap (Fig. 5(b)). The effect on the cold parameters due to these defects were simulated by eigenmode code (beam-voltage 12 kV) and compared to the nominal values, for different values of displacement Δx. The relevant variation of the cold parameters shown in Fig. 6 demonstrates the high sensitivity of the wide corrugated waveguide to these fabrication defects (not present in the narrow corrugated waveguide).

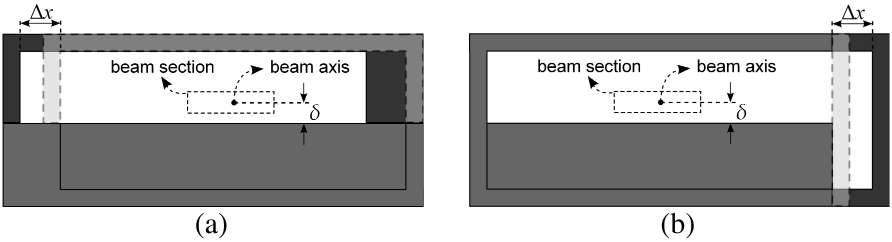


Figure 5. Schematic of Defect 1 (a) and Defect 2 (b).

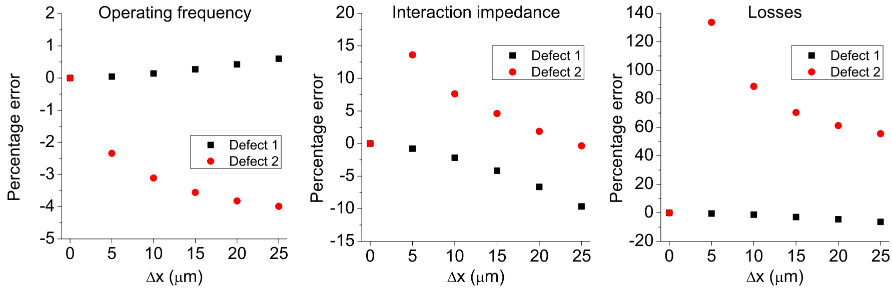


Figure 6. Cold parameters as a function of Δx for Defects 1 and Defect 2.

3. RESULTS

The hot simulations were performed by a three dimensional particle-in-cell code [20]. Fig. 7 shows the power spectrums obtained for the wide corrugated waveguide BWO (a), and the narrow corrugated waveguide BWO (b), for five of different beam voltages in the tuning range 8–16 kV.

The two BWOs provide a similar frequency tuning range from about 0.85 THz to 1.03 THz. The tuning bandwidth is +/− 10% with about 0.94 THz central frequency. The output power and the electronic efficiency are compared in Fig. 8. The narrow corrugated waveguide BWO provides better performance in most of the frequency band of operation. The output power is higher than 23 dBm in most of the frequency range, with a 4% maximum variation with respect to the average value of 24 dBm. The higher electronic efficiency demonstrates a better beam-wave interaction.

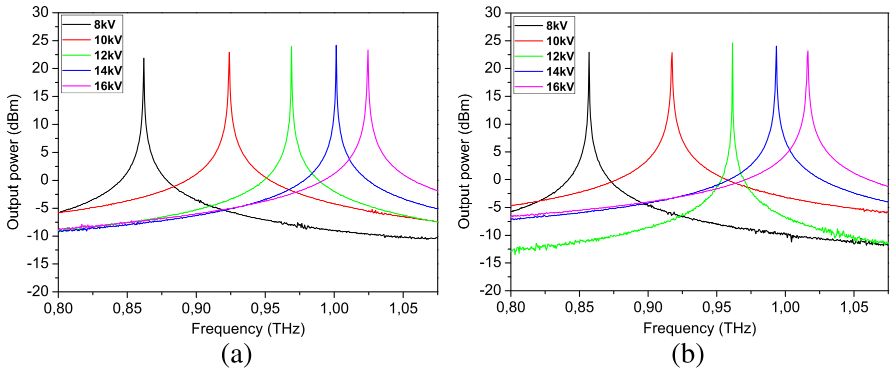


Figure 7. Comparison of power spectrum as function of the beam voltage tuning range. (a) Wide corrugated waveguide. (b) Narrow corrugated waveguide.

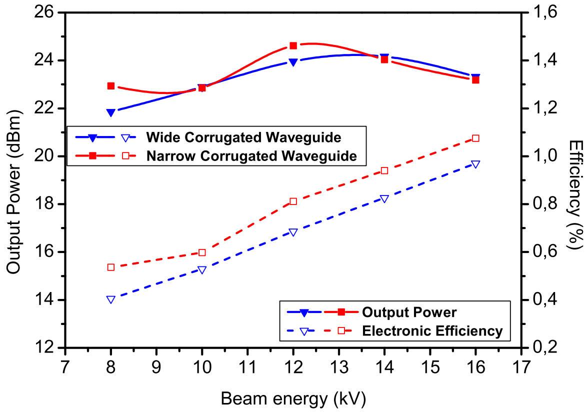


Figure 8. Comparison of the output power, electronic efficiency.

4. CONCLUSIONS

The use of the narrow corrugated waveguide in the design of THz BWO was proved convenient and effective in comparison to the use of a conventional wide corrugated waveguide. The better output power performance, together with the advantages from the point of view of fabrication and vacuum pumping, demonstrate the validity of the choice. The high level of output power, better than 23 dBm, and the frequency range of tuning wider than 20% confirm the BWO based on corrugated waveguides as a promising source for generation of power at THz frequencies.

REFERENCES

1. Federici, J. F., B. Schulkin, F. Huang, D. Gary, R. Barat, F. Oliveira, and D. Zimdars, "THz imaging and sensing for security applications — Explosives, weapons and drugs," *Semiconductor Science and Technology*, Vol. 20, No. 7, S266–S280, 2005.
2. Siegel, P. H., "Terahertz technology," *IEEE Transactions on Microwave Theory Techniques*, Vol. 50, 910–928, Mar. 2002.
3. Sirtori, C., "Applied physics: Bridge for the terahertz gap," *Nature*, Vol. 417, 132–133, May 2002.
4. Booske, J., R. Dobbs, C. Joye, C. Kory, G. Neil, G.-S. Park, J. Park, and R. Temkin, "Vacuum electronic high power terahertz sources," *IEEE Transactions on Terahertz Science and Technology*, Vol. 1, No. 1, 54–75, Sep. 2011.
5. Korolev, A. N., S. A. Zaitsev, I. I. Golenitskij, Y. V. Zhary, A. D. Zakurdayev, M. I. Lopin, P. M. Meleshkevich, E. A. Gelvich, A. A. Negirev, A. S. Pobedonostsev, V. I. Poognin, V. B. Homich, and A. N. Kargin, "Traditional and novel vacuum electron devices," *IEEE Transactions on Electron Devices*, Vol. 48, 2929–2937, Dec. 2001.
6. Gewartowski, J. and H. Watson, *Principles of Electron Tubes*, Van Nostrand, NJ, 1965.
7. Johnson, H., "Backward-wave oscillators," *Proceedings of the IRE*, Vol. 43, No. 6, 684–697, Jun. 1955.
8. Borisov, A., U. Budzinsky, S. Bykovsky, A. Galdetskiy, A. Korolev, M. Lopin, A. Negirev, V. Pugnin, G. Ruvinsky, and B. Sazonov, "The development of vacuum microwave devices in Istok," *IEEE International Vacuum Electronics Conference (IVEC)*, 437–438, Feb. 2011.
9. Shin, Y.-M., D. Gamzina, L. Barnett, F. Yaghmaie, A. Baig, and N. Luhmann, "UV lithography and molding fabrication of ultrathick micrometallic structures using a KMPR photoresist," *Journal of Microelectromechanical Systems*, Vol. 19, No. 3, 683–689, Jun. 2010.
10. Shin, Y.-M., J.-K. So, S.-T. Han, K.-H. Jang, G.-S. Park, J.-H. Kim, and S.-S. Chang, "Microfabrication of millimeter wave vacuum electron devices by two-step deep-etch x-ray lithography," *Applied Physics Letters*, Vol. 88, No. 9, 091916, 2006.
11. Guidee, P. and L. Teyssier, "A 850–1000 GHz backward-wave oscillator for advanced applications," *Society of Photo-optical Instrumentation Engineers (SPIE) Conference Series*, ser. Society

of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, E. Kollberg, Ed., Vol. 598, 93–98, 1986.

12. Tucek, J., D. Gallagher, K. Kreischer, and R. Mihailovich, "A compact, high power, 0.65 THz source," *IEEE International Vacuum Electronics Conference (IVEC)*, 16–17, Apr. 2008.
13. Mineo, M. and C. Paoloni, "Corrugated rectangular waveguide tunable backward wave oscillator for terahertz applications," *IEEE Transactions on Electron Devices*, Vol. 57, No. 6, 1481–1484, Jun. 2010.
14. Mineo, M. and C. Paoloni, "Backward wave oscillators for THz applications based on corrugated waveguide," *IEEE International Vacuum Electronics Conference (IVEC)*, 265–266, Feb. 2011.
15. Mineo, M. and C. Paoloni, "Narrow corrugation rectangular waveguide for terahertz TWTs," *Electronics Letters*, Vol. 46, No. 13, 927–928, 2010.
16. Field, M., R. Borwick, V. Mehrotra, B. Brar, J. Zhao, Y.-M. Shin, D. Gamzina, A. Spear, A. Baig, L. Barnett, N. Luhmann, T. Kimura, J. Atkinson, T. Grant, Y. Goren, and D. E. Pershing, "1.3 : 220 GHz 50 W sheet beam travelling wave tube amplifier," *IEEE International Vacuum Electronics Conference (IVEC)*, 21–22, IEEE, May 2010.
17. Shin, Y.-M., L. R. Barnett, and N. C. Luhmann, "Phase-shifted traveling-wave-tube circuit for ultrawideband high-power submillimeter-wave generation," *IEEE Transactions on Electron Devices*, Vol. 56, No. 5, 706–712, May 2009.
18. *CST User Manual*, [Online]. Available: http://www.cst.com.
19. Mineo, M., A. Di Carlo, and C. Paoloni, "Analytical design method for corrugated rectangular waveguide SWS THz vacuum tubes," *Journal of Electromagnetic Waves and Applications*, Vol. 24, Nos. 17–18, 2479–2494, 2010.
20. Goplen, B., L. Ludeking, D. Smith, and G. Warren, "User-configurable MAGIC for electromagnetic PIC calculations," *Computer Physics Communications*, Vol. 87, Nos. 1–2, 54–86, 1995.