Status and Ongoing Development of a kW-level Broadband W-band Gyro-TWA

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***Abstract* — A broadband, kW-level gyrotron traveling wave amplifier (gyro-TWA) in W-band was developed based on a helically corrugated interaction region and a cusp electron gun. Experiments were carried out to demonstrate the versatility of the gyro-TWA and to investigate its broad instantaneous amplification bandwidth. Following the successful prototyping, research is being carried out to improve the stability of the amplifier and widen its capability for continuous wave operation for long-range high-data-rate communication applications.**

***Keywords* — gyrotron traveling wave amplifier, broadband amplification, helically corrugated waveguide, frequency-swept.**

I. Introduction

High-power millimeter and submillimeter-wave sources have many applications in plasma diagnostics, communication, accelerator physics, high-resolution radar and wireless communications. Although great progress has been made in recent decades the solid-state sources from one transistor device are limited to a power in the Watts level at ~100 GHz. Similarly, the vacuum electronic devices based on slow-wave interaction structures have achieved around 100 W at ~100 GHz. The fast-wave gyrotron devices based on the cyclotron resonance maser instability have superior power capability, compared to these sources, in the hundreds of GHz frequency range [1]. For example, the fixed frequency gyrotron oscillator used for plasma heating at ITER can achieve more than 1 MW continuous wave (CW) output power at 170 GHz [2]. 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 microwave radiation at millimetre and submillimeter wavelengths. As an amplifier, the amplitude and phase of the gyro-TWA can be precisely controlled therefore it is attractive in applications such as wireless communications, radar and magnetic resonance spectroscopy.

A broadband gyro-TWA operating at W-band that has been developed at the University of Strathclyde is presented. In the experimental measurement, it achieved a 3-dB gain bandwidth of over 5.5 GHz. The output power was more than 3.4 kW and the gain was around 36–38 dB [3].

The kW-level gyro-TWA can be further enhanced through incorporating state-of-the-art W-band solid-state amplifiers as its source. Watt-level millimetre wave source c covering the full amplification bandwidth (~10%) are required for the many important applications of the amplifier listed. A ~40 Gbits/s data rate can be realized over a distance of 13 km if it is used in a communication application. With a high-gain antenna, it can also be used as a ground-to-satellite uplink to provide a data rate ~100 times faster than the current Ka-band satellite communication.

II. Development of Broadband W-band Gyro-TWA

A. Helically corrugated interaction region

Different high-frequency circuits have been developed for beam-wave interaction in gyro-TWAs. Among them, the helically corrugated interaction region (HCIR) with a surface profile of $r(\theta,z) = R_0 + R_1 cos(m\theta + 2\pi z/d)$ that has both azimuthal and axial periodicities shows superior bandwidth capability. Based on the mode-coupling theory, the HCIR can couple two different modes in the circular waveguide to generate new dispersion curves. For example, the three-fold HCIR (m=3) can couple the TE_{21} mode and the spatial harmonic of the TE_{11} mode, to generate two eigenmodes (coupled-mode 1 and 2 in Fig. 1(b)). By carefully choosing the geometry parameters, the coupled-mode 2 can have a nearly constant group velocity at small wavenumber values crossing a large frequency bandwidth and it is ideal for broadband amplification. More details on the HCIR design can be found in references [3-8].

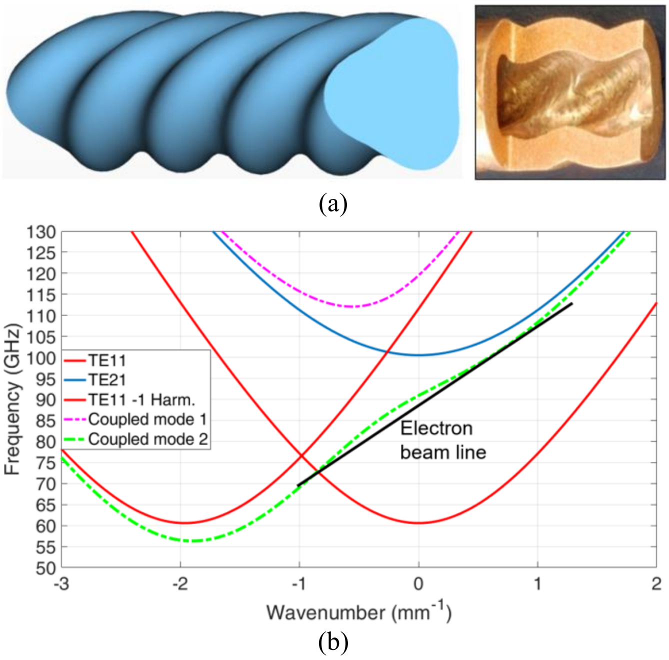
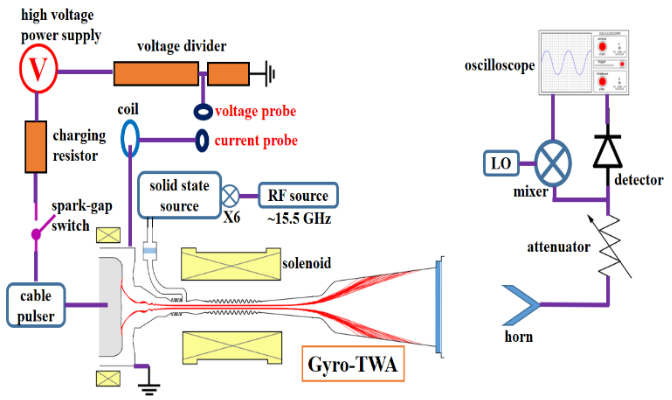


Fig. 1. The CAD drawing (left) and the cut view of a manufactured HCIR (right) (a), and the dispersion curves (b).

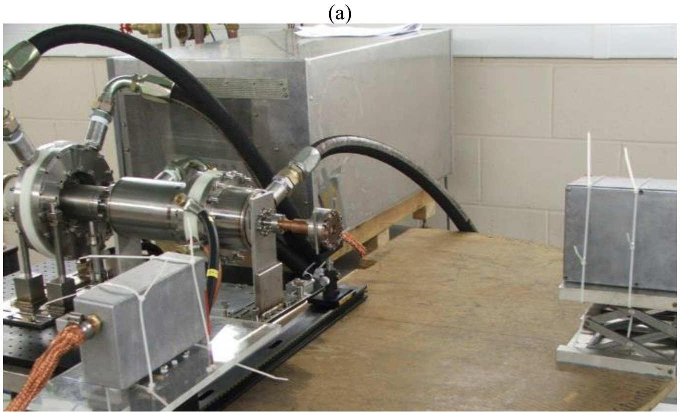
B. Components and experimental setup of the gyro-TWA

Based on the HCIR as the interaction circuit, a W-band gyro-TWA operating in the frequency range of 90 – 100 GHz was developed. The gyro-TWA was driven by an axis encircling large orbit electron beam which was generated by a cusp electron gun [9, 10]. The cusp electron gun also allows the gyro-TWA to operate at the 2nd harmonic electron cyclotron frequency. Therefore, only half of the magnetic field strength was required as compared to fundamental harmonic interaction. For the W-band gyro-TWA, operating at the 2nd electron cyclotron harmonic, the magnetic field strength needed was ~1.8 T.

Apart from the HCIR and the cusp electron gun, the gyro-TWA contains other key components for example: the pillbox-type input window [11] and broadband low reflection multiple-layer output window [12] to ensure the vacuum integrity of the gyro-TWA, the mode converters (input coupler [13], polarization converter [14] and output launcher [15, 16]) to control the mode purity and wave polarization, and a water-cooled solenoid system to generate the required magnetic field profile. The electron beam is accelerated by a high-voltage cable pulser which is able to generate voltage up to 60 kV with a pulse duration of 400 ns. The assembly of the gyro-TWA and a schematic drawing of the experimental setup with the diagnostics circuits are shown in Fig. 2.



(a)



(b)

Fig. 2. The diagram (a) and the setup (b) of the W-band gyro-TWA experiment.

III. Experimental Results

The gain of the gyro-TWA was first measured at discrete frequency points. When driven by a 55 kV, 1.5 A electron beam, it demonstrated a 3-dB gain bandwidth over the frequency range of 91–96.5 GHz. The measured unsaturated output power of 3.4 kW was achieved, and the gain was 36–38 dB. Further study of operating the gyro-TWA at a lower operating voltage at 40 kV was carried out to investigate its versatility. In this case, the other parameters, such as the beam alpha value and the magnetic field strength were adjusted accordingly. Fig. 3 shows the 3D particle-in-cell (PIC) MAGIC simulations with the new parameter sets. As compared with higher operating voltage, the gain dropped about 7 dB and the bandwidth was reduced. However, the radiated microwave power was still over 1 kW.

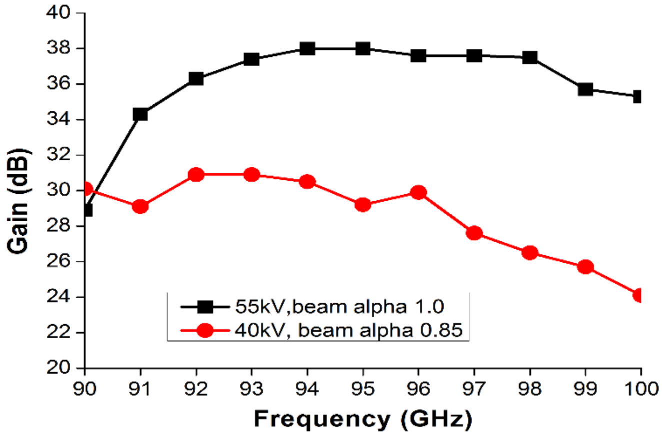


Fig. 3. Comparison of the gain at different parameter sets.

IV. Broadband Amplification for Communication Application

The W-band gyro-TWA has great potential in the communication application to provide long-range high-data-rate communication, for example, ground-to-satellite uplink and city-to-city backhaul communications. To demonstrate the potential of the gyro-TWA for future applications, further improvements were achieved by building an integrated signal generation and measurement system using advanced equipment, from Keysight Ltd, as shown in Fig. 4 [17]. It includes a Keysight arbitrary waveform generator (AWG, model M8190A) to generate an arbitrary waveform with analogue bandwidths up to 5 GHz. The signal was then modulated onto a ~15.5 GHz carrier signal by a Keysight vector signal generator. Then the microwave signal was used to drive a low-power solid-state source to generate the seed signal for the gyro-TWA. To measure the amplified microwave signal and to determine the power level, as well as the spectrum of the time-correlated signal, a waveguide harmonic mixer (Keysight M1970W), a signal analyser (Keysight PXA model N9030A) and a real-time digitizing oscilloscope (Keysight MSOS804A), were used. The whole signal generation and data acquisition/processing system can operate automatically and be controlled remotely.

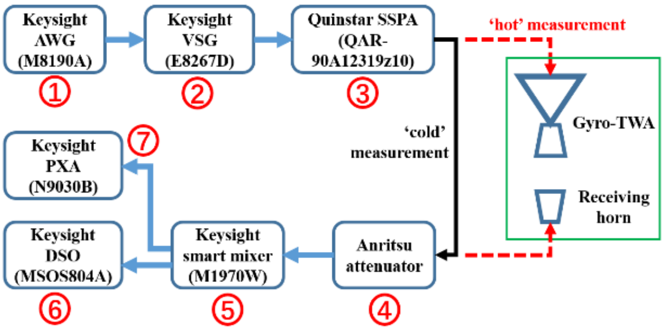
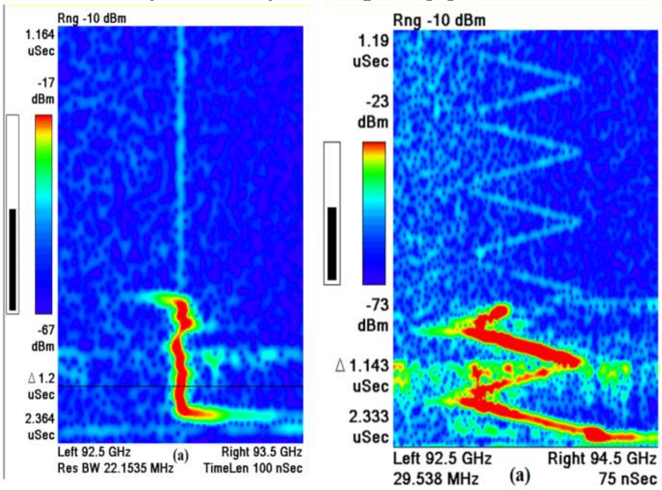


Fig. 4. Signal generation and data acquisition/processing system.

Fig. 5 shows the experimental measurement results for the cases of the single-frequency input signal at 93 GHz (a) and frequency-swept signal (b). It shows clearly that the input signal was amplified by the gyro-TWA. The changes in the frequency component are due to the variation of the output voltage from the high-voltage cable pulser and its rising and falling edge.

The frequency-swept experiment was aimed to study the wide instantaneous bandwidth of the gyro-TWA. However, in the experiment, it was found that the signal was distorted when the bandwidth exceeded 1.0 GHz due to the nonlinear behaviour of the frequency multipliers used in the solid-state source. The noise level can also be examined from Fig. 5. To minimize the noise from the input source in the experiment, the frequency-swept signal was set to a bandwidth of 1.0 GHz at the central frequency of 93.5 GHz. The amplified signal in Fig. 5 showed clear frequency sweeping that aligned well with the input signal. The correlated millimetre-wave signal and the beam voltage are shown in Fig. 5(b). The spectrum of the amplified millimetre-wave signal in Fig. 5(c) showed a bandwidth close but smaller than 1 GHz due to the variation of the beam voltage. The phase information after post-processing shows good agreement between the input and amplified signals [8].



(a)

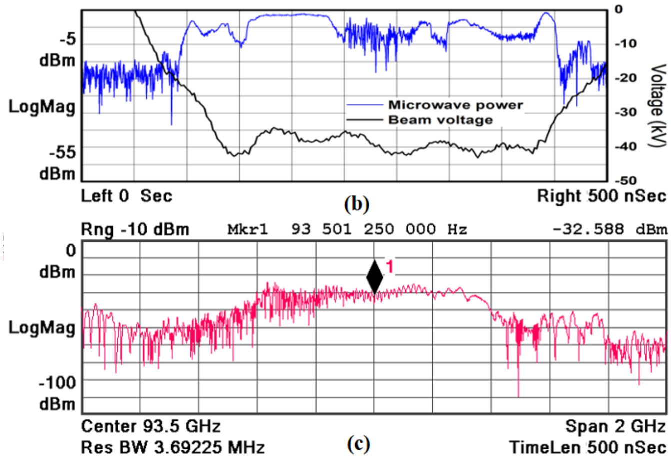


Fig. 5. Gyro-TWA experimental results with the single input frequency at 93 GHz and frequency-swept signal (a), and microwave signal and its spectrum at the frequency-swept experiment (b).

V. Ongoing Upgrade

The prototype of the W-band gyro-TWA presented in this paper successfully validated the physics principles of operation and the design and construction of many of the amplifier components. However, there are still a few factors that stop its immediate readiness for use in a wireless communication system. These include the high voltage cable pulser power supply used to drive the gyro-TWA which can only operate in pulse mode with a pulse duration of 400 ns and a repetition rate of 100 Hz. A DC high-voltage power supply will allow investigation of amplifier stability and CW operation of the gyro-TWA. The magnet field was generated by a water-cooled copper DC solenoid which requires a bulky cooling system as well as a high current DC power supply to drive it. However it is still difficult to achieve the required magnetic field stability which is critical for the gyro-TWA for continuous-wave operation. A closed loop superconducting magnet will be able to eliminate this problem and achieve a much better magnetic field stability. Also a broad instantaneous bandwidth solid-state source is required as the driving source for the amplifier.

Ongoing research is being carried out to address these issues with a further upgrade of the prototype gyro-TWA to increase its technology readiness level. A high-voltage DC power supply (maximum voltage of 60 kV and maximum output current of 1.5 A) with an embedded floating power supply for the cathode heater, and a power supply for depressed collector (maximum voltage of +25 kV and maximum output current of 1.5 A) have been procured from Genvolt Ltd. The power supplies have passed the factory acceptance test (FAT) and will be delivered in a few months' time. A closed loop superconducting magnet that is able to achieve a maximum magnetic field strength of 5.5 T has also been ordered and has passed the on-site test.

An upgrade version of the W-band gyro-TWA is under design to generate output power of 3 kW, bandwidth over 10 GHz and a gain larger than 30 dB that can operate continuously. The improvements include, (1) matching the magnetic field profile of the superconducting magnet to the cusp electron gun; (2) an improved purity of the Gaussian output mode; (3) design of a collector and better management of the thermal load for the

CW operation. These improvements together with the availability of the key hardware including the DC power supply, the superconducting magnet as well as the high-power solid-state source will allow the full demonstration of the capability of the gyro-TWA in the applications of ground-to-satellite uplink and city-to-city backhaul communications. At the same time, a modulation-anode controlled triode-type cusp electron gun for a fast turn on/off the electron beam all of which is required for future applications such as nuclear magnetic resonance spectroscopy is being developed.

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