A W-band gyrotron traveling wave amplifier

C.R. Donaldson, W. He, L. Zhang, P. McElhinney, K. Ronald, and A.W. Cross

Department of Physics, SUPA, University of Strathclyde, Glasgow, Scotland, UK, G4 0NG
craig.donaldson@strath.ac.uk

Abstract:
A gyrotron traveling wave amplifier (gyro-TWA) with a cusp electron gun and a helically corrugated waveguide operating in the W-band is presented. When driven by an electron beam of energy 40 keV and current 1.5 A, the amplifier is simulated to output 5-10 kW (CW) with a 3 dB frequency bandwidth of 90-100 GHz and saturated gain of 40 dB. Linear analysis, numerical simulation and experimental results will be presented.

Introduction:
The Gyro-devices are high power coherent microwave sources that excel at high frequencies (up to the terahertz range). The Gyro-devices are suited to high frequency operation due to the fast-wave cyclotron resonance maser instability. Due to these attractive properties there are a number of application for such devices including high resolution RADAR, plasma diagnostics, communications and cloud imaging. Recently Gyro-devices in the form of both a gyro-TWA and gyrotron backward wave oscillator (gyro-BWO) [1] operating in the W-band have been developed at the University of Strathclyde. The design, simulation and experimental results of the gyro-TWA are presented.

The gyro-TWA has a wide bandwidth of operation compared to conventional devices. Using an interaction region with a helical corrugation [2] of the inner surface can further increase the frequency bandwidth while maintaining the already high efficiency. These devices are driven by a cusp electron gun [3,4,5] which can generate an axis-encircling annular electron by passing an electron beam through a magnetic field direction reversal just in front of the cathode surface. The University of Strathclyde has been undertaking experiments on helically corrugated waveguides in the last few years. These are on both the gyro-TWA [6] and the gyro-BWO. Experiments in X-band have achieved 1.1 MW output power with 29% electronic efficiency and 21% relative 3 dB bandwidth [7]. While a gyro-BWO operating in the W-band has achieved 12 kW output power over 88-102.5 GHz [8].

Beam-wave interaction:
A gyro-TWA amplifier with helically corrugated waveguide [9] is capable of achieving broadband amplification with superior efficiency to smooth bore gyro-TWAs due to its favourable dispersion. The wave dispersion is changed such that the eigenwave has an almost constant value of group velocity of a wide frequency band in the region of small axial wavenumbers. This increases the band if resonant electron-wave interaction.

The 3D PiC code MAGIC was used to simulate the interaction between electron beam and microwaves. The predicted performance can be seen in Fig. 1. This shows the output power of 5 kW with a 3 dB frequency bandwidth with saturated gain of 40 dB can be achieved over the 90-100 GHz range.

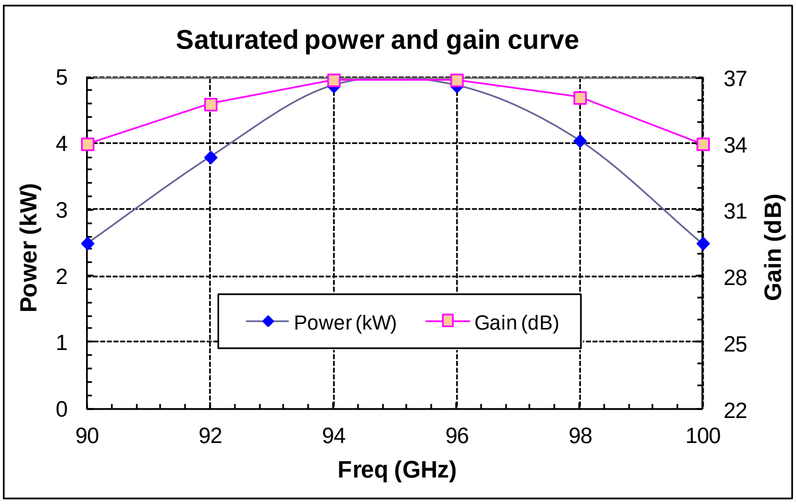

Fig. 1 Simulated saturated power and gain as a function of input frequency..

Broadband components:
Many broadband components have had to be designed and measured for application in the circuit of the microwave system including: input coupler, window [10], polarizer [11] and Bragg reflector. A side-wall rectangular to circular input coupler has been designed that introduces the microwave signal to the interaction region. This uses a pill-box cavity with ceramic disc to seal the vacuum. In conjunction with the input coupler a Bragg reflection is used to stop microwaves entering the diode region. This is used instead of a normal cut-off filter as it enlarges the beam tunnel to assist electron beam transport.

Quasi-optical output system:
A quasi-optical mode converter, shown in Fig 2, in the form of a corrugated horn has been designed through numerical simulation, manufactured and experimentally measured for application in the gyro-TWA [12]. The horn will convert a cylindrical TE_{11} mode into a free space TEM_{00} mode. This also allows for transportation through an electrical break to enter a collector system [13,14], which will increase the overall efficiency of the device. The horn was modelled effectively using the mode-matching method. Mician uWave Wizard was employed to allow fast implementation and optimization of various geometries. The simulated results showed a Gaussian couple efficiency of ~98% and measured results show a reflection of better than -30 dB, as shown in Fig. 2, over 88-102 GHz, and directivity of 26.6 GHz at 95 GHz.

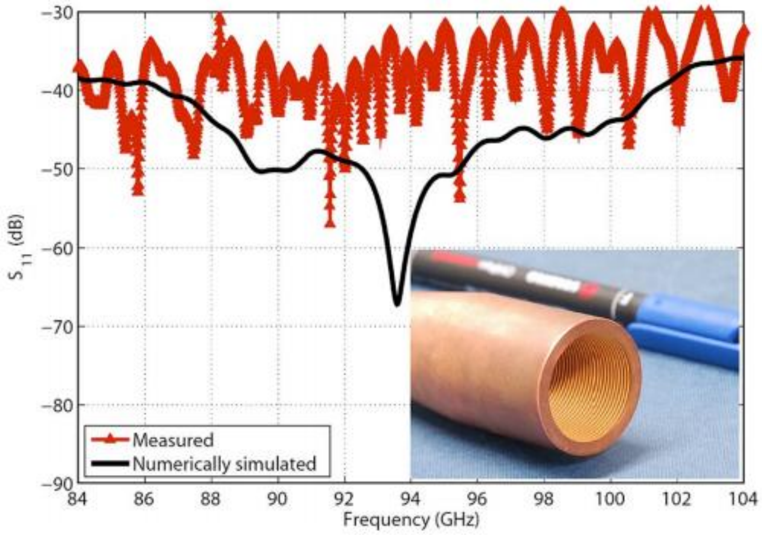

Fig. 2 Numerically simulated and measured reflection of the microwave window. A photo and block diagram of the measurement setup are inset.

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References:

[1] W. He, C.R. Donaldson, L. Zhang, K. Ronald, A.D.R. Phelps, and A.W. Cross, "Numerical simulation of a gyro-BWO with a helically corrugated interaction region, cusp electron gun and depressed collector," Numerical simulations of physical and engineering processes, ISBNL 978-953-307-620-1. InTech.
[2] V.L. Bratman, G.G. Denisov, N.G. Kolganoc, S.V. Mishakin, S.V. Samsonov, A.W. Cross, W. He, L. Zhang, M. McStravick, C.G. Whyte, A.R. Young, K. Ronald, C.W. Robertson, and A.D.R. Phelps, “Generation of 3 GW microwave pulses in X-band from a combination of a relativistic backward-wave oscillator and a helical-waveguide compressor,” *Phys, Plasmas*, **17**, 110703, 2010.
[2] C.R. Donaldson, W. He, A.W. Cross, A.D.R. Phelps, et al., “Design and numerical optimization of a cusp-based electron beam for millimetre-wave gyro-devices,” *IEEE Trans. Plasma Sci*., **37**, pp. 2153-2157, 2009.
[3] C. R. Donaldson, W. He, A.W. Cross, F. Li, et al., “A cusp electron gun for millimeter wave gyro-devices”, *Appl. Phys. Lett*., **96**, 141501, 2010.
[4] A.W. Cross, W. He, A.D.R. Phelps, K. Ronald, C.G. Whyte, A.R. Young, C.W. Robertson, E.G. Rafferty, J, Thomson, “Helically corrugated waveguide gyrotron traveling wave amplifier using a thermionic cathode electron gun,” *Appl. Phys. Lett*., **90**, 253501, 2007.

[5] W. He, C.G. Whyte, E.G. Rafferty, A.W. Cross, A.D.R. Phelps, K. Ronald, A.R. Young, C.W. Robertson, D.C. Speirs, and D.H. Rowlands, "Axis-encircling electron beam generation using a smooth magnetic cusp for gyrodevices," Appl. Phys. Lett., **93**, 121501, 2008.
[5] V.L. Bratman, A.W. Cross, G.G. Denisov, W. He, A.D.R. Phelps, K. Ronald, S.V. Samsonov, C.G. Whyte, and A.R. Young, "High-gain wide-band gyrotron traveling wave amplifier with a helically corrugated waveguide," *Phys. Rev. Lett*. **84**, pp. 2746-2749, 2000.
[6] W. He, C.R. Donaldson, L. Zhang, K. Ronald, et al., "High power wideband gyrotron backward wave oscillator operating towards the terahertz region," *Phys. Rev. Lett*. **110**, 165101, 2013.
[7] L. Zhang, W. He, K. Ronald, A.D.R. Phelps, C.G. Whyte, C.W. Robertson, A.R. Young, C.R. Donaldson, and A.W. Cross, "Multi-mode coupling wave theory for helically corrugated waveguide," *IEEE Trans. Microw. Theory Tech*., **60**, pp. 1-7, 2012.
[8] C.R. Donaldson, W. He, L. Zhang, and A.W. Cross, "A W-band multi-layer microwave window for pulsed operation of gyro-devices," *IEEE Microw. Wireless Compon. Lett*., **23**, pp. 237-239, 2013.
[9] L. Zhang, C.R. Donaldson, and W. He, "Design and measurement of a polarization converter based on a truncated circular waveguide," *J. Phys. D: Appl. Phys*., **45**, 345103, 2012.
[10] P. McElhinney, C.R. Donaldson, L. Zhang, and W. He, "A high directivity broadband corrugated horn for W-band gyro-devices," *IEEE Trans. Antennas Propag*. **61**, pp. 1453-1456, 2013.
[11] L. Zhang, W. He, A.W. Cross, A.D.R. Phelps, K. Ronald, and C.G. Whyte, "Numerical optimization of a multistage depressed collector with secondary electron emission for an X-band gyro-BWO," *IEEE Trans. Plasma Sci*., **37**, pp. 2328-2334, 2009.
[12] L. Zhang, W. He, A.W. Cross, A.D.R. Phelps, K. Ronald, and C.G. Whyte, "Design of an energy recovery system for a gyrotron backward wave oscillator," *IEEE Trans. Plasma Sci*., **37**, pp. 390-394, 2009