CNC machined helically corrugated interaction region for a THz gyrotron traveling wave amplifier

Craig R. Donaldson, Liang Zhang, Mat Beardsley, Michael Harris, Peter G. Huggard and Wenlong He

Abstract—This paper reports the development of a helically corrugated interaction region (HCIR) for a 100 W gyrotron traveling wave amplifier operating at a central frequency of 0.37 THz. This HCIR has a corrugation amplitude of 42 μm , with a nominal waveguide diameter of 0.760 mm. The HCIR was made by electroforming copper on a sacrificial aluminium mandrel: the latter was precision CNC milled using a 0.2 mm diameter ball nose cutter. The dispersion characteristics of the HCIR were measured and found to be in good agreement with the analytical calculation and numerical simulation. Measured insertion loss was between 2 dB and 4 dB.

Index Terms—gyro-amplifier, helically corrugated waveguide

I. INTRODUCTION

Gyrotron traveling wave amplifiers (gyro-TWAs) promise unmatched capabilities in achieving broadband, high power amplification up to the THz frequency regime [1], [2]. There is a great requirement for such amplifiers due to their wide scope of applications including high precision radar [3], electron paramagnetic resonance (EPR) and dynamic nuclear polarisation (DNP) [4], telecommunications [5], [6] and so on. At the University of Strathclyde a gyro-TWA with a central frequency of 0.37 THz is being developed. The amplifier is designed for an output power of 100 Watts with gain of 37 dB and a 3-dB bandwidth of 24 GHz. It will be driven by a 45 kV, 0.5 A axis-encircling electron beam which will be generated by a cusp electron gun. It is challenging to design a cusp electron gun operating at high peak magnetic field (~ 7.3 T) and high magnetic compression ratio of about 2000. However, it is achievable through careful design [7].

There are many components within the gyro-TWA waveguide circuit which need to achieve high transmission and low reflection over a broad bandwidth. Such components can include: input coupler [8], Bragg reflector [9], polariser [10], interaction region, output mode-converter [11], [12] and microwave windows [13], [14]. Conventionally, gyro-TWAs employ a smooth-circular waveguide interaction region for beam-wave interaction [15]. Usually the maximum bandwidth achieved in this arrangement is a few percent. However, if

a helically corrugated interaction region (HCIR) is used, an eigenwave is formed as a result of coupling between two modes, one close to cut-off (1) and one far from cut-off (2). This eigenwave has a dispersion characteristic [16] which is near ideal for an amplifier. Experiments have shown that much broader amplification bandwidth, over 20%, can be achieved, accompanied by high output power, high efficiency and high gain [17]. The present gyro-TWA is designed to have a bandwidth of 24 GHz which is enough for EPR and DNP applications. The benefit of high efficiency is due to the fact that the beam-wave interaction within the HCIR is at small k_z values which reduces the effect of electron beam velocity spread. Also, the HCIR allows the use of the second harmonic of the electron cyclotron mode allowing a reduction of the focusing/confining magnetic field strength by a factor of 2.

HCIRs have been used in many gyro-amplifiers and gyro-oscillators, from X-band [18], [19], Ka-band [20], [21], to W-band [1], [22]–[24]. As the output frequency of the device increases, the geometrical size of the helical corrugation correspondingly decreases and manufacturing becomes increasingly difficult. Currently no HCIR has been reported for operation above the W-band, largely due to the manufacturing challenge. This paper presents the development of a HCIR for the 0.37 THz range and details the design, manufacture, sensitivity to tolerance and measured waveguide dispersion and insertion loss.

II. HELICALLY CORRUGATED WAVEGUIDE

The HCIR has both an azimuthal and axial corrugation and its surface is described through the following relation, in polar cylindrical coordinates (r, θ, z) .

$$r(\theta, z) = r_0 + r_1 \cos(m_B \theta + \frac{2\pi z}{d}) \quad (1)$$

where r_0 is the mean radius of the circular waveguide, r_1 is the corrugation depth, m_B is the azimuthal perturbation number, and d is the period of the corrugation. The geometrical profile for this waveguide is shown in Fig. 1 (a) and (b). For a non-zero corrugation depth, two modes will couple when their axial and azimuthal wave numbers satisfy the synchronism conditions given by Eq. 2.

$$k_{z1} - k_{z2} = \frac{2\pi}{d}, m_1 - m_2 = m_B \quad (2)$$

where k_{z1} and k_{z2} are the axial wavenumbers of modes 1 and 2, and m_1 and m_2 are the corresponding azimuthal indices.

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Fig. 1. (Color online) Analytically calculated helical corrugation.

This paper will concentrate on the three-fold ($m_B = 3$) right handed HCIR, in which the right-hand polarised TE_{21} mode couples with the spatial harmonic of the left-hand polarised TE_{11} mode to form an eigenmode.

The dispersion of this coupled mode is unique: at low frequencies it will mostly follow the TE_{11} mode while at high frequencies it will be set by the TE_{21} mode. At the transition between the two modes the dispersion is a combination of both. If the waveguide's geometrical parameters are chosen correctly this dispersion can be favourable to the broadband operation of the gyro-TWA. This dispersion relation can be calculated through [25], [26] or approximated [27] through the following equation

$$(k^2 - k_z^2 - k_{t1}^2)[k^2 - (k_z - k_B)^2 - k_{t2}^2] = 4\kappa^2 k_0^4 \quad (3)$$

where

$$\kappa = \frac{1}{2r_0^3 k_0^2} \frac{v_1^2 v_2^2 - m_1 m_2 r_0^2 (k_0^2 + k_{z1} + k_{z2})}{\sqrt{(v_1^2 - m_1^2)(v_2^2 - m_2^2)}} \quad (4)$$

where, k_B is the Bragg periodicity vector, k_0 is the wavenumber corresponding to the cutoff frequency of mode 1, v_1 and v_2 are the roots of the derivative of the corresponding Bessel function for modes 1 and 2 respectively, k_{t1} and k_{t2} are equal to v_1/r_0 and v_2/r_0 respectively.

Through optimization of the dispersion characteristics the operating eigenwave can interact with the electron beam line over a large frequency band, meaning that the amplification bandwidth would satisfy the application requirements. The dimensions of the optimized HCIR are: a mean radius, r_0 , of 0.380 mm, a corrugation amplitude, r_1 , of 42 μm and corrugation period, d , of 0.882 mm. For optimized coupling the electron beam should be of 0.5 A at 45 kV with a velocity pitch factor ($v_\perp/v_z$) of 1.1 in an axial magnetic field of 7.01 T. The dispersion characteristics for TE_{11} , TE_{21} , the resultant eigenwaves and the electron beam are shown in Fig. 2.

III. TOLERANCE

The effects of geometrical tolerance are related to the operational wavelength. At this frequency, 0.37 THz, the freespace wavelength is ~ 0.8 mm. By careful design of the geometrical dimensions it is possible to achieve a near-constant group

Fig. 2. (Color online) Dispersion diagram showing right-hand polarised TE_{21} mode and the first spatial harmonic of the left-hand polarised TE_{11} mode, the resultant eigenwave and the electron beam.

velocity to match the speed of the electron beam over a certain frequency band, as shown in Fig. 2. The beam-wave interaction in the HCIR will be driven by a large-orbit electron beam generated through a cusp electron gun [28], of parameters described in the introduction, which were simulated through the use of the particle-in-cell code MAGIC-3D [29]. The optimum interaction occurs for a HCIR with the given dimensions. Usually the cyclotron resonance maser instability is strongest when the detuning (wave frequency minus the frequency of harmonic electron cyclotron mode) is about 1% of the wave frequency. Therefore, a deviation of the eigenwave dispersion of greater than 1% could result in a much weaker beam-wave interaction for the gyro-TWA. The dependence of the eigenwave frequency on the waveguide geometry has been studied in a tolerance analysis.

The corrugation period, corrugation amplitude and nominal waveguide diameter were individually changed in the analytical calculations. Fig. 3 shows the effects of these geometrical variations on eigenwave dispersion. The deviation is presented in percentage from the optimal value. Assuming an acceptable maximum deviation of 0.5%, it was found that the corrugation period is not sensitive to machining errors of up to ± 20 μm . The nominal waveguide diameter can vary by ± 10 μm while the frequency of operation is very sensitive to the corrugation amplitude: this needs to be kept within ± 5 μm . Therefore, a precision manufacturing approach is required to realize the HCIR.

IV. MANUFACTURE

The selected manufacturing process must create the helical structure on the inside of a 23.8 mm long high conductivity copper waveguide. Due to the HCIRs length/diameter aspect ratio it is not possible to directly cut the corrugations; instead the method of electroforming around a sacrificial aluminium alloy is adopted. This involves machining the surface of a 6082 grade alloy rod to the desired waveguide profile, electroforming copper onto the aluminium and finally dissolving the aluminium by immersion of the workpiece in a strong alkaline bath. The main machining challenge is thus shaping the

Fig. 3. (Color online) Calculated effects of geometrical variations on the eigenwave frequency as percent differences from the original value for the (top) corrugation period, (middle) corrugation amplitude, and (bottom) nominal waveguide diameter. Note the different vertical scale on the plots.

aluminium with the required accuracy, $< 5 \mu\text{m}$ in the case of the corrugation amplitudes. Conventional lathe and milling can achieve tolerances of order $20 \mu\text{m}$, precision CNC machining provides a tolerance of less than $5 \mu\text{m}$ while grinding can reach $1 \mu\text{m}$ accuracy but is not suitable for machining aluminium due to the rough surface finish obtained. Thus precision milling using a 5-axis CNC Kern Micro machine was selected. This was used with a 0.2 mm diameter ball nosed cutter rotating at 9000 revolutions/minute. The manufacturing process was as follows:

- 1) A 10 mm diameter aluminium rod was first turned in a lathe to 0.880 mm diameter. This is approximately $35 \mu\text{m}$ larger than the largest external diameter of the completed waveguide. Part of the rod was left at 10 mm diameter for handling purposes.

- 2) The 10 mm diameter end of the turned rod was centered in the collet chuck of the rotary fourth axis on the milling machine. A Delrin support plate was located under the 0.880 mm diameter section of the aluminium former. A clearance of approximately $5 \mu\text{m}$ was maintained. The Delrin prevented the former deforming and moving during the milling process.

- 3) The cut was taken in one pass. Excess material ahead of the form acted as a support as it rotated in the fixture while the machined form trailed behind, now in clearance within the support fixture. Only one cutting pass was possible, as once material had been removed from the 0.880 mm diameter it was no longer supported. High performance CAM software was used to program the complex cutter path. This was applied directly to the supplied STEP model of the part.

A photograph of a completed mandrel is shown in Fig. 4(a),

with a close-up of the corrugations in Fig. 4(b). Great care is taken during machining to ensure the straightness of the mandrel. Measurements on one piece show a deviation from linearity at the free end of the 35 mm length of around $25 \mu\text{m}$. This small run-off can be corrected after electroforming by centering the hollow waveguide ends with respect to the alignment features. Copper was subsequently electroplated on the machined mandrels to a thickness of 4 mm . The aluminium was removed in a hydroxide solution to provide the waveguide shown in Fig. 5.

(a) Whole Aluminium former

(b) Close-up of corrugations

Fig. 4. (Color online) Photographs of the aluminium mandrel for the HCIR.

Fig. 5. (Color online) A photograph of the electroformed helical waveguide after chemical removal of the aluminium former and before machining of the waveguide flanges.

V. MEASUREMENT

The dispersion characteristics of the HCIR were measured using a vector network analyser (VNA). An Anritsu 37393D VNA with OML frequency extension heads allowed measurement of S-parameters from 0.32 THz to 0.50 THz . To calculate the HCIR dispersion two sets of measurements were required, a reference phase response through the microwave circuit without the HCIR present and the phase through the

same circuit with the HCIR. The axial wavenumber (k_z) was then calculated through the phase change ($\Delta\theta$) caused by the HCIR of length L and converted through $k_z = \Delta\theta/L$. The output from the VNA is in WR 2.2 rectangular waveguide, therefore this was converted to propagate in a circular waveguide, 0.70 mm in internal diameter. This was followed by a rotatable circular polarizer, then the HCIR and the same components in reverse order: Fig. 6. The circular polarizer at the output of the HCIR is set at 90° degrees to the input one in order that the transmitted circularly polarized waves revert to a linearly polarization. For one setting of the circular polarizers, the microwaves traveling through the HCIR co-rotate with the helix twist. These waves are not perturbed by the corrugations, and instead exhibit a smooth-bore waveguide like dispersion. An orthogonal polarizer setting generates the desired counter-rotating waves which interact with the corrugations.

Fig. 6. (Color online) A photo showing the setup when measuring waveguide dispersion through the HCIR on the VNA.

The measured dispersion is shown in Fig. 7. This shows excellent agreement with both the analytically calculated dispersion, from eq. 3, as-well-as the numerically calculated dispersion from CST Microwave Studio [30]. The measured unperturbed wave agrees very well over the full frequency range. The measured perturbed wave agrees well over the frequency range from 0.36 THz to 0.38 THz. Deviations at the higher or lower frequencies arise because the circular polarizers used in the measurement have only a limited bandwidth. The insertion loss was also measured and is shown in Fig. 8. The measurement showed some sharp losses due to the cavity effect from the misalignment of the components in the measurement circuit. On average, insertion loss of about 2 dB to 4 dB was measured. The reflection measurement with and without the HCIR was similar, approximately -15 dB in average. The reflection from the HCIR itself was negligible.

VI. CONCLUSION

This paper presents the design, manufacture and measurement of a three-fold HCIR for a gyro-TWA operating at a frequency above 0.37 THz with a bandwidth greater than 20 GHz. Operating at such a high frequency presents particular difficulties for the manufacturing of the component. Aspects such as sensitivity to tolerances, small dimensions and surface finish mean that the manufacturing method is critical to the overall success of the waveguide in the intended application. This waveguide was designed from analytical calculation,

Fig. 7. (Color online) Measured and predicted waveguide dispersion for the three-fold HCIR for both perturbed and unperturbed waves.

Fig. 8. (Color online) Measured insertion loss through the HCIR.

manufacturing using a high precision CNC machine and then measured on a VNA. The measured dispersion shows excellent agreement with the calculated and simulated dispersions and this indicates that the shape of the constructed waveguide is correct, and within the application requirements.

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