Design and Simulation of a High-Power 48GHz Gyroklystron Amplifier for Accelerator Applications

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***Abstract*—A 48GHz gyroklystron amplifier has been designed using particle-in-cell (PIC) simulation techniques. The beam is provided by a magnetron injection gun (MIG). The gyroklystron is predicted to deliver 2MW of output power at 48GHz with a gain of 35dB and an efficiency of 38%. The design was developed with consideration of the harmonic linearizer of a linear accelerator (linac) that is being designed as part of the H2020 CompactLight X-ray free electron laser (XFEL) project.**

Keywords—Gyroklystron; Magnetron Injection Gun; Microwave Amplifier; Vacuum Electronic Devices

I. Introduction

The gyroklystron is an amplifier based on the principle of the cyclotron resonance maser (CRM) mechanism [1], wherein power is extracted through interaction of an electron beam with the fields in a series of cavities. The application of gyroklystrons has mainly been in radar applications [2, 3]. Although the prospect of gyroklystron-driven accelerators has been explored [4], klystrons are still favored in practice. However, the output power that can be achieved with a klystron falls off at very high frequencies. C-band and X-band drive frequencies are currently of interest to improve acceleration gradients in linacs. While the drive power can be delivered at these frequencies by commercial klystrons, to achieve high-quality bunching requires a linearization system. The most well-developed technique is harmonic linearization [5] which utilizes an additional cavity driven at a harmonic of the drive frequency. The harmonic frequency may be K-band or higher, at which point the gyroklystron is a strong candidate to overcome the difficulty of delivering high power. MW-level, K-band multi-beam klystrons are also being designed but as yet no commercial amplifiers are available [6]. The gyroklystron presented in this work operates at 48GHz and is appropriate to drive an 8^{th} harmonic linearizer for a 6GHz injector or a 4^{th} harmonic linearizer for a 12GHz injector.

II. Design Mehtodology

A. Magnetron Injection Gun (MIG)

A triode-type magnetron injection gun has been developed as part of this work [6]. The initial parameters were estimated using the Baird trade-off equations for MIG design [8]. These parameters were then optimized in TRAK [9]. A multi-objective genetic algorithm considering 11 geometric parameters and 4 field parameters was used to develop an optimized design.

B. Interaction Circuit

The interaction circuit was developed through a combination of theoretical models in conjunction with particle-in-cell simulation techniques [10]. Reference [10] details the process and main results. The analysis of the interaction circuit has been presently expanded upon with consideration of phase stability and further analysis on the effect of the spread in velocity ratio α.

C. Vacuum Windows

Vacuum windows have been designed using CST microwave studio to analyse the S-parameters in detail. The input window uses a pillbox-type window, with rectangular sections equivalent to a WR22 standard waveguide which was selected to match the input waveguide structure without introducing the need for additional tapers or steps. For the same reason, a single-disc simple output window was selected for the output.

III. Results and Analysis

A. MIG and Interaction Circuit

The gyroklystron was predicted to achieve 2.3MW of output in the ideal beam case as presented in [10], as shown in Fig. 1. In practice, an ideal beam cannot exist and as there is always some level of spread in the values for velocity v and velocity ratio α, arising from cathode geometry and space-charge effects. The trajectories of the electrons in the MIG are shown in Fig. 2.

The spread was minimized by the design of the MIG, with a resulting α-spread of 8.9%. The expected power output accounting for this spread is 2.0MW. More detailed discussions of the interaction circuit and MIG are presented in [10] and [7] respectively. The linearizer requires a high level of phase-stability. The phase stability can be calculated by the method presented in [11].

This work was supported by the EPSRC, UK, with additional support from the Cockcroft Institute, UK, and the European Union's Horizon2020 research and innovation programme "Compact-Light" under Grant Agreement No. 777431.

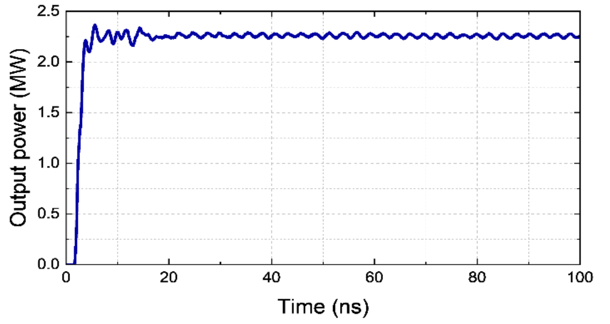

Fig. 1. Output power of the gyroklystron with an ideal beam.

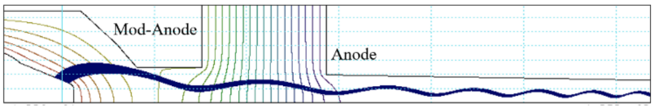

Fig. 2. Geometry, field lines, and electron beam trajectories in the triode-type magnetron injection gun.

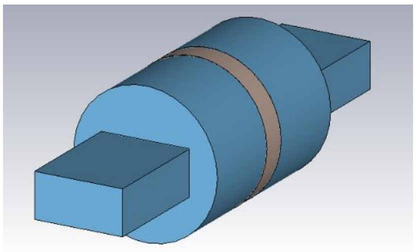

Fig. 3. Geometry of the pillbox-type input window

The phase stability was calculated to be 0.26° per 0.01% of the modulator's voltage stability. Therefore, with the current standard of modulator commercially available [12], the gyroklystron is theoretically able to meet the high stability requirement of a typical linearizer system.

B. Vacuum Windows

The input window was designed with a pillbox-type structure, as shown in Fig. 3. The ceramic disc was assigned a relative dielectric constant of 9.4 matching that of 99.4% Al_2O_3, which was selected for its balance of mechanical, thermal, and optical properties. The initial estimates of pillbox radius and ceramic thickness were optimized to minimize reflection. The maximum allowable reflection signal amplitude was chosen as -35dB at the centre frequency (48GHz) and -20dB within the gyroklystron's 3-dB bandwidth (47.8 to 48.2GHz). Based on a conservative estimate of 10μm precision in machining, the reflected amplitude was at most -44dB at 48GHz and -26dB within the bandwidth as shown in Fig. 4. With higher machining precision, these reflection characteristics may be improved by a modest amount. The output window design was a single disc matched to the cylindrical output section of the gyroklystron. Boron nitride was selected as the window material as it is a relatively low-cost material that can still offer appropriate thermal properties for the high pulse repetition frequency of 1kHz and 1.5μs pulsed operation regime required by the harmonic lineariser for the X-ray FEL. Power reflected from the output window is more harmful than the input window as it would travel back toward the interaction circuit. Therefore, a stricter limit of -35dB reflection was set as the target maximum over the device bandwidth. This was achieved in simulation, but sub-μm precision would be required to meet this threshold in practice.

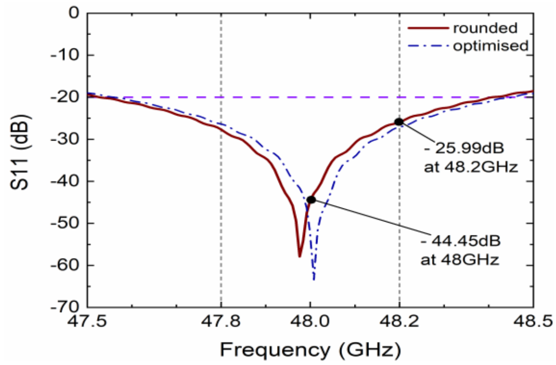

Fig. 4. Reflection Parameters of the input window with optimal dimensions and with dimensions rounded to the nearest 10μm.

IV. CONCLUSIONS

The design of a high-power 48GHz gyroklystron has been presented. The MIG is predicted to achieve an α-spread of 8.9%. Further simulations of the interaction circuit conclude that this level of spread makes the expected output power 2.0MW, compared with the ideal beam case of 2.3MW. Phase stability calculations show that the gyroklystron is able to deliver good stability, but this is primarily dependent on the modulator properties. Input and output windows have also been designed. The input window displays excellent reflection properties. The output window can also meet the chosen reflection requirement if machining tolerance is high enough.

REFERENCES

[1] J. L. Hirshfield and J. M. Wachtel, "Electron Cyclotron Maser," *Physical Review Letters,* vol. 12, no. 19, pp. 533-536, 1964.

[2] A. A. Tolkachev, B. A. Levitan, G. K. Solovjev, V. V. Veytsel, and V. E. Farber, "A megawatt power millimeter-wave phased-array radar," *IEEE Aerospace and Electronic Systems Magazine,* vol. 15, no. 7, pp. 25-31, 2000.

[3] G. J. Linde, M. T. Ngo, B. G. Danly, W. J. Cheung, and V. Gregers-Hansen, "WARLOC: A high- power coherent 94 GHz radar," *IEEE Transactions on Aerospace and Electronic Systems,* vol. 44, no. 3, pp. 1102-1117, 2008.

[4] W. Lawson, J. P. Calame, G. S. Nusinovich, and B. Hogan, "Reflections on the university of Maryland's program for investigating gyro-amplifiers as potential sources for linear colliders," *Terahertz Science and Technology,* vol. 10, no. 1, pp. 1-43, 2017.

[5] T. I. Smith, "Production of intense low emittance beams for free electron lasers using electron linear accelerators," *Nuclear Instruments and Methods in Physics Research, A,* vol. 250, no. 1, pp. 64-70, 1986.

[6] I. Syratchev, J Cai et al, G. Burt et al, "Design and simulation of a 36GHz, 2.5MW Multi Beam (20) Klystron for accelerator applications", accepted for IEEE Transactions on Electron Devices, 2020.

[7] L. Zhang, L. J. R. Nix, and A. W. Cross, "Magnetron Injection Gun for High-Power Gyroklystron," *TED,* vol. 67, no. 11, pp. 5151-5157, 2020.

[8] J. Mark Baird and W. Lawson, "Magnetron injection gun (MIG) design for gyrotron applications," *International Journal of Electronics,* vol. 61, no. 6, pp. 953-967, 1986.

[9] *Trak 8.0: Electron/ion Gun Design and Charged Particle Dynamics (User Manual).* Albuquerque, New Mexico, USA: Field Precision LLC.

[10] L. J. R. Nix *et al.*, "Demonstration of efficient beam-wave interaction for a MW-level 48 GHz gyroklystron amplifier," *Physics of Plasmas,* vol. 27, p. 053101, 2020.

[11] G. S. Park, V. L. Granatstein, P. E. Latham, C. M. Armstrong, A. K. Ganguly, and S. Y. Park, "Phase stability of gyroklystron amplifier," *IEEE Transactions on Plasma Science,* vol. 19, no. 4, pp. 632-640, 1991.

[12] Scandinova, "Product Sheet: K-series K100," *https://scandinovasystems.com/products/k-series/k100*