Experimental test of a W-band gyro-TWA for cloud radar applications

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***Abstract*—In this paper initial experimental results of a W-band gyrotron travelling wave amplifier (gyro-TWA) which is upgraded to operate at a high pulse repetitive frequency of 2 kHz will be presented. The gyro-TWA based on a helically corrugated interaction region and cusp electron beam source can output a maximum power of 5 kW at its centre frequency of ~94 GHz with an instantaneous frequency bandwidth of 10 GHz. The design, upgrade and performance of the amplifier and its components will be presented.**

***Keywords*—Gyrotron travelling wave tube, gyro-TWT, gyro-TWA, gyro-devices, gyro-amplifiers**

I. Introduction

High power broadband gyrotron traveling wave amplifiers (Gyro-TWAs) have promising applications in radar, communications, plasmas diagnostics, imaging, remote sensing, electron spin resonance spectroscopy, and so on. Due to its high performance of power bandwidth the gyro-TWA operating in the Ka and W band have been developed for radar applications [1,2]. In the past gyro-TWA and gyrotron backward wave oscillators based on helically corrugated interaction regions (HCIR) have achieved unprecedented power bandwidth performance [3-7]. The W-band gyro-TWA is designed to amplify with a wide instantaneous frequency bandwidth of 10 GHz (90-100 GHz) and to generate output power of ~5 kW when driven by a 40 kV, 1.5 A large-orbit electron beam. An upgrade of the W-band gyro-TWA, as shown in Fig. 1, to operate at a high pulse repetitive frequency of 2 kHz, is currently being carried out for cloud profiling radar applications at the university of Strathclyde.

The observation and monitoring of clouds, aerosols and precipitation is critical to understanding the earth's atmosphere and a vital prerequisite for the validation of global climate models [8]. Millimetre wave radars are uniquely placed to serve as atmospheric remote sensing tools since their wavelength is appropriate to the size of the particles being probed. In this paper a new class of high power, wideband millimetre wave amplifier which offers a ten-fold increase in available bandwidth and a five-fold increase in available peak power over the amplifiers used in current cloud profiling radars will be presented. This will lead to greater sensitivity of such radars, enabling measurement of smaller or more tenuous particulates, with finer resolution, at longer ranges or in a shorter timescale.

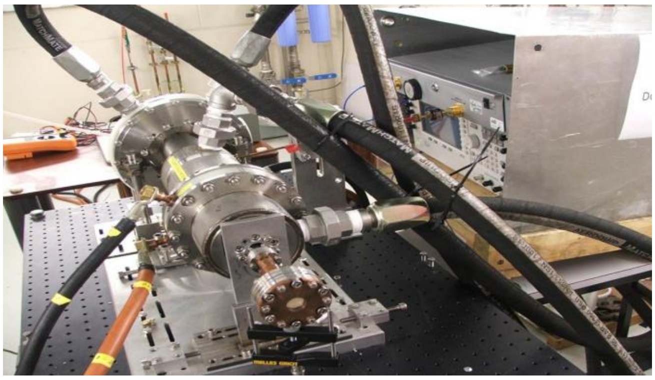

Fig. 1 A photograph of the W-band gyro-TWA experiment.

II. Principle

To increase the bandwidth of the amplifier a three-fold HCIR has been used. The resonant coupling of the TE_{21} mode and the first spatial harmonic of the TE_{11} mode in the HCIR gives rise to an "ideal" eigenwave for the amplifier. The eigenwave, which has an almost constant value of group velocity over a wide frequency band in the region of small axial wave numbers [9], can be readily matched by the dispersion line of an electron cyclotron mode or its harmonics allowing broadband microwave amplification to be achieved in a gyrotron travelling wave amplifier. The HCIR can also be designed to compress microwave pulses [10].

The large-orbit electron beam, generated from a cusp electron gun [11], is ideal for harmonic operation of gyro-devices as the mode selectivity nature of such a beam requires that the harmonic number is equal to the azimuthal index of a waveguide mode for effective beam wave coupling, which leads to a reduced possibility of parasitic oscillations.

III. Structure of the Gyro-TWA

A schematic diagram of the gyro-TWA is showing figure 2. A seed signal, up to 1.5 W was coupled into the gyro-TWA using a rectangular (TE_{10} mode) to circular (TE_{11}), high transmission input coupler [12, 13]. A Bragg reflector was used

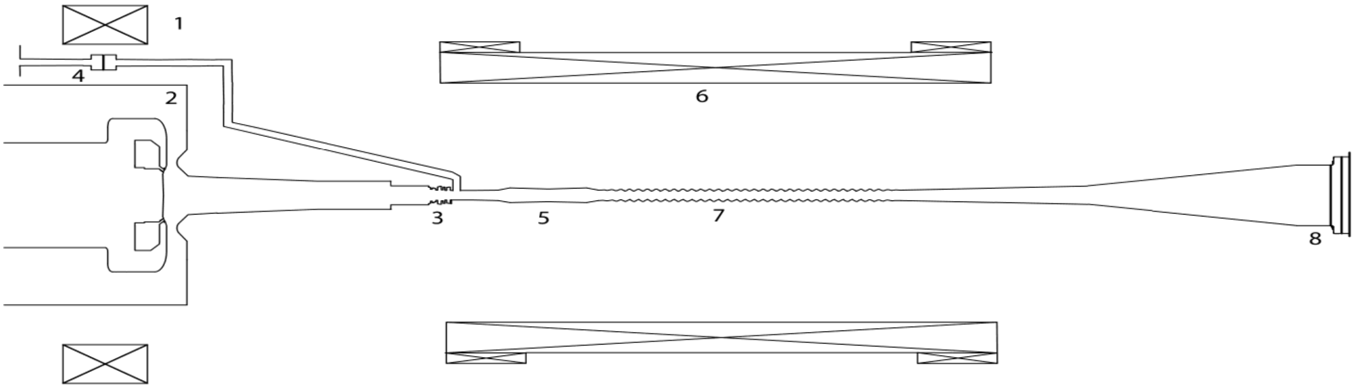

Fig. 2 A schematic drawing of the mm-wave/Terahertz gyro-TWA. (1, 6 - coils, 2 - cusp electron gun, 3 - Bragg reflector, 4 - input coupler, 5 - Elliptical converter, 7 - HCIR, 8 - Corrugated mode converter and output window)

to avoid the electromagnetic wave in the device going back to the electron gun region. An elliptical converter [14] was used to convert the linearly polarized TE_{11} wave into a circular polarized wave which the HCIR requires. The output power of the gyro-TWA was radiated out in the fundamental free space Gaussian mode through a corrugated horn and a low reflection window [15-17]. A long life thermionic annular shaped cathode produced a beam current of 1.5 A and the cusp electron gun generated an annular shaped, axis encircling electron beam with a suitable velocity ratio. Two water-cooled electric magnets were used to generate the required cusp magnetic field for the generation of the axis encircling electron beam and the uniform magnetic field of high amplitude (up to 2.1 T) in the beam-wave interaction. When the beam reaches the HCIR efficient beam-wave interaction based on the cyclotron resonance maser instability occurs and if it is optimally designed the electron beam will coherently give up its energy to the interacting electromagnetic wave and hence the wave grows in power.

IV. Results

Many components have been upgraded for operation at a high pulse repetition rate (PRF) and their microwave properties measured including: broadband input coupler, corrugated quasi-optical mode converter, output window, pulsed power system and water-cooled beam dump.

The new output window was optimized through computer simulation, manufactured and measured to have a reflection of -27 dB which was a nearly 10 times improvement in comparison to the previous output window (Fig. 3 and 4).

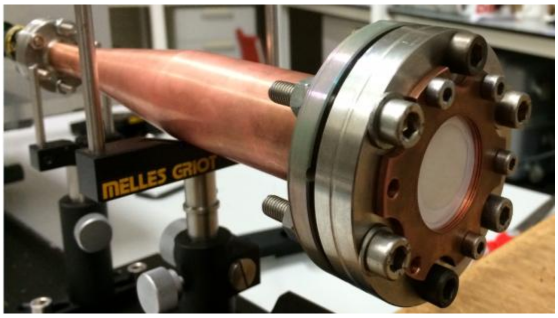

Fig. 3 A photo of the corrugated horn and the output window.

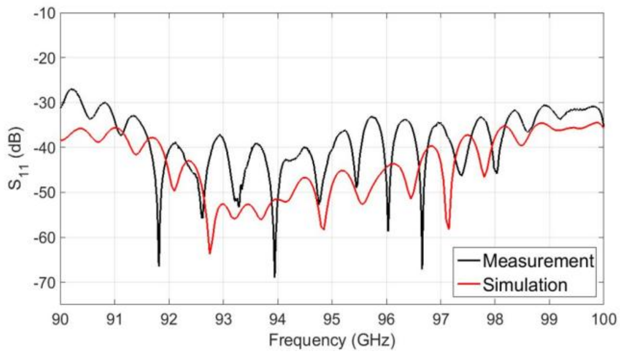

Fig. 4 Measured reflection of the corrugated horn and output window assembly.

The upgraded input coupler (Fig. 5) was improved from its predecessor in three aspects. Its reflection was measured to be 2 dB better, its vacuum leak rate was reduced by an order of magnitude to 10^{-9} mbar/s and it was mechanically more robust.

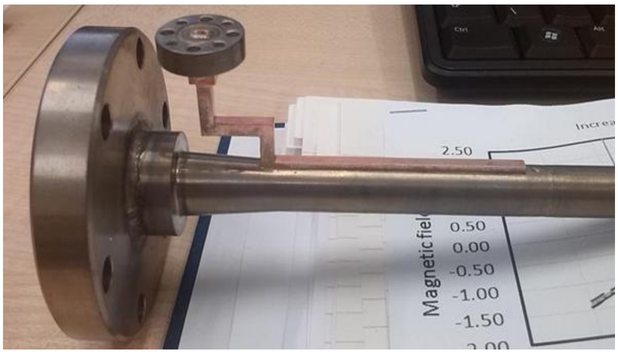

Fig. 5 A photo of the input coupler.

A water-cooled beam dump to accommodate the higher average power associated with an increased PRF has been designed and optimised through thermal simulations and manufactured (Fig. 6). Also a newly designed pulsed power unit (Fig. 7) based on a thyratron as the closing switch has been constructed and measured to be able to operate at a PRF of 2 kHz.

Fig. 6 A photo of water-cooled electron beam dump.

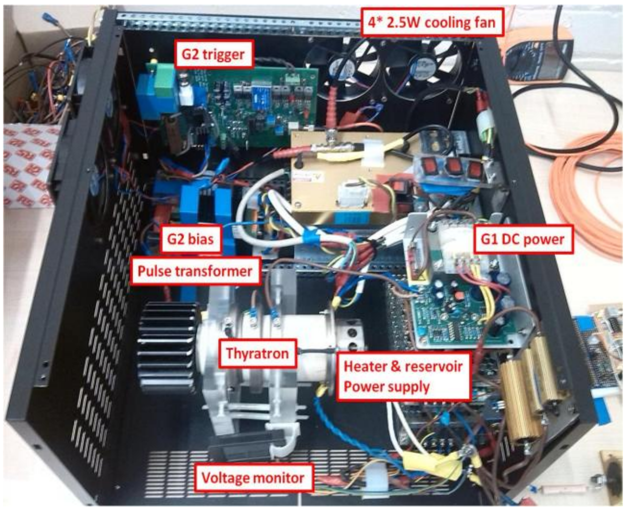

Fig. 7 A photo of the thyratron based pulsed power unit.

The corrugated horn could be used to separate the output electromagnetic wave from the spent electron beam so that the energy of the spent electron beam could be recovered by a depressed collector system. The corrugated horn acts as a mode converter to convert a cylindrical TE_{11} mode into the free space TEM_{00} mode over the frequency band of 90–100 GHz with a reflection better than -30 dB and a coupling efficiency of ~99.4%.

A new thyratron based trigger system was designed and manufactured in conjunction with a double-Blumlein pulse forming network that was used to provide the accelerating field for the electron beam. The electron accelerating potential was measured using a resistive voltage divider, while electron current, typically 1.5 A at operating temperature, was measured using a current transformer. The beam current was measured in the cavity using a Faraday cup, inserted into the beam tube. This beam current of 1.5 A was measured at the normal operating cathode temperature, although it was variable by adjusting the heating power applied to the cathode. The output microwave radiation was detected by two crystal detectors situated inside screened boxes. The output power was calibrated using a known microwave source. The experimental results including the output powers and operating frequency bands were measured. With an input seed signal from an 1.5 W, 90-96 GHz solid state source a gain of 27 dB was measured from the experiment. The bandwidth was measured to be at least 5 GHz.

The radar was prepared in order to integrate it with the gyro-amplifier. Low noise voltage regulators were added to enable operation from a single +24V supply, an adjustable trigger circuit was added to match the radar pulse generator to the pulsewidth and PRF of the gyro-amplifier, and suitable filters was procured to ensure matched filter operation with the gyro-amplifier pulse characteristics. Finally, integration of the radar with the gyro-amplifier was completed by the use of shielded interconnect cables and careful grounding to suppress the interference effects of the high voltage pulse power supply.

The radar's pulsed coherent performance was characterised at low power (~100 mW) at the University of St Andrews to evaluate the baseline performance of the transceiver. This was then compared with the performance obtained at Strathclyde with the gyro-amplifier inserted into the radar circuit to assess the coherent performance in high power (~5 kW) mode. Characteristics including pulse rise/fall time, amplitude flatness, jitter, phase stability, and the effect of PRF were completed. The gyro-amplfifier output signal was measured at short range by reflecting off a low reflectivity target (small sphere) with absorbing beam dumps collecting the stray signal.

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References

[1] K. T. Nguyen, J. P. Calame, D. E. Pershing, B. G. Danly, M. Garven, B. Levush, "Design of a Ka-Band Gyro-TWT for Radar Applications", IEEE Trans. Electron Dev., vol. 48, pp. 108-115, 2001.

[2] M. A. Kempkes, T. J. Hawkey, M. P. J. Gaudreau, R. A. Phillips, "W-Band Transmitter Upgrade for the Haystack UltraWideband Satellite Imaging Radar (HUSIR)", 2006 IEEE International Vacuum Electronics Conference, pp. 551-552, 2006.

[3] 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., vol. 84, pp. 2746-2749, 2000.

[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., vol. 90, 253501, 2007.

[5] W. He, K. Ronald, A. R. Young, A. W. Cross, A. D. R. Phelps, C. G. Whyte, E. G. Rafferty, J. Thomson, C. W. Robertson, D. C. Speirs, S. V. Samsonov, V. L. Bratman, and G. G. Denisov, "Gyro-BWO experiments using a helical interaction waveguide", IEEE Trans. Electron Dev., vol. 52, pp. 839-844, 2005.

[6] W. He, C. R. Donaldson, F. Li, L. Zhang, A. W. Cross, A. D. R. Phelps, K. Ronald, C. W. Robertson, C. G. Whyte, and A. R. Young, "W-band

gyro-devices using helically corrugated waveguide and cusp gun: design, simulation and experiment”, Terahertz Science and Technology, vol. 4, no. 1, pp. 9-19, 2011.

[7] W. He, C. R. Donaldson, L. Zhang, K. Ronald, P. McElhinney, and A.W. Cross, "High power wideband gyrotron backward wave oscillator operating towards the terahertz region," Phys. Rev. Lett., vol. 110, no. 16, 165101, 2013.

[8] K. P. Moran, B. E. Martner, M. J. Post, R. A. Kropfli, D. C. Welsh, and K. B. Widener, "An Unattended Cloud-Profiling Radar for Use in Climate Research", Bulletin of the American Meteorological Society, Vol. 79, No. 3, March 1998.

[9] 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 Techn., vol. 60, no. 1, pp. 1-7, 2012.

[10] L. Zhang, S. V. Mishakin, W. He, S. V. Samsonov, M. McStravick, G. G. Denisov, A. W. Cross, V. L. Bratman, C. G. Whyte, C. W. Robertson, A. R. Young, K. Ronald, A. D. R. Phelps, "Experimental study of microwave pulse compression using a five-fold helically corrugated waveguide", IEEE Trans. Microw. Theory Tech., 63 (3), pp. 1090-1096, 2015.

[11] C. R. Donaldson, W. He, A. W. Cross, F. Li, A. D. R. Phelps, L. Zhang, K. Ronald, C. W. Robertson, C. G. Whyte, and A. R. Young, "A cusp electron gun for millimeter wave gyrodevices," Appl. Phys. Lett., vol. 96, no. 14, 141501, 2010.

[12] J. R. Garner, L. Zhang, C. R. Donaldson, A. W. Cross, and W. He, "Design Study of a Fundamental Mode Input Coupler for a 372-GHz Gyro-TWA I: Rectangular-to-Circular Coupling Methods," IEEE Trans. Electron Devices, vol. 63, no. 1, pp. 497-503, 2016.

[13] L. Zhang, W. He, C. R. Donaldson, J. R. Garner, P. McElhinney, and A. W. Cross, "Design and measurement of a broadband sidewall coupler for a W-band gyro-TWA," IEEE Trans. Microw. Theory Techn., vol. 63, no. 10, pp. 3183-3190, 2015.

[14] L. Zhang, C. R. Donaldson and W. He, "Design and measurement of a polarization convertor based on a truncated circular waveguide", J. Phys. D: Appl. Phys., vol. 45, 345103, 2012.

[15] 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., vol. 61, no. 3, pp. 1453-1456, 2013.

[16] 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., vol. 23, no. 5, pp. 237-239, 2013.

[17] C. R. Donaldson, P. McElhinney, L. Zhang, and W. He, "Wide-band HE11 mode terahertz wave windows for gyro-amplifiers," IEEE Trans. THz Sci. Technol., vol. 6, no. 1, pp. 108-112, 2016.