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Design, Development and Characterization of Indigenously Developed High Temperature Black Body Source for Calibration of ECE Diagnostics

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Abstract. The design, development, and characterization of a Silicon Carbide (SiC) based high temperature black body source at 600 ºC for Electron Cyclotron Emission (ECE) measurements has been done. The design has been optimized for higher emissivity performance in 65-140 GHz frequency range using CST Microwave Studio. The innovative design features a pyramid-based structure, incorporating a heater and emitter surface, integrated with an electrical control system. The improvement in emissivity with variation in pyramid slant angle was analysed. The design was refined to ensure surface temperature consistency within a range of ± 15 ºC and rapid heating, taking less than 60 minutes to reach 600 ºC from room temperature. The developed black body calibration source was thermally characterized using IR camera for different set of temperatures and mean temperature distribution was determined. The microwave characterization of the calibration source has been performed in 65-80 GHz frequency range using Vector Network Analyser (VNA) and reflectivity of more than 20 dB has been obtained. The results highlight the synergy between advanced design methodologies, and precise engineering, leading to the development of an efficient SiC-based black body source. This research work not only contributes significantly to the field of engineering but also paves the way for enhanced accuracy and reliability in ECE measurements.

1 Introduction

Electron Cyclotron Emission (ECE) measurement diagnostic at IPR such as Michelson interferometer and radiometer, undergoes calibration using the hot-cold technique. In this technique a hot and a cold black body source is used [1]. When conducting absolute calibration with a long transmission line using a low temperature source, the signal received at the input of the instrument is very weak, requiring very long integration time to enhance the low signal-to-noise ratio (S/N). Sometimes it takes around one to two week time to complete the entire calibration procedure. Hence, there's a need for a high-temperature calibration source to minimize the long measurement integration time. This paper discusses the design, simulation, and characterization of a high-temperature black body calibration source which operates at 600 °C. The performance of the source has been optimized for high emissivity in the 65-140 GHz frequency range for 2nd harmonic ECE measurements using CST Microwave Studio in Section-2. The development of the heater, emitter, and their integration testing is discussed in Section-3. Section-4 describes the infra-red thermography imaging of the calibration source and Section-5 discusses the characterization of the emitter plate with a two port vector network analyser for emissivity measurements.

2 Design and Simulation

The calibration source consists of an emitter plate and a heater. The heater is used to heat the emitter plate to a temperature of 600 °C. The design of the emitter plate is carried out by machining pyramids on a silicon carbide block. The pyramids were simulated for various slant angles starting from 40° to 80° using the CST microwave studio [2]. Through simulations it was found that emissivity values were highest and near unity when the pyramid slant angle is near to 80°. The same has been shown in figure 1.

Fig. 1. Simulation results showing emissivity values for different slant angles of the pyramids.

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As a result the design finalized for fabrication was silicon carbide pyramidal structure with slant angle 80°. The base and slant height of the pyramid was 2.5 mm and 7.1 mm respectively. The dimension of the pyramids were chosen as per the wavelength requirements of the design. A model of the designed prototype emitter plate is shown in figure-2.

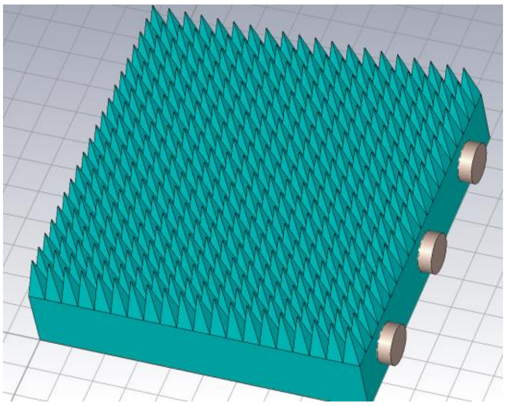

Fig. 2. Design of the prototype emitter plate with 80° pyramidal slant angle used for CST simulation.

3 Development and Testing

The machining of such fine pyramids on a silicon carbide surface was a challenging task and required a high purity silicon carbide block. This was necessary for sustaining high temperatures with black body properties. The selected silicon carbide sample had a purity of 99% with a density of 3 gram/cm^3. The thermal conductivity and coefficient of thermal expansion were 125 $Wm^{-1}K^{-1}$ and 10^{-6}/°C respectively ensuring it to be a material suitable for the design of the high temperature calibration source. A special disc cutting tool was developed for fine machining of the pyramids. The emitter plate obtained after machining has been shown in figure-3.

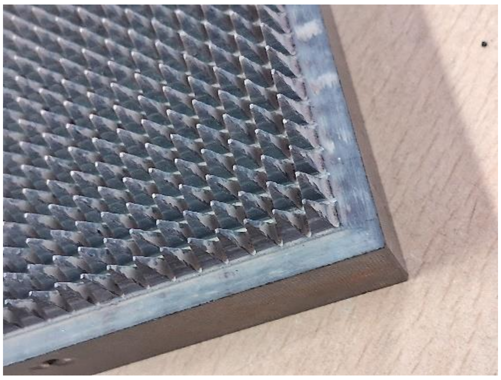

Fig. 3. Fabricated emitter plate obtained by fine machining of pyramids with slant angle 80° on a silicon carbide block.

For heating of the emitter plate, an efficient PID controller based heating system was developed. The heating system comprises of 10 high temperature cartridge rod heaters, each of 300 W capacity for rapid heating. The heating system takes about 55 minute time to heat up the emitter plate from room temperature to a temperature of 600 °C. The integration of the emitter plate and the heating system has been shown in figure-4.

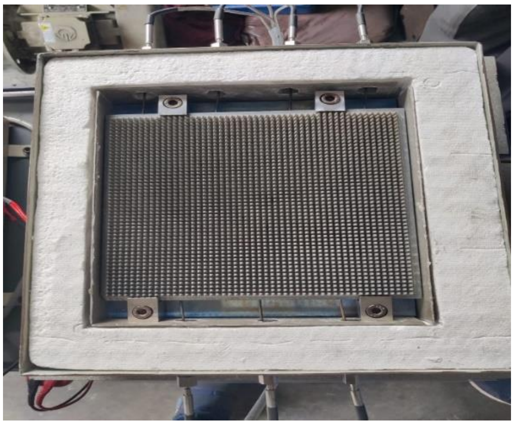

Fig. 4. Integration of heating system with emitter plate and thermocouples inside a thermally insulated box.

Seven thermocouples have been embedded inside emitter plate to gather temperature information from each section of the emitter plate. The entire assembly has been thermally insulated to avoid heat leakage to the outer atmosphere. During testing, the calibration source remained in operation for a continuous period of 15 hours, with numerous repetitions of such cycles. The maximum temperature variation among the seven thermocouples of the emitter plate was within 13°C when operated at a set temperature of 600 °C for long hours. The estimated deviation is about 2% from the set temperature. The thermocouple temperature display is shown in figure-5 and developed source in figure-6.

Fig. 5. Thermocouple temperature display showing maximum temperature variation of the emitter plate is within 2% of the set temperature.

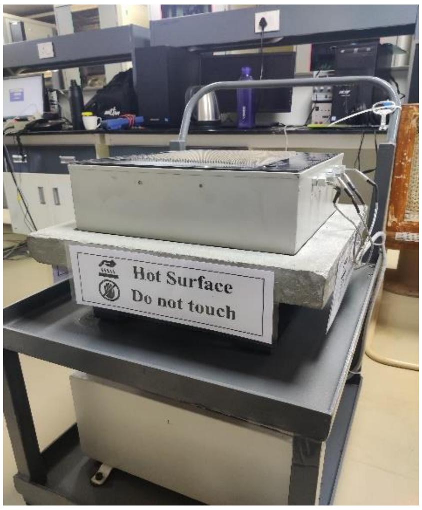

Fig. 6. Developed high temperature black body calibration source with heater and emitter assembly (top shelf) and electrical control system (bottom shelf).

4 Characterization

The characterization of the back body emitter plate was performed using the (i) Infra-red thermography camera and (ii) Vector network analyser. Following section discusses the results of characterization.

4.1 Characterization with Infra-Red (IR) Thermography Camera

The black body calibration source was characterized using infrared thermography camera at a temperature of 600°C. The operational wavelength of the IR camera was 1.5 um to 5 um which corresponds to a frequency of 60–200 THz.

Figure 7 shows the mean temperature distribution of black body source at 600°C with a frame rate of 100 Hz. The image below is an average of 100 frames acquired in 1 second time duration. The observed temperature is around 560°C for a set temperature of 600°C.

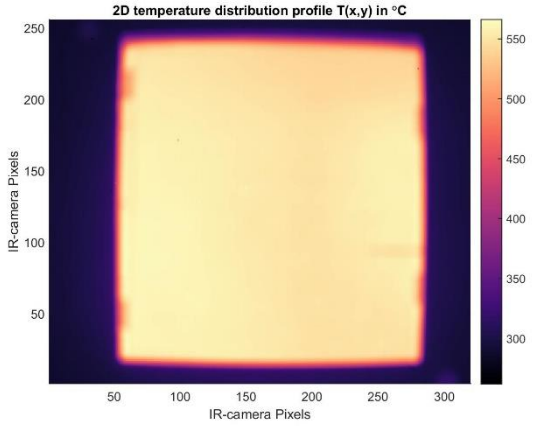

Fig. 7. Mean temperature distribution of black body source at 600°C with frame rate of 100 Hz

The 3-dimensional Temperature Distribution of Black Body Source at 600°C is shown in figure 8 again acquired with a frame rate of 100 Hz and averaged over 1 second time duration.

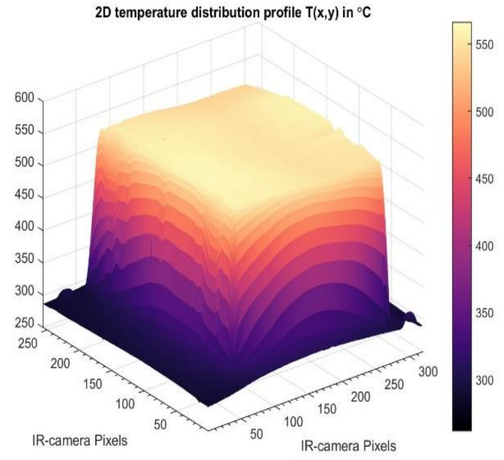

Fig. 8. 3D Temperature Distribution of Black Body Source at 600 with frame rate of 100 Hz

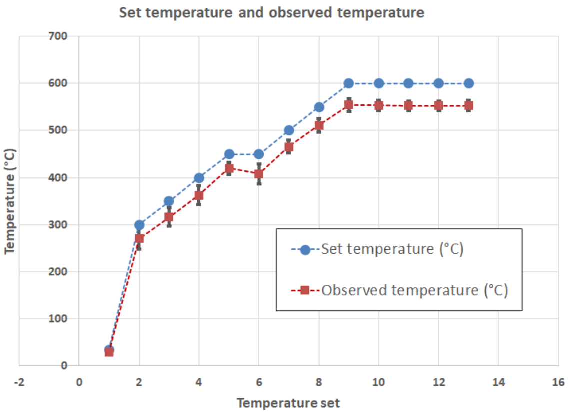

Fig. 9. Comparison between set temperature and observed temperature.

Outcome of the Analysis:

(1) The observed temperature using the IR camera is about ~40°C lesser than that of the set temperature of the black body source. This suggests that the surface emissivity of the black body source is less than unity for the IR frequency range. This has been plotted and shown in figure 9 above.

(2) The surface emissivity of the black body source is estimated at about ~0.91 for the 1.5 um to 5 um (60– 200 THz) operation wavelength band of the IR camera.

(3) After considering the emissivity correction in the observed temperature data, the deviation is ≤ ± 2 % and the average surface uniformity is roughly estimated at about ≤ ± 3 %. This has been shown in figure 10 below.

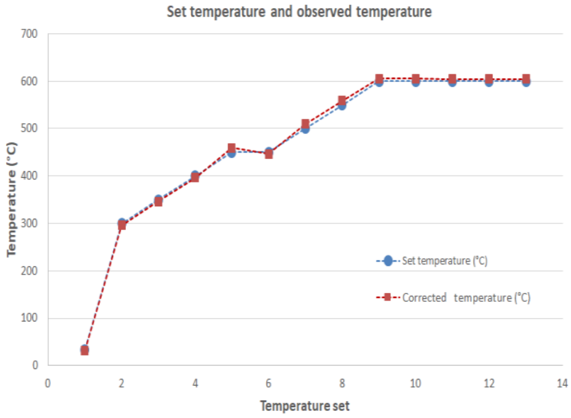

Fig. 10. Corrected plot between set temperature and observed temperature.

The calibration source has been designed for operation in the GHz range and optimized for higher emissivity in the frequency range of 65-140 GHz for 2nd harmonic ECE measurements. The characterization by IR camera has been done at a much higher frequency range of 60-200 THz. It is obvious that the emissivity values will not be high in this frequency region as expected in the gigahertz range. The next section discusses the characterization of the black body emitter by vector network analyser in the gigahertz range. This will provide a better idea of the emissivity of the designed emitter plate in its desired frequency range.

4.2 Characterization with Vector Network Analyser (65 -220 GHz)

To determine the performance of the developed silicon carbide emitter plate in gigahertz range, its characterization was performed using the two port vector network analyser (VNA). Measurements were carried out in the W-Band (65-110 GHz) and D-Band (110-170 GHz) frequency range. Measurements were done for specular angles 36°, 50° and 65° through the NRL Arc method keeping the angle of incidence and reflection equal as shown in figure 11. The reason to choose three different incident angles was to observe reflection and scattering characteristics in a broad field of view.

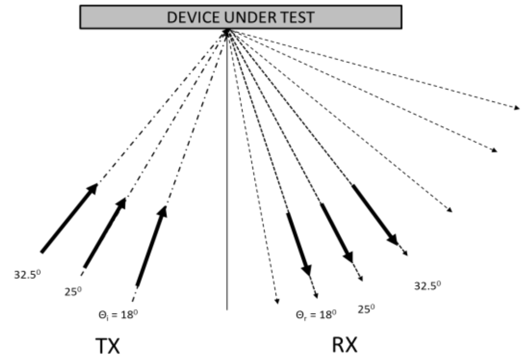

Fig. 11. Schematic Diagram Depicting Specular Measurements in the three selected incident angles.

The setup for 50° specular angle measurement in W-Band (75-110 GHz) using the NRL arc method has been shown in figure 12. The silicon carbide emitter plate is kept at a distance of 55 cm from the transmitting antenna in the far field region. Standard corrugated horns have been used to transmit and receive the electromagnetic signals to and from the plate respectively at similar angle of incidence and reflection. Standard microwave absorbers have been used to absorb unwanted reflections and noise from the surroundings.

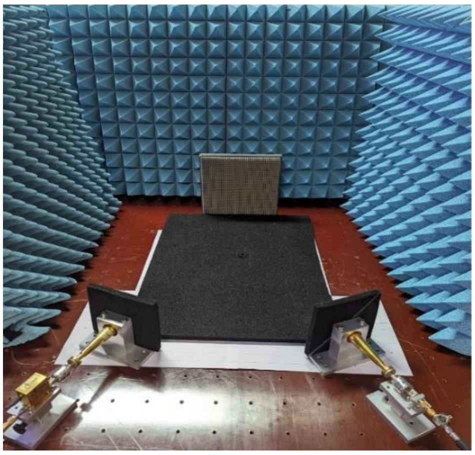

Fig. 12. W-band measurement setup for 50° specular angle using corrugated horn antennas and VNA

Figure 13 shows the calibration setup for D-Band (110-170 GHz) 65° specular angle measurements. The setup uses a metallic reflector plate having mirror like properties to allow maximum reflection. The metallic plate is positioned precisely where the silicon carbide plate is located. The calibration setup is same for both the measurement bands.

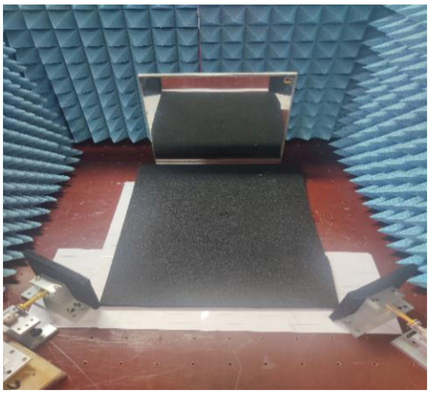

Fig. 13. Calibration setup for D-Band (110-170 GHz) 65° specular angle measurements.

The reflectivity results obtained for measurement at specular angles 36°, 50° and 65° in W-Band has been shown in figure 14. The plot in blue at 0 dB is the calibration plot. The signal level remains in the range -20 to -35 dB for different angles of measurement. It is clear from the measurements that the silicon carbide emitter plate has reflectivity better than -20 dB in the entire frequency band.

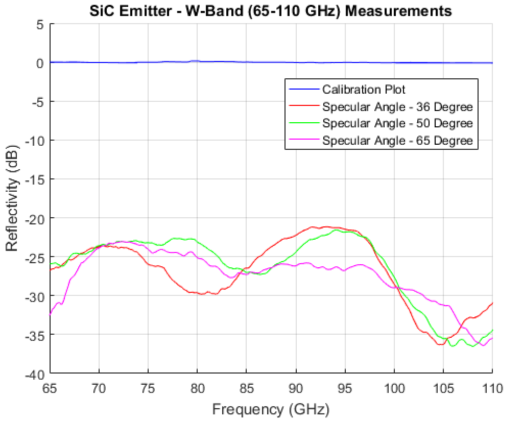

Fig. 14. W-Band characterization results for three different specular angles using VNA

D-Band characterization results have been shown in figure 15 at three different specular angles. For 50° and 65° measurements the reflectivity remains below -25 dB whereas for 36° it remains below -20 dB. The calibration data acquired with a metal plate remains at 0 dB and acts as a reference for these measurements.

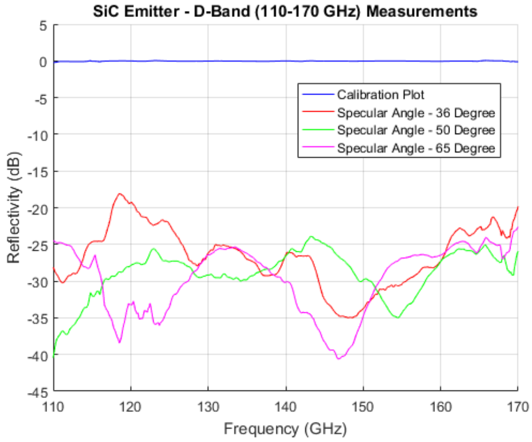

Fig. 15. D-Band characterization results for three different specular angles using VNA

In summary, the reflectivity of the silicon carbide emitter remained below -20 dB in the frequency range of 65-170 GHz for measurements at specular angles of 36°, 50° and 65°. Emissivity is a function of reflectivity and transmitivity [3]. The measured transmission coefficient remained below -25 dB for all the measurements. The emissivity of the emitter plate estimated from the above measurements and was found to be around 0.98 (Emissivity = 1 – Reflectivity – Transmitivity). This is near to the emissivity values obtained from CST simulation for the designed prototype model at 80° pyramid slant angle in the same frequency range

5 Conclusion

The design of a silicon carbide emitter plate was carried out using CST simulation software and emissivity values near to unity were obtained. Similar model was fabricated for pyramid slant angle 80° and integrated with a heating and electrical control system. Surface temperature uniformity was found to be in tolerance level. The source was characterized with IR thermography imaging at 600°C and emissivity at IR frequency range was determined. Characterization of the emitter plate was performed with vector network analyser in the W-Band and D-Band and reflectivity values were obtained. The reflectivity remained below -20 dB in the frequency range 65-170 GHz. Based on the obtained reflectivity values, the emissivity was calculated which was found to be around 0.98. This is near to simulated emissivity value in the same frequency range.

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