0.37 THz gyro-TWA with a cryo-free SCM: Design and simulation

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***Abstract*—** This paper reports the work being carried out to realize a gyrotron-traveling wave amplifier operating at 372 GHz based on a helically corrugated interaction region (HCIR). The high magnetic field will be provided through a cryo-free superconducting magnet. There are many components in the waveguide circuit, which must achieve very low reflection targets. The design and simulation results of the gyro-TWA, the cusp electron beam source, the sub-millimetre wave components, as well as measurement of the HCIR will be presented in this paper.

I. INTRODUCTION

THE demand for THz amplifiers is ever increasing and the gyrotron-traveling wave amplifier (gyro-TWA) is a natural and ideal choice to meet those needs. Unlike conventional TWT-like amplifiers, gyro-TWA's [1] operate with a fast-wave interaction and so do not require a slow-wave structure. It further benefits from an enlarged interaction region. These properties greatly assist design of the gyro-TWA's operating at very high frequencies. It allows the output power to be comparatively large, as well as reducing the effect of manufacturing techniques and tolerances, therefore making it possible to construct components that can operate at sub-millimetre wavelengths. At the University of Strathclyde, a gyro-TWA operating at 0.37 THz is being designed which has a calculated output power in the 100's W range. The beam-wave interaction will be driven by an electron beam produced by a cusp electron gun [2] and traveling through a helically corrugated interaction region (HCIR) with a magnetic field of 7.3 T. A cryogenic-free superconducting magnet (SCM) will provide the required field. The HCIR enables a favorable dispersion characteristic [3] allowing for even more broadband amplification, higher power capabilities, reduced effect of electron beam velocity spread and a second harmonic interaction. Further waveguide components will be required such as a circular polarizer [4], input [5, 6] and output couplers [7] and microwave windows [8], see Fig. 1. This paper will present the design of the gyro-TWA, its components with particular focus on the design and measurement of the HCIR as well as the design of the microwave window.

II. HELICALLY CORRUGATED INTERACTION REGION

The HCIR offers unmatched capabilities in achieving broadband, high power amplification. Two modes, in this case the first spatial harmonic of the TE_{11} mode and the TE_{21} mode, couple together to form an eigenwave that is near ideal for an amplifier. It has reduced values of k_z which minimizes the effect of Doppler broadening of the electron beam line. As well, at low frequencies the eigenwave will mostly follow the TE_{11} mode, while at higher frequencies it will be determined by the TE_{21} mode, at the transition between modes it is a combination of them both. If the geometrical parameters of the HCIR are set properly then a straight dispersion line in this region can be achieved, which can be well-matched by the electron beam line over a very wide bandwidth.

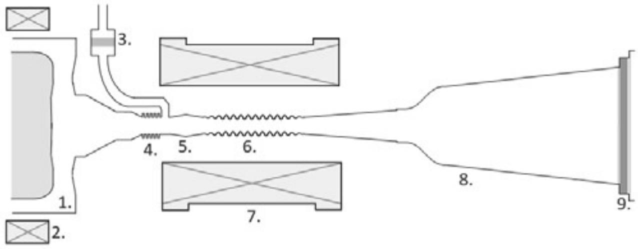

Fig. 1 Schematic of the gyro-TWA showing its many components; 1) Cusp electron gun, 2) reversed magnetic coil, 3) pillbox window, 4) Bragg reflector, 5) elliptical polarizer, 6) HCIR, 7) main magnetic coil, 8) output horn, and 9) multilayer window

The HCIR was designed for this gyro-TWA through analytical calculation and then its beam-wave interaction properties confirmed through the 3D PIC code MAGIC. The optimal 3-fold HCIR is found to have a corrugation amplitude of 42 μm with a nominal diameter of 0.76 mm and corrugation period of 0.882 mm. Of course such a guide cannot be directly machined from solid copper，so the electroforming method was chosen as a viable solution. This requires an aluminium mandrel and the scale of the corrugations, small nominal diameter and relatively long length of the guide made the manufacturing of such a mandrel to be a technically challenging task that was eventually overcome. Electrochemical deposition of copper on the aluminium mandrel with the aluminium mandrel later removed resulted in the 3-fold HCIR.

A vector network analyser (VNA) was used to measure the transmission and reflection from the HCIR [9]. The VNA-measured dispersion agreed well with the numerically calculated values, as shown in Fig. 2, which showed that the grown copper waveguide was accurately made.

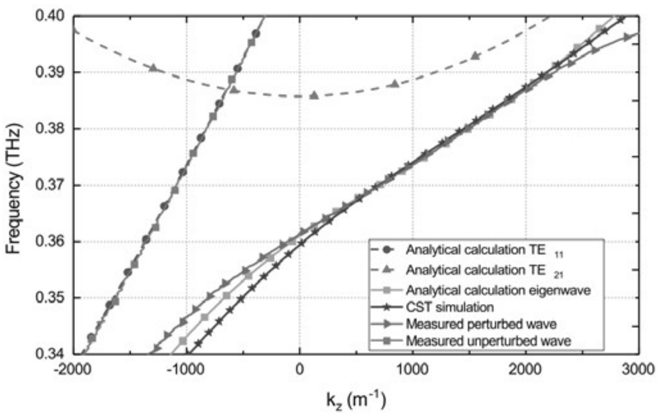

Fig. 2 The calculated, numerically simulated and measured dispersion characteristic of the 3-fold HCIR.

III. OUTPUT WINDOW

A key component in any amplifier design is the output window. This acts to separate the vacuum inside the experiment from the atmosphere outside it. However, it unavoidably causes both reflection and power absorption. The former may cause oscillations and cessation of the amplification if it is too high and the latter would cause a reduction in output power and possible breakage of the window itself when operating at CW mode. The proper design of the window aims to minimize both of those parameters, as well as maintaining mechanical strength and facilitating vacuum brazing. The window configuration choice is limited due to the broadband signal required to pass it, but from past experience a multilayer window can meet those requirements [10]. When working at low-THz frequencies the window design can prove challenging to realize in manufacturing. Problems include, very high sensitivity to geometrical and material tolerances, reduction of geometrical size and as a consequence becoming fragile.

To overcome those issues the window is proposed to be made from a singular disc of Alumina 94%. On each face of the disc many holes, with a certain depth, would be made in order to remove dielectric material, creating a layer with a reduced dielectric constant. The resulting disc would consist of three dielectric layers with different relative dielectric constants. As the size and density of the holes could be precisely maintained, as well as their depth, these layers can be fully optimized in both thickness and relative dielectric constant. This technique benefits from using a singular, relatively thick disc and so reduces alignment errors, it would be vacuum brazable to a mounting structure and could hold vacuum to the UHV level. The window, as displayed by CST Microwave Studio, is shown in Fig. 3.

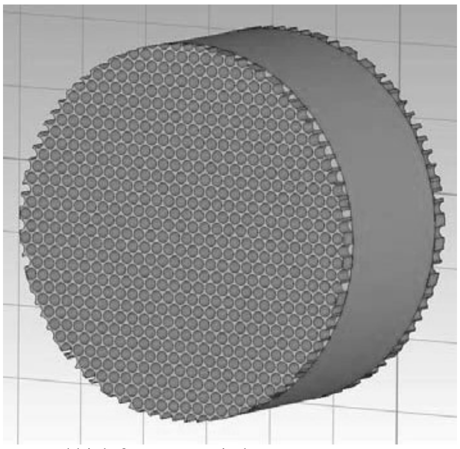

Fig. 3 The proposed high frequency window.

To design and optimize the window the mode-matching method can be employed. This will allow determination of the desired relative dielectric constants (ε_r) and thicknesses, afterwards CST-MS can be used to design the profiling window structure. Initially the diameter of the window was set to be 4 mm. The central disc (C) was Alumina 94% which has a dielectric constant of 9.4. On each side of that disc is another (L), which can have any dielectric constant and thickness. The optimal values of the window are as follow: Length of C = 1.052 mm, Length of L = 0.119 mm, ε_r of C = 9.4, ε_r of L = 2.89. The calculated reflection is shown in Fig. 4. A better than -40 dB value over the full frequency range can be achieved with this design, which meets the criteria.

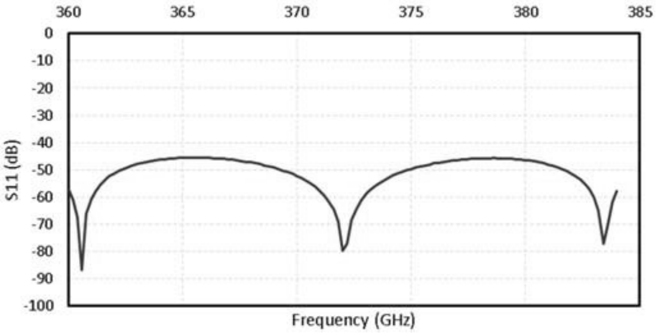

Fig. 4 The calculated reflection from the multilayer, single disc window.

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