Infrared monitoring of gyrotron windows

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Abstract

Ceramic and single crystal windows for the transmission of high average power (>50 kW) microwave and millimeter wave tubes such as the gyrotron are a key limitation in practical tube development. Thermal stresses can be calculated by computer modeling, but various assumptions lead to large uncertainties. To determine the actual window condition, a technique for monitoring the temperature distribution over the window surface with an IR camera while the gyrotron is in operation has been developed. The IR camera views the window through a perforated waveguide wall and serves both as a guide for the safe operation of the gyrotron as well as an aid in the analysis of new window designs. The technique is applicable to many types of high average power microwave and millimeter wave tubes.

Introduction

In microwave and millimeter wave tubes, such as the gyrotron, a dielectric window allows transmission but also acts as a barrier between the tube vacuum and the outside world. At high average output powers (>50 kW) absorption of the electromagnetic waves in the dielectric can lead to excessively high thermal stresses. These stresses can be calculated by computer modeling, but various assumptions such as flow velocity distribution and heat transfer coefficients, etc., can lead to large uncertainties. Additional factors include load matching, ghost modes, and especially for the gyrotron: overmoded waveguide. To determine the actual window conditions, a technique for monitoring the temperature distribution over the window surface with an IR camera while the gyrotron is in operation has been developed. This technique is quite useful in analyzing window designs as well as guiding a developmental tube to safe operating parameters. The ability to observe small hot spots due to tiny metallic specks on the window surface is also of great value in quality control and window failure prevention. The gyrotrons available for examination at Varian include 28 GHz to 70 GHz tubes at 200 kW pulsed and CW. The output power of these tubes is in the TE02 mode through a window in 2.5" diameter waveguide. In addition, Varian has a development program for a 140 GHz gyrotron with an output power of 100 kW CW in the TE03 mode.

A schematic of the IR diagnostic test setup is shown in Figure 1. The air side of the window is observed through a pattern (grid) of tiny holes in the output waveguide wall. Proper selection of grid hole diameter, wall thickness, viewing angle and hole spacing optimizes the transmission of the infrared but maintains a safe level of microwave leakage. The holes are radially inward at a declination angle \( \theta \), see Figure 1. A regular hole pattern was selected due to ease of machining. The concept is to focus on the window surface while defocusing the grid. Simple geometrical optics calculations estimated the grid transmittance, see Figure 2. The proximity of the grid and window requires a shallow depth of focus. An AGA-780 camera with a 12° FOV lens and extension rings was selected. Both the short wave (SW 3-5 \( \mu m \) In Sh) and the long wave (LW 8-12 \( \mu m \) HgCdTe) are used, depending on window material. Typical window materials include ReO, alumina ceramic or sapphire. The thermal emissivity \( (\varepsilon_w) \) of the window materials is usually greater than 0.8. A test to observe a 330°C object behind sample windows at room temperature confirmed the high thermal emissivity. Reflections from the window are negligible due to the high emissivity. Reflections of the window from the internal waveguide walls occur at angles which appear external to the window edge, and thus are neglected. To minimize the problem of external waveguide wall reflections, the outside waveguide wall is painted with a flat paint. However, in order to reduce the thermal emission of the painted waveguide wall, the waveguide is cooled slightly below room temperature.

The system presently views only about half of the window surface. Rotation of the camera support about the waveguide axis permits examination of the entire window.

The IR camera scans the window area and measures the photon flux. This flux, \( I_a \), is a function of the window temperature at each point, the grid transmittance, \( t_g \), and the grid reflection \( r_g \), along the optical path. The operational equation is essentially:

\[
I_a = I_w \varepsilon_w + I_g (1 - t_g - r_g) + I_{amb} r_g
\]

where \( I_w, I_g \) and \( I_{amb} \) are the blackbody equivalent intensities of the window, grid and ambient "background", respectively. A calibration of the system determines the grid transmission function. This is achieved by heating the window coolant steady state at several temperatures.

The temperature resolution of the system depends on the relative temperature difference between the waveguide and window as well as the grid transmission coefficient. For a waveguide at or below room temperature, the temperature resolution near the center of the
window is about 1°C for an alumina ceramic window temperature of 70°C (3-5 μm system). It improves as the window temperature increases. The temperature resolution using the 8-12 μm system is about 2°C due to the reduced sensitivity of the detector. Spatial resolution is better than 2 mm and hot spots smaller than 1 mm are easily observed with either system.

Results

Measurements were primarily taken during CW operation of the gyrotron. Microwave leakage and x-rays did not appear to have any effect on the IR camera. Ground loops must be avoided especially when an arc occurs in the microwave tube or modulator.

Figure 3 is a graph of the maximum window temperature as a function of output power. Two different window baffle designs were examined. A maximum temperature of 120°C was selected due to the boiling point of the dielectric window coolant (FC-75). Cooling of the FC-75 by 5-10°C was found to be beneficial.

In an earlier tube the window broke while operating at about 130 kW CW with the FC-75 flow rate at 4 gpm. A subsequent examination of the maximum window temperature versus flow rate at several output powers suggested a probable thermal runaway condition, see Figure 4. A conservatively extrapolated temperature suggests that the FC-75 was boiling when the window broke.

Another phenomenon that was observed in early tubes was the variation in the heating pattern of the window due to a variation in operating parameters. Figure 5 shows two thermographs with the tube output power fixed. This was later found to be primarily due to the fact that the tube output consisted of several waveguide modes. These modes, traveling at different velocities resulted in beat patterns. Figure 6 is a graph of maximum window temperatures as a function of output power for a variety of tube parameters. An understanding of what tube parameters gave the lowest window temperature resulted in the first 200 kW CW 60 GHz gyrotron operation.

Pulsed power operation is a little more difficult. A synchronizing trigger and a freeze frame is necessary. A synchronized signal and fast digital recording is desired.

Summary

The IR monitoring technique described above has proven to be invaluable to the development of the 60 GHz, 200 kW CW gyrotron. It is particularly useful in evaluating window designs and revealing tiny heated specks that may have fallen onto the window surface. The diagnostic is expected to play a major role in the development of a 140 GHz, 100 kW CW gyrotron for the National Gyrotron Development Program.
This work is supported in connection with 60 GHz and 140 GHz gyrotron oscillators developed under contract with Oak Ridge National Laboratory, operated by Martin Marietta Energy Systems, Inc. for the U.S. Department of Energy, Office of Fusion Energy, under prime contract DE-AC05-840R21400.
CALCULATED GRID TRANSMITTANCE AND SENSITIVITY CONTOURS ON WINDOWS

GRID 1 (THIN)

GRID 2 (THICK)

EDGE OF WINDOW
MAXIMUM WINDOW TEMPERATURE vs OUTPUT POWER

BEAM VOLTAGE = 80 kV NOMINAL

LEAST SQUARES FIT: Y = AX + B

A = 0.53°C/kW
B = 10.30°C

NEW BAFFLE 7.85 GPM
NEW BAFFLE 7.3 GPM
OLD BAFFLE 8.3 GPM
OLD BAFFLE 7.3 GPM
TEMPERATURE vs FC-75 FLOW

Fig. 4

VGE-8005 S/N 1
56 GHz CW
IR CAMERA f/1.8
PWR = PWRWL

130 kW
111 kW
91 kW
70 kW
49 kW

INLET
FC-75 TEMPERATURE

FC-75 FLOW (GPM)
Fig. 6

**PEAK WINDOW TEMPERATURE vs OUTPUT POWER (X-6)**

FC-75 FLOW = 8.5-8.7 GFM

![Graph showing peak window temperature vs output power](image-url)
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