W-band Brewster window for a wideband gyro-TWA

Liang Zhang, Yanyan Zhang, Wenlong He, Craig R. Donaldson, Paul McElhinney, Alan D. R. Phelps and Adrian W. Cross
Department of Physics, SUPA, University of Strathclyde
Glasgow, G4 0NG, Scotland, UK
liang.zhang@strath.ac.uk

***Abstract*—This paper presents the design of a Brewster window for a W-band gyrotron travelling wave amplifier (gyro-TWA). To maintain the Gaussian-like HE_{11} mode from the corrugated horn, a corrugated waveguide was optimized to host the Brewster window. The Brewster window was simulated and measured to have a lower than -20 dB reflection over the frequency band 85 - 101 GHz.**

Keywords— Brewster window, Gyro-devices, corrugated waveguide.

I. Introduction

Gyro-devices are fast wave devices based on the principle of the electron cyclotron maser. Gyrotron amplifiers are one of the gyro-devices that are being developed for a wide range of of applications, including high resolution radar ranging and imaging, deep-space and specialized satellite communications, plasma diagnostics and materials processing [1]. A W-band gyrotron-travelling wave amplifier (gyro-TWA) based on a helically corrugated waveguide [2-5] and a cusp electron gun [6, 7] is currently being studied at the University of Strathclyde. It is predicted to achieve an output power of 5 kW at the frequency band of 90 - 100 GHz. To operate such a wide bandwidth amplifier successfully, the output microwave window requires a reflection lower than -20 dB.

A window for which the effective reflectivity does not vary appreciably with frequency can be achieved by constructing a 'thin' window in which the window thickness is designed to be significantly less [8] than a half wavelength of the electromagnetic waves. For such windows in the millimetre-wave region their thinness can result in their mechanical strength being limited. 'Thicker' windows are desirable in practice in order to withstand the stresses imposed by the atmospheric pressure. Windows of both the pillbox type (as for the input microwave window) and multi-disk type (as for the output microwave window) have been designed and tested for the same W-band gyro-TWA experiment and good results have been achieved [9]. It was found that the performances of these windows are sensitive to the machining and assembly tolerances. Also the difficulty in manufacture increases as the operating frequency increases. The Brewster window has broad bandwidth based on its operating principle and reflections can be minimised if the Brewster angle is used. In this paper, the design and simulation of a Brewster window in W-band is presented.

II. The principle of the Brewster window

Fig. 1 shows the schematic diagram of the wave reflection and refraction on the single dielectric disk. The Brewster angle θ_{Brew} is given by,

$$\theta_{Brew} = \arctan\left(\sqrt{\varepsilon'_{r2} / \varepsilon'_{r1}}\right) \tag{1}$$

where ε'_{r1} and ε'_{r2} represent the relative permittivity of the incident and refractive media.

Due to the parallel polarization boundary conditions of the window plates, there are further frequency dependent angles where the reflections vanish independently of the polarization. The relationship between the incident angle and the optimal thickness of the dielectric material d with vacuum as the background medium can be derived based on Fig. 1 and it follows [10] that,

$$d_N = N \frac{c}{2f} \frac{\sqrt{\varepsilon'_{r2} + 1}}{\varepsilon'_{r2}} \tag{2}$$

where N is an integer, ε'_{r2} is the relative permittivity of the dielectric disc, c is the speed of light and f is the desired frequency that has minimal reflection. Table I summaries the Brewster angles and the thicknesses of different window materials at a center frequency of 95 GHz and N = 1. In this paper, quartz was chosen as the window material and N = 1 was used in the simulation.

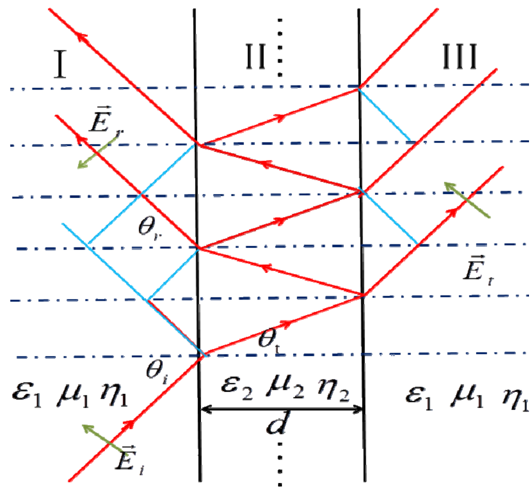


Fig. 1. A schematic diagram of a plane wave incident on a plane dielectric boundary.

TABLE I

THE BREWSTER ANGLES AND THEORETICAL THICKNESSES FOR DIFFERENT WINDOW MATERIALS AT 95GHZ.

Material	ε_r'	θ_{Brew}	Thickness (mm) (when N=1)
Quartz	3.75	62.7°	0.92
Diamond	5.67	67.2°	0.72
Ceramic	9.4	71.9°	0.54

III. SIMULATION OF THE BREWSTER WINDOW

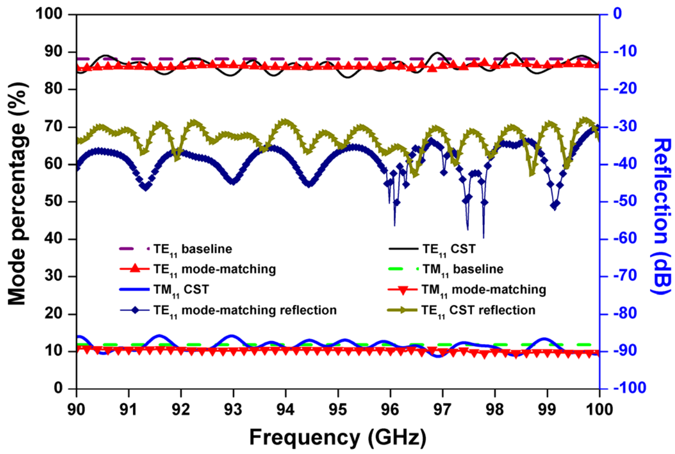
A corrugated horn that is able to convert the TE_{11} mode radiated from the gyro-TWA into the Gaussian-like HE_{11} mode, was designed and measured [11]. It has a low reflection around -30 dB and a Gaussian percentage of 98%. To maintain the Gaussian-like HE_{11} mode for the Brewster window, a corrugated waveguide can be used. The Brewster window will be located inside the corrugated waveguide to satisfy the required boundary condition.

The corrugated waveguide was simulated and optimized by the mode-matching technique. The Gaussian-like HE_{11} mode from the corrugated horn can be approximated as 88.1% TE_{11} mode and 11.9% TM_{11} mode with a relative phase difference of 180 degree. In the mode-matching calculation, the hybrid mode content was excited at the input port, and the overall mode content at the output port can be obtained from the generalized scattering matrix calculation. The goal function in the optimization is to minimize the differences between the input and output hybrid mode content over the desired operating frequency band. After the optimization, the performance of the corrugated waveguide was then verified by using the 3D FDTD code CST Microwave Studio. The mode contents of TE_{11} and TM_{11} modes at the input and output port as well as the reflection are shown as Fig. 2(A). A good agreement was found between the two methods. The field pattern inside the corrugated waveguide is shown in Fig. 2(B). It shows that the Gaussian-like HE_{11} mode was well-maintained during the propagation in the corrugated waveguide.

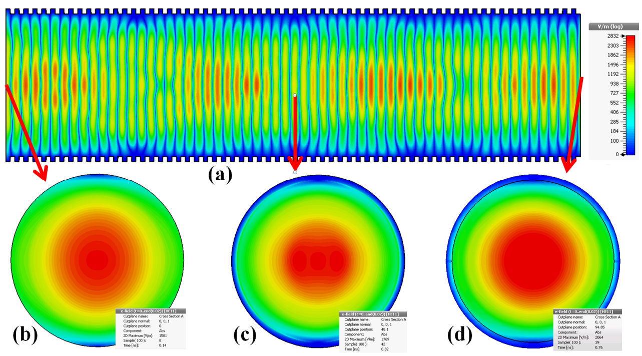
After the optimization of the corrugated waveguide, the quartz disc was then added to the CST microwave studio simulation to study the performance of the Brewster window. The quartz disk with a thickness of 0.92 mm was initially used and placed at the Brewster angle of 62.7°. Further parameter sweeps of different quartz thicknesses was carried out and it was found that the thickness of 0.90 mm was able to achieve a better performance over the frequency band of 90 – 100 GHz. The view of the Brewster window assembly in the corrugated waveguide is shown in Fig. 3.

In the simulation, a reflection of less than -20 dB was found for the TE_{11} mode, which meets the requirement of the W-band gyro-TWA. Parameter sweeps were carried out to study the sensitivity of the angle of assembly of the window and the results are shown in Fig. 4. The tolerance of the assembly angle is about ±1° if the reflection is required to be maintained lower than -20 dB over the whole frequency band from 90 GHz to 100 GHz. However, the reflection in the frequency range of 91.6 GHz to 97.1 GHz still remains lower than -25 dB.

A Brewster window was then manufactured to verify the simulations. The corrugated waveguide was manufactured by the 3D printing technology and then measured by a Vector Network Analyzer (VNA). The dielectric constant of the quartz disc was also measured, which was about 3.82. It is quite close to the estimated value of 3.75 used in the simulation, and the Brewster angle remains the same. The corrugated waveguide was then cut open at the Brewster angle and assembled with the quartz disc. The reflection of the corrugated horn as well as the Brewster window is shown in Fig. 5. The TE_{11} mode reflection is lower than -22 dB over the frequency band of 85 GHz to 101 GHz. This covers the operating frequency range of the gyro-TWA and satisfies the design requirement.



(A)



(B)

Fig. 2. (A) The simulated mode contents of the TE_{11} and TM_{11} modes as well as the reflection of the TE_{11} mode and (B) the electric field at 95 GHz: (a) x-z plane where $y = 0$; (b) x-y plane where $z = 0$ (c) x-y plane at the centre of the waveguide; (d) x-y plane at the end of the waveguide.

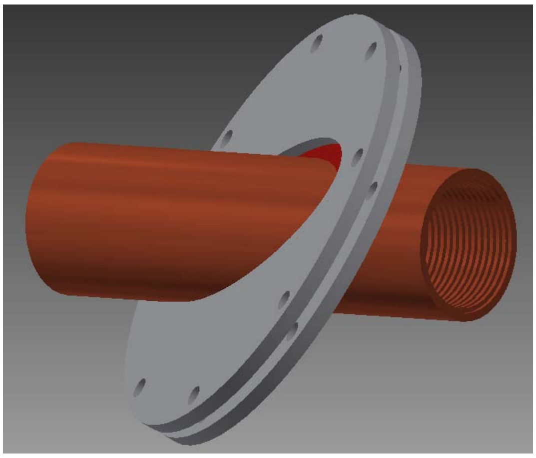


Fig. 3. The view of the Brewster window assembly.

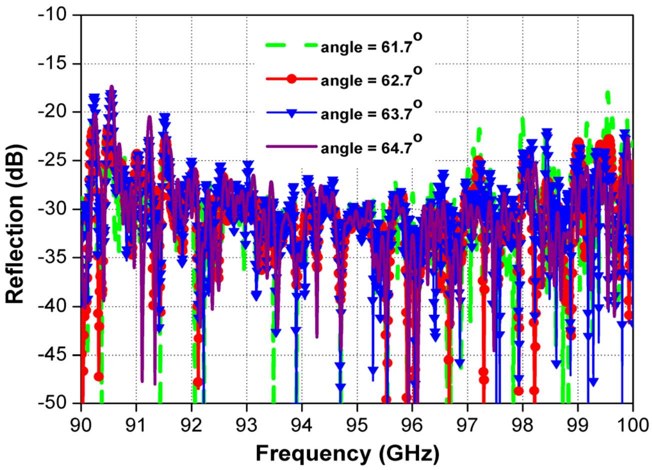


Fig. 4. The reflection of the Brewster window at different assembly angles.

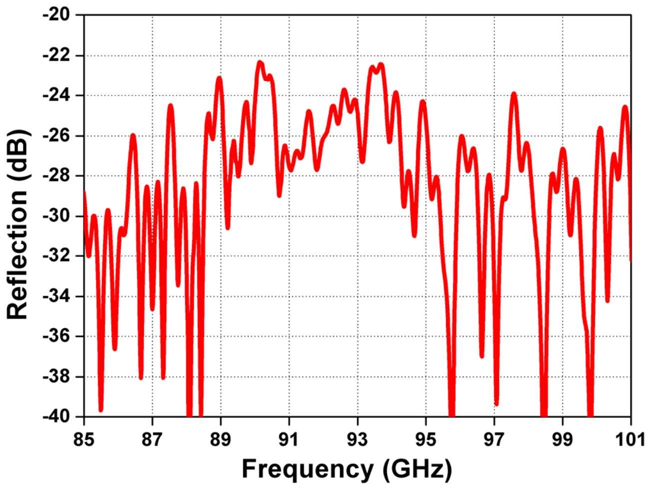


Fig. 5. Measured reflection of the Brewster window.

Acknowledgment

This work was supported by the Engineering and Physical Sciences Research Council (EPSRC) U.K. under Research Grant EP/K029746/1. The EPSRC Engineering Instrument Pool is gratefully acknowledged for providing the Vector Network Analyzer (VNA) used in the experiments. Y. Zhang would like to thank the China Scholarship Council for its financial support.

References

[1] M. Thumm, "High power gyro-devices for plasma heating and other applications," *Int. J. Infrared Millimeter Waves*, vol. 26, no. 4, pp. 483-503, Apr. 2005.

[2] A. W. Cross, W. He, A. D. R. Phelps, K. Ronald, C. G. Whyte, A. R. Young, C. W. Robertson, E. G. Rafferty, and J. Thomson, "Helically corrugated waveguide gyrotron traveling wave amplifier using a thermionic cathode electron gun," *Appl. Phys. Lett.*, vol. 90, no. 25, 253501, June 2007.

[3] 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," *Int. J. Terahertz Sci. Techn.*, vol. 4, no. 1, pp. 9-19, Mar. 2011.

[4] 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, Apr. 2013.

[5] 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, Jan. 2012.

[6] C. R. Donaldson, W. He, A. W. Cross, A. D. R. Phelps, F. Li, K. Ronald, C. W. Robertson, C. G. Whyte, A. R. Young, and L. Zhang, "Design and numerical optimization of a cusp-gun-based electron beam for millimeter-wave gyro-devices," *IEEE Trans. Plasma Sci.*, vol. 37, no. 11, pp. 2153-2157, Nov. 2009.

[7] 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, Apr. 2010.

[8] S. N. Spark, and A. D. R. Phelps, "Negligible absorption, broad passband, output window for a millimetre-wave electron cyclotron maser," *J. Phys. E: Sci. Instrum.*, vol. 22, no. 12, pp. 1015-1016, Dec. 1989.

[9] 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 Microwave Wireless Compon. Lett.*, vol. 23, no. 5, pp. 237 - 239, May 2013.

[10] M. Thumm, A. Arnold, E. Borie, O. Braz, G. Dammertz, O. Dumbrajs, K. Koppenburg, M. Kuntze, G. Michel, B. Piosczyk, "Frequency step-tunable (114-170GHz) megawatt gyrotrons for plasma physics applications," *Fusion Eng. Des.*, vol. 53, pp. 407-421, Jan. 2001.

[11] 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, Mar. 2013.