Upgrades of W-band gyro-TWA system for high PRF operation

Craig R. Donaldson, Liang Zhang, Adrian W. Cross, and Colin G. Whyte
Department of Physics
University of Strathclyde
Glasgow, UK

Abstract: *A broadband, high-power gyrotron traveling wave amplifier (gyro-TWA) was demonstrated to show single-shot millimeter wave output over a 3 dB bandwidth of 91-96.5 GHz, with max. power of 3.4 kW and gain of 36-38 dB. Following on from this, the system will be upgraded for high, Pulse Repetition Frequency (PRF) output, suitable to be employed in radar applications. Amongst the changes required is the design and construction of a modulated anode electron gun and water cooled collector system to be installed with a cryogenic liquid free, up to 5.5 T, superconducting magnet to replace a conventional solenoid.*

Keywords: gyrotron traveling wave amplifier; broadband amplification; helically corrugated waveguide.

Introduction

The realization of millimeter wave (mm-wave) amplifiers has increasingly become in-demand due to their many emerging applications. Slow-wave vacuum electron devices, such as the traveling wave tubes, are increasingly limited in both power and bandwidth at mm and sub-mm wavelengths, while also relying on difficult micromachining techniques. The gyrotron devices, based on the cyclotron resonance maser instability, are in the fast-wave class and can circumvent some of the problems experienced with their slow-wave counterparts such as electron beam propagation through the slow wave structure. The gyrotron traveling wave amplifier (gyro-TWA) is one of the members of the gyro-device family and it is able to produce high power coherent mm-wave and sub-mm-wave radiation. As an amplifier, the amplitude and phase of the gyro-TWA can be precisely controlled therefore it is attractive in applications such as communications, radar and electron spin resonance spectroscopy.

A W-band gyro-TWA using a helically corrugated interaction region (HCIR) [1] has been developed at the University of Strathclyde. The measured output from the gyro-TWA of amplification over 91-96.5 GHz with a maximum output power of 3.4 kW at a gain of 36-38 dB matched well with expectations but was limited by the maximum power and bandwidth available from the input source [2]. To realise many of the aforementioned applications the output is required to have a high PRF of around 10 kHz, while both the power and bandwidth being closer to simulated maximums of 5 kW and 10 GHz respectively. This paper reports the upgrades to the gyro-TWA system to meet these targets.

The main reason why this gyro-TWA has been able to show such high power over a wide bandwidth is because its interaction region is not smooth-bore but has an internal helical corrugation. The HCIR has both azimuthal and axial periodicities and the geometry is chosen so that two modes one close to cutoff and one propagating far from, are resonantly coupled creating an eigenmode closely aligned with the second harmonic electron beam dispersion. By carefully choosing the corrugation parameters, an ideal dispersion curve that has a nearly constant group velocity over small wavenumber values crossing a large frequency bandwidth can be achieved. The gyro-TWA was driven by an axial encircling large orbit electron beam which was generated by a cusp electron gun [3]. It was able to operate at the 2nd cyclotron harmonic therefore only half of the magnetic field strength as compared to the fundamental harmonic interaction was required.

Measured Results

The previous iteration of the gyro-TWA [2] was constructed and microwave output measured. The electron beam was 1.5 A with an accelerating voltage of -55 kV. The microwave input was from a solid state source with maximum power of 1.5 W. The amplified microwave signal, shown in Fig. 1, demonstrated a bandwidth of 91-96.5 GHz which was limited by the input source. The simulated performance was determined by the 3D Particle-In-Cell (PIC) code MAGIC and shows a larger 91-100 GHz range could be achieved with the same input parameters.

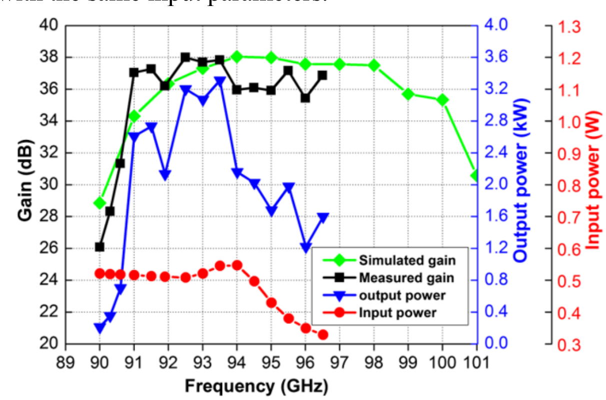

Figure 1. Measured output from the gyro-TWA with simulated data.

Further experiments investigated further the potential for this amplifier to be used in communication experiments. The voltage was reduced to 40 kV and a frequency-swept input signal was amplified over a 1 GHz bandwidth with a gain of 30 dB demonstrated [4].

Proposed Experimental Setup

The improved gyro-TWA design is shown in schematic diagram, Fig. 2. The key components of the amplifier include; cusp electron gun, pillbox window, input coupler, elliptical polarizer, input and output windows, HCIR, and the solenoid systems. The experiment also required a high-voltage power supply to drive the electron beam. In the updated gyro-TWA changes include, an enclosed cryo-free superconducting magnet (CFM) (1), water cooled collector (2) and modulated anode electron gun (3). Further work will investigate a reduction in loss through the input coupler, where the 1.5W of output power from the solid state source is is fed into the fast-wave circuit where 0.5W is available for amplification. Recently a lot of work has gone into the design of low loss input couplers [5].

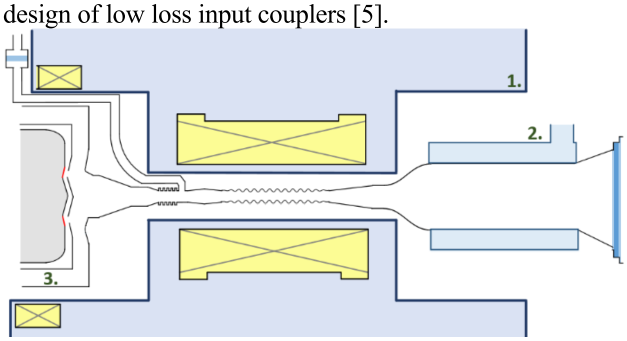

Figure 2. Schematic of the experimental setup of the updated gyro-TWA.

The CFM superconducting magnet has many benefits over a conventional solenoid including stable and stand-alone operation, especially when operating at a DC magnetic field of 2 T. This magnet has been designed with the reverse coil, required by the cusp electron gun, included within the superconducting magnet enclosure which can be varied enabling the beam alpha to be adjusted.

The collector would be situated after a nonlinear waveguide taper to allow the electron beam to spread over a large surface area. Water cooling will suffice to handle the expected heat load and maintaining the waveguide temperature is key when looking to increase the PRF rate up to 10 kHz with the mm-wave pulse length adjusted to ensure a maximum duty cycle of 1.5% where both the rising temperate and also worsening vacuum levels will be monitored to remain within limits for reliable operation.. A temperate and also worsening vacuum levels will be monitored to remain within limits for reliable operation. A high average power modulator to drive the gyro-TWA is currently under procurement.

Modulated Anode Electron Gun

The operation of the modulated anode electron gun [6] employs an electrode just in front of the cathode surface with a -1 kV bias voltage. The modulated anode electrode can be quickly switched on-off through adjustment of the applied voltage from -1 kV to +500 V. The structure was fully optimised through simulations in MAGIC with the electron beam trajectories of the ideal geometry shown in Fig. 3. Analysis of the beamlets in the flat-top magnetic field region gives an alpha spread of 11% at a centre value of 1.12 and with a biased voltage in the range of 950-1050 V.

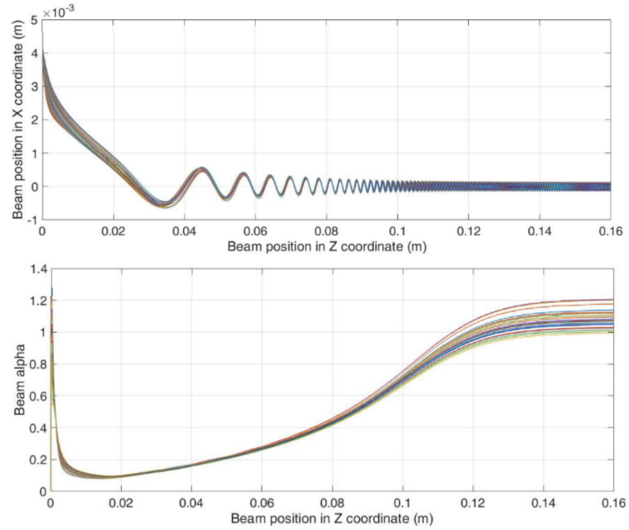

Figure 3. Modulated anode cusp electron gun (top) electron trajectories and (bottom) beam alpha

Acknowledgement

This work was supported by EPSRC UK (research Grant No. EP/G036659/1, EP/K029746/1) and STFC UK (research Grant No. ST/N002326/1, ST/P001890/1 and ST/T003227/1).

References

1. S. V. Mishakin, S. V. Samsonov, “An Approach to Thermal Analysis of Helically Corrugated Waveguide Elements of Vacuum Electron Devices,” IEEE Trans. Microw. Theory Techn., 66, pp. 5206-5211, 2018.
2. W. He, et. al, "Broadband Amplification of Low-Terahertz Signals Using Axis-Encircling Electrons in a Helically Corrugated Interaction Region," Phys. Rev. Lett., 119, 184801, 2017.
3. C.G. Whyte, et. al, “Wideband gyro-amplifiers,” IEEE Trans. Plasma Sci., 40, pp. 1303-1310, 2012.
4. L. Zhang, et. al, "Amplification of frequency-swept signals in a W-band gyrotron travelling wave amplifier," IEEE Electron Dev. Lett., 39, pp. 1077-1080, 2018.
5. G. G. Denisov, et. al, Radiophysics and Quantum Electronics, "New radiation input/output systems for gyrotron traveling-wave tubes," Radio. Quantum Electron., 58, pp. 769-776, 2016.
6. L. Zhang, C. R. Donaldson, and W. He, "Optimization of a triode-type cusp electron gun for a W-band gyro-TWA," Phys. Plasmas, 25, 043120, 2018.