Wide-Band HE_{11} Mode Terahertz Wave Windows for Gyro-Amplifiers

Craig R. Donaldson, Paul McElhinney, Liang Zhang, and Wenlong He

***Abstract*—Broadband HE_{11} mode output windows, based on the multilayer concept, are studied for high power gyro-amplifiers operating in the low terahertz region. As the wave power in the hybrid HE_{11} mode is concentrated in the center of the circular waveguide, smaller reflection and better coupling to the fundamental free space Gaussian mode can be achieved for the windows. Two windows are designed for optimized performance through simulations for operation in two frequency ranges of 360–400 GHz and 90–100 GHz. The simulated performance, practical constraints in realization and manufacturing methods of the 90–100 GHz window is discussed. This window was constructed and microwave properties measured showing a lower than −27 dB reflection. This result agrees with simulation data which validates the simulation methodology and effectiveness of the design.**

***Index Terms*—Broadband window, gyro-amplifier, multilayer window, output window.**

I. Introduction

GYRO-AMPLIFIERS based on helically corrugated interaction region promise unmatched capabilities in achieving high frequency (up to terahertz range) wave amplification with a high power and wide frequency bandwidth [1], [2]. It is the extent of the broadband amplification range that make the device both attractive and challenging. Each component of the amplifiers must achieve very low reflection through the entire operating frequency range which makes its design and fabrication difficult. This is especially true at the THz range where manufacturing tolerances become hard to achieve. Poorly controlled reflections in an amplifier would cause oscillations to be stimulated and lead to cessation of the amplification and in some situations the oscillation may damage some components of the amplifiers, such as the low-power seeding source. Thus the most desirable performance of a window will be to maintain the vacuum inside the device whilst allowing radiation power to travel out with minimum absorption and reflection from itself.

A multilayer window, which consists of layers of different dielectric materials, is often used to achieve maximum microwave transmission over a broadband frequency range in the gyro-amplifiers. Such windows have been realized over a wide range of frequency bands for example: in X-band with reflections lower than −20 dB over 7.5–9.2 GHz [3], Ka-band with reflections lower than −30 dB over 32.5–37 GHz [4] and W-band with reflections lower than −20 dB over 80–107 GHz [5]. Previously a multilayer window was reported over the 90–100 GHz range operating with the TE_{11} mode as the input microwave signal [6]. That window was measured and had a better than −20 dB reflection. The window presented in this paper was designed for operating at a Gaussian-like HE_{11} mode. More wave power in such a mode would be concentrated in the center of the waveguide. This would reduce the effect of any waveguide discontinuities in the window structure and will therefore reduce the overall microwave reflection, when compared to the TE_{11} mode. This would also facilitate the application of a depressed collector system for energy recovery of spent electron beam. This paper reports the first broadband window operating in the low-THz range with a reflection better than −27 dB, over a 10% bandwidth.

The University of Strathclyde is currently developing two gyrotron-traveling wave amplifiers (gyro-TWAs) in the low terahertz range of 90–100 GHz and 360–400 GHz. Broadband amplifiers operating in these frequency bands have many applications, for instance in electron spin resonance [7], [8] and high resolution radars [9]. These applications desire that the radiation output is a Guassian beam. A quasi-optical mode converter in the form of a corrugated horn can be used to output a Guassian-like, hybrid HE_{11} mode [10], [11].

This paper concentrates on the design methodology of a multilayer window for a THz gyro-TWA. The design goal is to achieve a reflection of better than −25 dB for a HE_{11} output mode. The microwave window geometry is scalable with the operating frequency therefore throughout following section the simulated performance of the window is given with respect to the center frequency (f_0). A discussion of the constraints on the layer thickness and radial dimensions is then presented.

II. Simulation

The simulation of the microwave window was conducted using the mode matching method [12] through an in-house code. In the design process the initial step was to select the dielectric materials for the layers of the window. Gyro-amplifiers, such as considered in this study, often use a thermionic cathode so the dielectric material should be compatible with the environment. As one of the dielectric discs will be used to seal the vacuum, that disc should facilitate brazing to a mounting structure. For these reasons ceramic in the form of 97% pure Al_2O_3, which has a relative dielectric constant, ε_{rc}, of 9.4, was chosen as the central dielectric disc. Previously [6] it was shown that Quartz, with ε_{rq} of 3.75, is a suitable choice as the

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The authors are with SUPA, Department of Physics, University of Strathclyde, Glasgow, G4 0NG, U.K. (e-mail: craig.donaldson@strath.ac.uk; paul.mcelhinny@strath.ac.uk; liang.zhang@strath.ac.uk; w.he@strath.ac.uk).

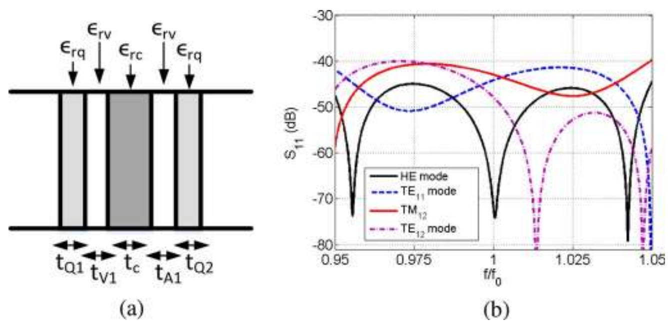

Fig. 1. Configuration and reflection of an ideal multilayer window. (a) Window geometry. (b) Simulated reflection.

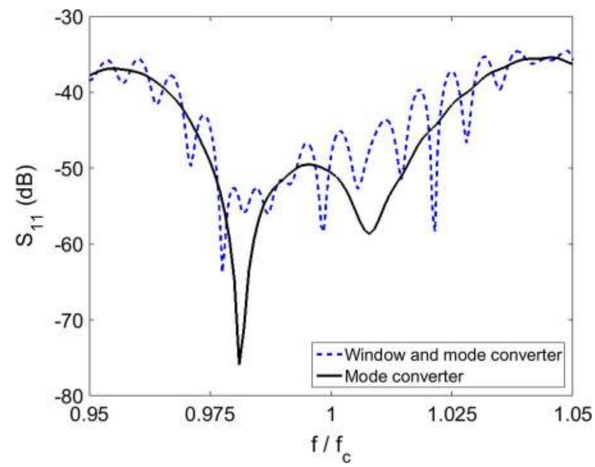

Fig. 2. Simulated reflection of the mode converter with and without the ideal multilayer window.

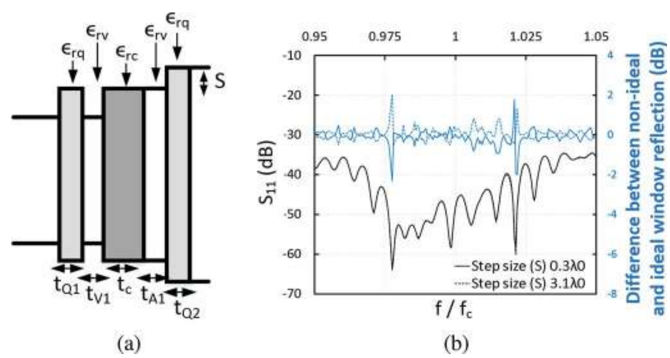

Fig. 3. (a) A non-ideal multilayer window with radial steps—Window geometry. (b) Effects of the steps on the reflection of the window with the corrugated horn used as the input source—Simulated reflection.

matching disc. This configuration allows the highest bandwidth performance whilst not violating the requirements from the operating environment mentioned. Between each Quartz disc and the central disc is a vacuum or air gap. Therefore, this multilayer window has five layer of different dielectric materials.

In order to obtain the Gaussian-like HE_{11} mode, a mode converting corrugated horn based on the $\sin^2$ profile with a corrugated phase matching section was used before the multilayer window. To achieve a high Gaussian content with a specific beam waist the mode mixture at the output is 73.04% TE_{11}, 23.06% TM_{11}, and 3.75% TE_{12} at phase angles of -11.3, 167.6, and -27.1 deg, respectively.

An ideal multilayer window with no geometry discontinuities is shown in Fig. 1(a). Firstly the diameter of the dielectric discs and the thickness of the ceramic disc should be decided. After that the thicknesses of the vacuum/air gap and Quartz disc can be optimized to achieve the widest frequency bandwidth. The diameter of the discs was decided upon by the aperture size of the quasi-optical mode converter, which in this case was 28.9 mm. The thickness of the ceramic disc was chosen as a compromise between the operating bandwidth and robustness of the disc. Generally the thinner the disc is, the wider the operating bandwidth is, but adversely, the more fragile it is and the more difficult it is to braze the vacuum-sealing ceramic disk to the mounting structure due to reduced contacting area. An in-house code was used to calculate the reflections of the multilayer window. The exact mode content at the end of the corrugated horn was used as the input source. The overall reflection of the HE_{11} mode can be calculated by combining the amplitude and phase of the reflection from individual input mode. Calculation demonstrated that a thickness of a half the central wavelength (λ_0) allows better than -45 dB reflection over a 10% bandwidth. The window configuration in this case has the optimized thickness of the Quartz discs and vacuum/air gaps to be $t_{Q1} = t_{Q2} = 0.064\lambda_0$, and $t_{V1} = t_{A1} = 0.059\lambda_0$ respectively. The resultant reflections of the window for HE_{11} mode and its composite modal mixtures are shown in Fig. 1(b). To achieve a minimum HE_{11} reflection it is obvious that the reflections from all its modal mixture should be minimized.

In order to obtain the HE_{11} mode, a mode converting corrugated horn was used before the multilayer window. The simulated reflection of the corrugated horn is shown in Fig. 2. When the multilayer window was added to the corrugated horn the window structure had to be re-optimized in order to maintain the correct phase difference between the three modes at the aperture. The optimized dielectric layer thicknesses were found to be $t_c = 0.51\lambda_0, t_{Q1} = t_{Q2} = 0.063\lambda_0$, and $t_{V1} = t_{A1} = 0.060\lambda_0$. The reflection of the window was simulated, Fig. 2, which shows that both the corrugated horn and the window have a reflection of less than -30 dB in the 10% frequency band. The multilayer window did not significantly increase the overall reflection.

III. Dimension Constraints and Tolerances

The ‘ideal’ multilayer window has been shown to achieve a lower reflection than the gyro-TWA design targets. However, in order to facilitate the brazing and to secure the discs in positions it is necessary to introduce radial steps in the waveguide, as illustrated in Fig. 3(a). The introduction of those steps may adversely affect the reflection and cause mode conversion. In this particular window it was advantageous to use HE_{11} waveguide mode as the wave power is more concentrated in the center of the waveguide which should markedly reduce the effect of the radial steps on the wave reflection. Indeed, this was confirmed by simulations. When the step size was as large as $3.1\lambda_0$ its effect on the wave reflection was at maximum -2 dB worse as compared to the ideal case, as shown in Fig. 2. The step size of $0.3\lambda_0$ was used for this window to keep the dielectric discs diameter small therefore physically stronger and less prone to

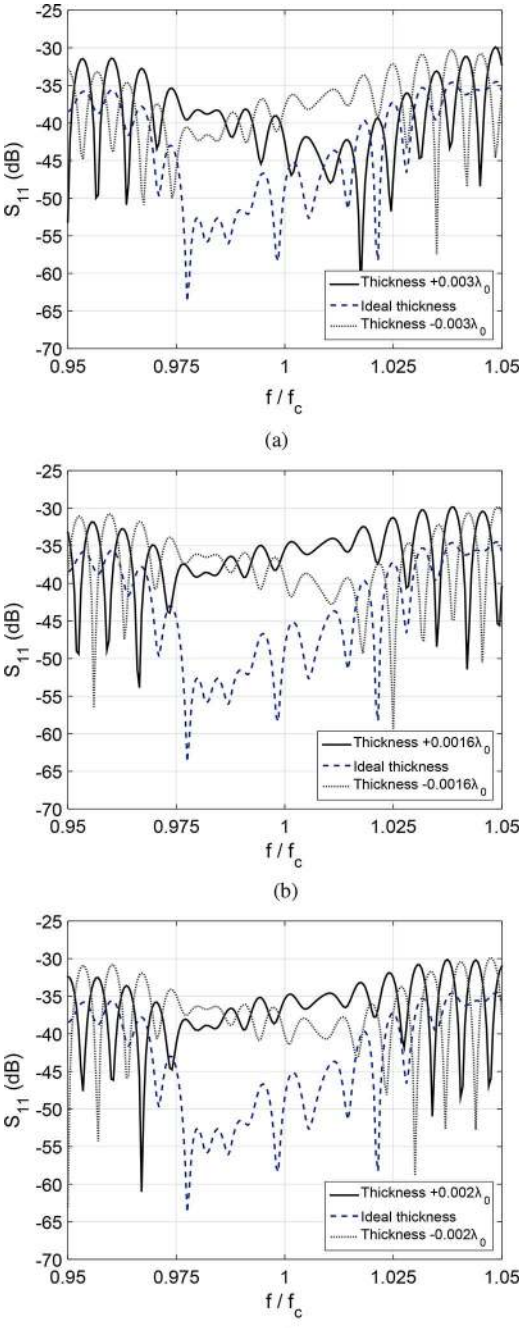

Fig. 4. Simulated reflection for changed values of dielectric disc or vacuum/air thickness. (a) Ceramic disc (t_C); (b) Quartz disc $(t_{Q1})(t_{Q2})$: (c) Vacuum/air gap $(t_{V1})(t_{A1})$.

breakage. The simulated reflection in Fig. 3(b) shows that the reflection is around -35 dB and is about -10 dB worse than the ideal case of the window by itself, as shown in Fig. 1(b).

A study of the sensitivities of the thicknesses of the dielectric layers on the reflection of the window is required in order to determine their tolerances and further to decide the way the window could be practically realized. The maximum tolerances are the value of the change in layer thickness that would cause a maximum reflection of -30 dB. When each dielectric layer is changed independently its effect on the microwave reflection is shown in Fig. 4. The tolerance on the thickness of Quartz,

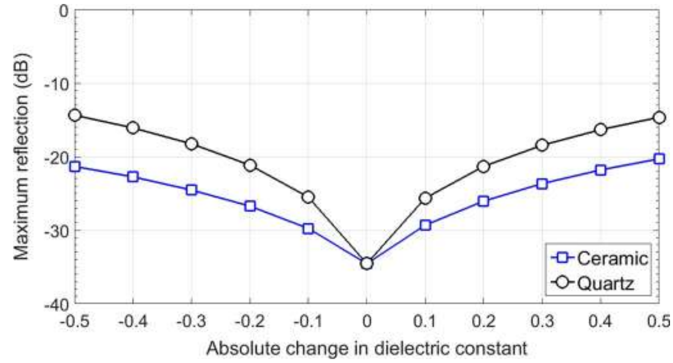

Fig. 5. Simulated effect of the dielectric constant of the window discs on the maximum reflection level.

vacuum/air and ceramic is found to be $0.0016\lambda_0$, $0.002\lambda_0$, and $0.003\lambda_0$, respectively. The practical design for the window must be able to meet these tolerances. The effect of the dielectric constants of central ceramic and matching quartz disks on the reflection of the window were simulated and is shown in Fig. 5. It was found that the reflection of the window was very sensitive to dielectric constants of the material. However the reflection due to differences of the dielectric constants could be avoided as they could be measured exactly before the design of the window and their effects could be compensated by changing the separations between the discs. The conclusion of this sensitivity analysis has shown that for the 90–100 GHz multilayer window the structure, and associated tolerances, of the window would be $t_C = 1.61 \pm 0.01$ mm, $t_{Q1} = t_{Q2} = 0.20 \pm 0.005$ mm and $t_{V1} = t_{A1} = 0.19 \pm 0.006$ mm. When operating over 360–400 GHz the window structure, and associated tolerances would be $t_C = 0.40 \pm 0.0025$ mm, $t_{Q1} = t_{Q2} = 0.05 \pm 0.001$ mm and $t_{V1} = t_{A1} = 0.05 \pm 0.0015$ mm.

IV. Manufacturing Methods

Tolerance testing has shown that small differences in the thickness of the dielectric layers affects the reflection of the multilayer window thus the manufacturing method of the window is very important. The 90–100 GHz window could be fabricated through traditional machining methods, such as turning, milling and polishing, as the size of various components of the assembly are large enough. The dielectric discs, both Quartz and ceramic, are able to be made through optical polishing and grinding, respectively, which is able to achieve the required tolerances. The housing structure, which will make the vacuum seal, can be made with a lathe which is able to achieve ± 0.02 mm. The most difficult part of the design and fabrication is to keep the distance between the dielectric discs. In order to achieve this, spacing rings were made. To prevent any damage to the dielectric discs theses rings were made from a metal that is softer than than the discs, in this case OFHC copper was used.

V. Window Manufacturing and Measurement

In order to verify the multilayer window design, as optimized through simulation, the microwave window was constructed and measured on a Vector Network Analyzer (VNA). Several

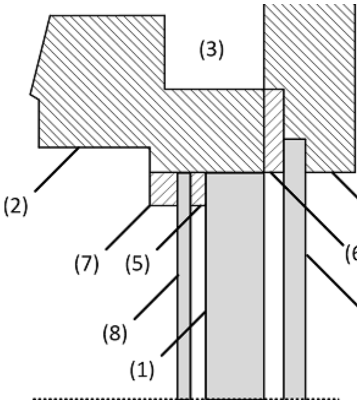

Fig. 6. Schematic of the multilayer window design.

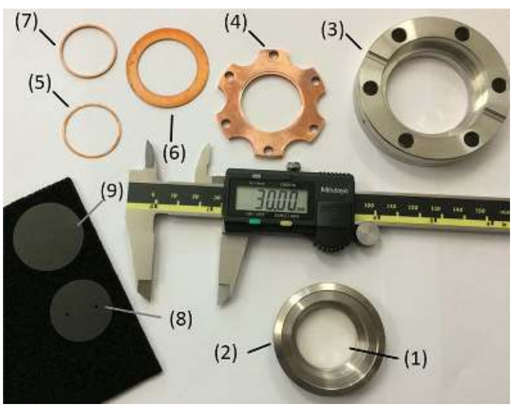

Fig. 7. Photograph illustrating the various components of the multilayer window.

challenges existed with the fabrication of the window, as the tolerances in the thicknesses of the dielectric layers are very small. When the window is assembled cares must be taken to balance the pressures applied to each Quartz disc and to fine adjust the vacuum/air gap spacing to achieve an optimal result.

A schematic drawing of the microwave window and a photo of its components are shown in Figs. 6 and 7. The alumina disc (1) is initially brazed into the conflat flange (2), (3). On the air side of the window is a copper plate (4) which is used to apply a pressure onto one of the Quartz discs. There exist three copper rings, two of which, (5) and (6), are used to separate the dielectric discs. The third copper ring (7), is used to ensure a smooth transition between the corrugated mode converting horn and window when they are joined together. Lastly, there are two Quartz discs (8), (9). The Quartz disc that is in the vacuum, (8), has two 1.5 mm diameter holes through the surface in order to allow a vacuum pumping path. These holes were located away from the centre of the disc, due to the field structure of the HE_{11} mode, field structure, i.e., most of the microwave power is centrally located.

The microwave properties of the window were measured using a VNA. The output of the VNA is linearly polarised and had a rectangular waveguide port which was then tapered to circular waveguide. The circular waveguide was then connected to the wideband corrugated horn without radial discontinuity to avoid possible refection. The multilayer window was connected to the corrugated horn through a conflat flange. After passing

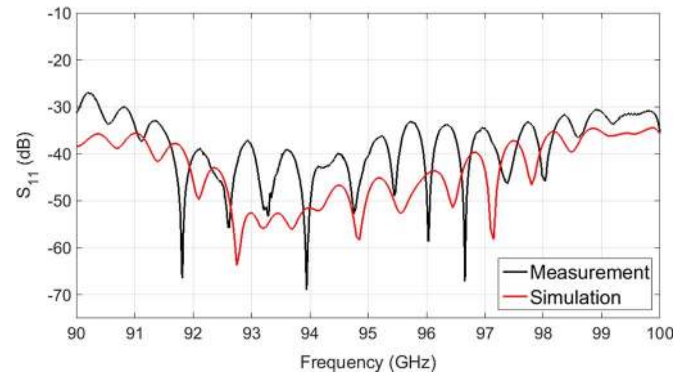

Fig. 8. Plot illustrating the comparison of the simulated and measured microwave window reflection.

through the window the microwave power was then radiated into free-space. Absorbing material was placed around the environment to reduce background reflections. It should be noted that it was impossible to measure the reflection of the HE_{11} mode albeit the window was numerically optimized for this mode. Nevertheless the measured TE_{11} mode reflection of the assembly of the corrugated horn and window was recorded and is shown in Fig. 8 which was in reasonable agreement with the simulated result. Measured reflection was better than -30 dB over almost the full frequency range with the exception of 90.5–90.8 GHz which was -27 dB. Differences between the simulated and measured reflection is likely caused by errors in gap distances as the other parameters such as dielectric constants and the thicknesses of the discs were accurately measured and found to be the designed values.

VI. Conclusion

The mode-matching method was employed to optimize the multilayer output window for application in terahertz gyro-amplifiers. It was found that the optimized window structure had a reflection of lower than -30 dB over a frequency bandwidth of 10%. Tolerance study on the window components showed that that the radial sizes of the layers have larger tolerances, however the thicknesses of the dielectric layers were found to have a much tighter tolerances. A window operating over the 90–100 GHz frequency range was constructed and measured reflection of better than -27 dB was in good agreement with the simulated data over the full frequency bandwidth. This multilayer window will be used in the 90–100 GHz gyro-amplifier and gyrotron backward wave oscillator [13].

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Craig R. Donaldson received the B.Sc.(Hons.) degree in physics, the M.Sc. degree in high power RF, and the Ph.D. degree in physics from the University of Strathclyde, Glasgow, U.K., in 2005, 2006, and 2009, respectively.

He is currently with SUPA, Department of Physics, University of Strathclyde, Glasgow, U.K.. His main research interests include electron-beam generation, gyro-TWT/BWOs, and helically corrugated waveguides.

Paul McElhinney received the B.Sc. degree in applied physics in 2005, the M.Sc. degree in high power radio frequency science and engineering in 2009, and the Ph.D. degree in physics in 2013, all from the University of Strathclyde, Glasgow, U.K.

He is currently a Research Associate with the Scottish Universities Physics Alliance, Department of Physics, University of Strathclyde, Glasgow, U.K. His main research interests include broadband quasi-optical components for high power gyro-amplifiers and oscillators.

Liang Zhang received the B.Sc. degree in applied physics from the University of Science and Technology of China, Hefei, China, in 2004, and the M.Sc. degree in application of nuclear techniques from the China Academy of Engineering Physics, Chengdu, China, in 2007, and the Ph.D. degree in physics from the University of Strathclyde, Glasgow, UK in 2012.

He is currently a Research Associate with the Scottish Universities Physics Alliance, Department of Physics, University of Strathclyde. His main research interests include pulse-power technology, and Gyrotron-TWA/backward-wave oscillators.

Wenlong He received the B.Sc. degree in physics from Suchow 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 Department of Physics, University of Strathclyde, Glasgow, U.K., in 1995.

He is currently a Senior Research Fellow with the Scottish Universities Physics Alliance, Department of Physics, University of Strathclyde, Glasgow, U.K. His main research interests include relativistic electron beams, cylotron autoresonance masers (CARMs), free-electron lasers (FELs), gyro-TWT/BWOs, and other high power microwave devices.