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

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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, 0.37 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.

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, sensitively 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).

\[ r(\theta, z) = r_0 + r_1 \cos(m_B \theta + \frac{2\pi z}{d}) \]  

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.

\[ k_{z1} - k_{z2} = \frac{2\pi}{d}, \quad m_1 - m_2 = m_B \]  

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.
This paper will concentrate on the three-fold \((m_B = 3)\) right-handed HCIR, in which the right-handed 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

\[
(k^2 - k_z^2 - k_{11}^2)[k^2 - (k_z - k_B)^2 - k_{21}^2] = 4\kappa^2 k_0^4 \tag{3}
\]

where

\[
\kappa = \frac{1}{2r_0^2k_0^2} \frac{v_1^2v_2^2 - m_1m_2r_0^2(k_0^2 + k_{11} + k_{21})}{\sqrt{(v_1^2 - m_1^2)(v_2^2 - m_2^2)}} \tag{4}
\]

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, \(k_{11}\) and \(k_{21}\) 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 \(\mu\)m 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 \((v_1/v_2)\) 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 \(\sim 0.8\) mm. By careful design of the geometrical dimensions it is possible to achieve a near-constant group 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 \(\pm 20\) \(\mu\)m. The nominal waveguide diameter can vary by \(\pm 10\) \(\mu\)m while the frequency of operation is very sensitive to the corrugation amplitude: this needs to be kept within \(\pm 5\) \(\mu\)m. 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, electro-forming 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
aluminium with the required accuracy, < 5 \mu m in the case of the corrugation amplitudes. Conventional lathe and milling can achieve tolerances of order 20 \mu m, precision CNC machining provides a tolerance of less than 5 \mu m while grinding can reach 1 \mu 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 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 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 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.

![Fig. 3](image3.png)

**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.

![Fig. 4](image4.png)

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

![Fig. 5](image5.png)

**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.](image)

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, 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.

REFERENCES


Wenlong He received the B.Sc. degree in physics from Soochow University, Jiangsu, China, in 1983, the M.Sc. degree in accelerator physics from the China Academy of Engineering Physics, Chengdu, China, in 1988, and the Ph.D. degree in relativistic electron beams and masers, from the University of Strathclyde (UoS), Glasgow, U.K., in 1995. He is currently a Senior Research Fellow with the Department of Physics, UoS.