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Development of a Forced Gas-Cooled Brewster Window for High-Power, CW Millimeter Waves

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Abstract

Development of a vacuum barrier window for high power millimeter waves is one of the key technical issues to realize CW (Continuous Waves) ECH system. For this purpose, we have been developing a forced gas-cooled Brewster window with low loss silicon nitride composite (SN-287 Kyocera) for megawatt and CW power transmission. The thermal analysis of the window with forced gas-cooling on the basis of the finite element method shows a 0.5 MW/CW, HE_{11} mode transmission is possible to the 100×300 mm^2 silicon nitride disk. Since this material has very low thermal expansion coefficient, we first designed and assembled a prototype Brewster window using normal silicon nitride (SN-220 Kyocera) to check the structure of brazing and welding. To transmit millimeter waves the corrugated waveguide sections are prepared at the both sides of the disk. At the atmospheric side of the waveguide nozzles for gas-cooling are drilled on the wall. The number of the nozzle holes is optimized to be nine with the diameter of 1mm, and air is blown on the disk unidirectionally. This structure is determined from the experimental results using a simulated heat source. On the basis of the experiments, we have assembled a real window and prepared to test it by high power CW power transmission.

Keywords:

brewster window, tunable gyrotron, electron cyclotron heating, vacuum window, silicon nitride

1. Introduction

Development of millimeter-wave vacuum barrier windows is one of the most important subject to accomplish windows of both high power, CW gyrotrons and ECH systems of the stellarators and tokamaks. Many efforts to make 1MW/CW windows have been made all over the world.

The concept of the RF window structures could be divided into two groups, such as multipule-disk windows with a surface cooling and single disk ones with circumference cooling. Besides the transmission ability depends strongly on the window materials themselves. It has been improved from the aspects of both structures and materials [1].

Single-disk windows have the merit of being simple structures which assure higher reliability than complicated multiple-disk designs. By means of gas-cooling, a surface-cooled single-disk window with a low loss and tough material might be possible to succeed in CW power transmission.

Kyocera Corporation in Japan developed new material (silicon nitride composite so called SN-287), which shows low loss tangent at the millimeter wave

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Table 1 Physical, electrical and mechanical characteristics of the low loss silicon nitride composite.

	uint	Silicon Nitride Composite
Density	g/cm3	**3.4**
Modulus of Elasticity	GPa	**318**
Poisson Ratio		**0.28**
Linear Expansion Coeff.	x 10^-6 /K	**2.4**
Thermal Conductivity	W/mK	**59**
Specific Heat Capacity	J/gK	**0.63**
Dielectric Constant		**7.9**
Loss Tangent	x10^-4	**1 (30-40GHz, R.T.)**
		1 -1.5 (84GHz, R.T.)
		2.4 (140-145GHz, R.T.)
Dielectric Strength	x 10^4 kV/m	**1.85**
Bending Strength	MPa	**800**
Compressive Strength	MPa	**5000 - 6000**
Thermal Shock Resistance		**>750 deg.C (Melting solder)**
Metalizing/Brazing		**Possible**
Possible size		**φ400mm**

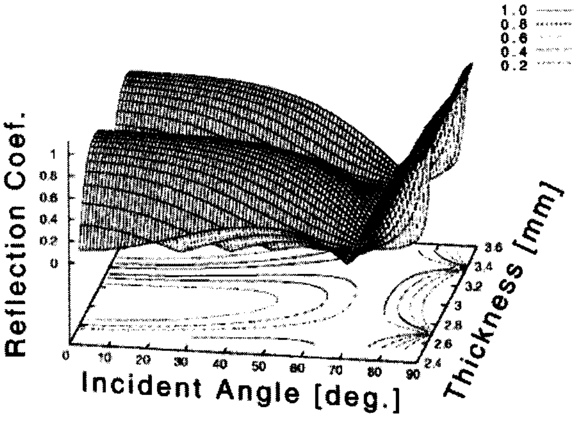

Fig. 1 Calculated result of incident angle dependence on the reflection coefficient, when the disk thickness is changed for 84 GHz, permittivity of 7.92.

range. The silicon nitride has higher thermal shock resistance, higher flexural strength and better thermal conductivity than sapphire. Metalizing and brazing with some metals are possible, though it is more difficult than sapphire because of its small thermal expansion characteristics. Table 1 presents the physical, electrical and mechanical characteristics of the silicon nitride.

Using the low loss silicon nitride composite, we assembled a forced gas-cooled single-disk window with edge-water cooling, and demonstrated the possibility of high power CW transmission in the circular shape [1]. In this work, the RF power (84 GHz, HE_{11} mode) of 130 kW could be transmitted continuously through the forced gas-cooled silicon nitride composite window with 88.9 mm in diameter. This experiment showed that the forced gas-cooling could handle the peak power flux density of 8 kW/cm^2 in steady state. The local heat transfer coefficient of the forced gas-cooling can be estimated by evaluating the decay time of the peak temperature on the disk after turning off of the millimeter-wave injection. The maximum value of the heat transfer coefficient is 1 kW/m^{2}K for a gas flow rate of about 400 liter/min. Now this type of window is adopted and used as both an output window of a 168 GHz gyrotron and an ECH injection window of Large Helical Device for half-megawatt, long pulse transmission [2].

With gas-cooling the Brewster window, which has a larger surface area and a stronger structure, is expected to be able to transmit megawatt CW power. We designed and assembled a 0.5 MW/CW Brewster window. By means of an electrically heated film resistor as a heating source, we made simulation experiments to optimize the nozzles of gas-cooling. This paper is organized as follows. The transmission characteristics of a Brewster window are described in Sec. 2. In Sec. 3 the thermal analysis of the Brewster window with forced gas-cooling on the basis of the finite element method (FEM) will be given. The results of simulation experiment by using electrically heated film resistor are shown in Sec. 4. In Sec. 5 the structure of the Brewster window will be shown in detail including water-cooling channels and gas-cooling structure. Finally, Sec. 6 is devoted to the conclusion of the paper.

2. Transmission Characteristics of a Brewster Window

From a viewpoint of high power windows, the Brewster window has a lot of merits. It has an effectively large area and the power density of an injected RF beam can be reduced by several times. Different from normally-injected resonant windows, the thickness of the Brewster window can be selected freely from the RF wavelength and determined from the aspect of mechanical designs [3]. The window with an elliptical shape also has less internal stresses and smaller deformation than that of a circular shape with the same surface area.

We have been adopted a low loss silicon nitride composite (SN-287 Kyocera) for a material of RF output windows. For the silicon nitride composite with a permittivity of 7.92, the Brewster angle θ_B is calculated to be 70.4 degrees.

Figure 1 shows a dependence of the millimeter wave incident angle on the reflection coefficient, when the disk thickness is changed on the assumption of a plane wave approximation. The reflection from the window disappears around the Brewster angle regardless with the disk thickness. The reflection coefficient also becomes zero when the thickness corresponds to the multiples of half wavelength in the material. If we choose multiples of the half wavelength as the disk thickness, the reflection coefficient remains low over the wide range of the incident angle.

3. Thermal Analysis of the Brewster Window

We performed the thermal analysis of the Brewster window with forced gas-cooling on the basis of the finite element method (FEM, ANSYS code). Figure 2 shows the calculated results of peak temperature time evolution during 0.5 MW, HE_{11} mode input to the 100×300 mm^2 silicon nitride disk with 3mm thickness, which is fixed at the Brewster angle to the incident RF beam.

In this calculation we take into account the temperature dependence of the loss tangent of the disk material which is low loss silicon nitride composite (SN-287). The heat transfer coefficients of 0–10 kW/m^{2}K are assumed on the one surface of the disk. For the case of 1 kW/m^{2}K which is the experimentally obtained heat transfer coefficient for forced gas-cooling, the peak temperature is completely saturated within 20 sec. This means that the Brewster window of this size has a capability of 0.5 MW CW transmission with the assistance of forced gas-cooling.

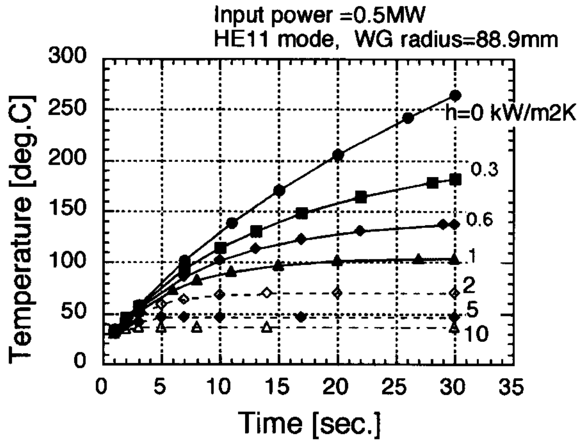

Fig. 2 Thermal analysis of a Brewster window with gas-cooling. Heat transfer coefficient is assumed to be given on the one surface of the disk.

4. Results of Simulation Experiments Using an Electrically Heated Film Resistor

In the previous experiment (circular window), the cooling gas was ejected to the disk center from the nozzles distributed on a circular aperture. For the elongated window, however, gas might be ejected in parallel along the minor axis. We have tested cooling performance of a rectangular window (particularly temperature uniformity) using not a microwave but a dummy heat source.

Figure 3 shows a schematic structure of the rectangular gas cooled single-disk window assembly used in the experiment. Two alumina (A 479, Kyocera) disks (1.6 mm thick each, 120 mm × 240 mm) are folded and held by the rectangular frame. Between these disks a film resistor (0.12 mm thick, 110 mm wide) is sandwiched and it is heated by a DC power supply (I = 0–120 A). The cooling gas (dry nitrogen at a pressure of several kg/cm^2) is ejected through the nozzles (1 mm diameter) distributed along the straight manifold. The disk surface is coated with lusterless black paint. The surface temperature distribution is measured by an Infrared (IR) camera.

Figure 4 shows a temperature distribution measured for the same gas flow pattern as in Fig. 3 (distance between nozzles in the central part = 40 mm, heating current = 90 A, total gas flow rate = 60 liter/min). The hotter part at right hand side is due to the current feeder. The temperature at the central part is about 50 degree C. If the total gas flow rate is kept constant, the cooling performance is better for smaller number of nozzles, i.e., for higher gas flow speed. This result is the same as those observed for the circular window assembly. As for the temperature distribution, we observe the non-uniformities of 10 and 5 degree C along the vertical and

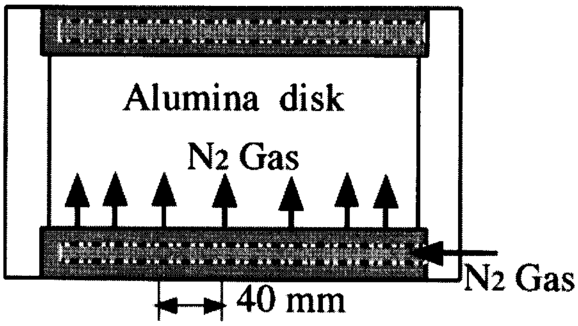

Fig. 3 Schematic structure of the rectangular gas cooled single-disk window assembly used in the simulation experiment.

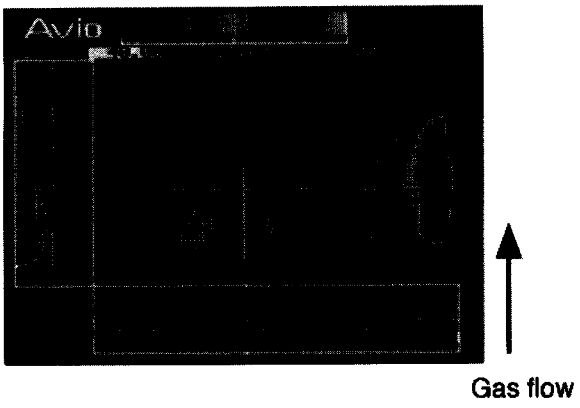

Fig. 4 Surface temperature distribution measured by infrared camera.

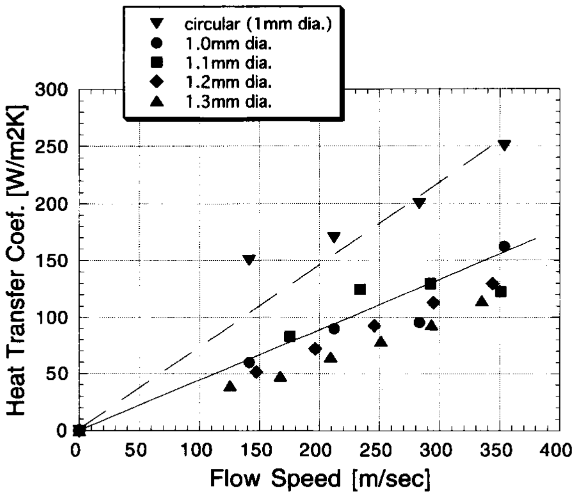

Fig. 5 Experimentally obtained heat transfer coefficient of gas-cooling plotted as a function of gas flow speed. It depends weakly on the nozzle diameter.

horizontal direction, respectively in Fig. 4. When the distances between the nozzles are reduced to 20 mm, the non-uniformity is suppressed less than 3 degree C in both directions.

Figure 5 shows the heat transfer coefficient at the disk center derived from temperature decay curve after the turn-off of the heating power as a function of the initial flow speed. Obtained heat transfer coefficient does not strongly depend on the nozzle diameter, but on the flow speed. These values are about 60 percents of the one obtained previously in the circular window assembly that is also indicated in the figure. The possible reasons of such difference are due to the difference of the effective window sizes and the direction of gas flow from the nozzles. The conduction of heat in the disks could also affect the 1/e time constant differently, leading to the error of the estimation of the heat transfer coefficients. This effect will be eliminated by FEM analysis. We also tried to eject gas from both bottom and top manifolds and collide to each other but cooling performance was not improved.

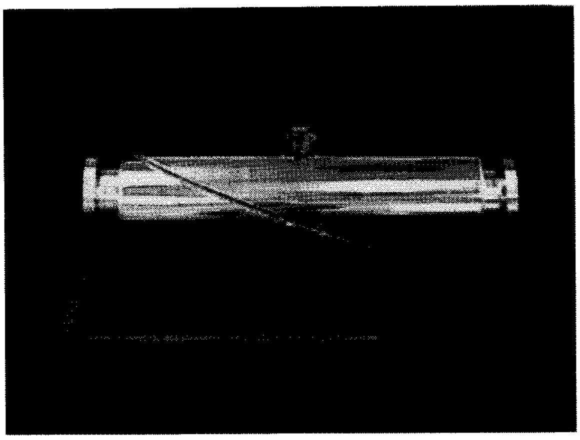

Fig. 6 Photograph of a prototype window with normal silicon nitride disk. The structure of brazing and welding of the disk was evaluated.

5. Structure of a Brewster Window

We fabricated a 120 × 320 mm^2, 2.53 mm thickness racetrack disk of the silicon nitride composite for a 0.5 MW CW window. Since the material has very low thermal expansion coefficient, we first designed and assembled a prototype Brewster window using usual silicon nitride (SN-220 Kyocera) to check the structure of brazing and welding. Figure 6 is a photograph of the prototype window itself. The circumference of the racetrack disk can be water-cooled. To transmit millimeter waves the corrugated waveguide sections are prepared at the both sides of the disk. At the atmospheric side of the waveguide some nozzles for gas-cooling are drilled on the wall. The number of the nozzle holes is optimized to be nine with the diameter of 1mm, and air is blown on the disk unidirectionally. This structure was determined from the experimental results using a simulated heat source as described in Sec. 4.

Using this prototype of the window, we preliminarily performed the simulation experiment by means of the electrically heated film resistor on the same manner as Sec. 4. The heat transfer coefficient is not so good compared with the simulation experiment, because the structure of the gas-cooling channel installed in the corrugated wave guide is not optimized. Now we are improving such gas-cooling channel.

On the basis of the experience of manufacturing, we have just assembled a real Brewster window with a low loss silicon nitride composite and prepared to test it by high power millimeter wave transmission from an 84 GHz gyrotron. High power transmission test will be performed in near future.

6. Conclusion

We design and fabricated a forced gas-cooled Brewster window with a low loss silicon nitride composite for high power CW millimeter wave transmission. For its design we calculated the transmission coefficient and analyzed the thermal characteristics basing on the finite element method. The cooling performance is also studied by using an electrically heated film resistor. The size, configuration and the number of nozzles for forced gas-cooling are determined on the consideration of the results of the simulation experiments described above. Obtained results are summarized as follows.

(1) For a 0.5 MW/CW Brewster window, the reflection coefficient is calculated. It turns out that the reflection is still low over wide range of the RF incident angle for a given disk thickness. Thermal analysis on the basis of FEM shows the Brewster window with the size of 100 × 300 mm^2 can persist in 0.5 MW/CW power transmission of an 84 GHz HE_{11} mode with the assist of forced gas-cooling.

(2) By using an electrically heated film resistor as a heat source, we performed the simulation experiments on the model window with alumina and the prototype Brewster window with normal silicon nitride (SN-220). Experimentally obtained heat transfer coefficient is about 60% of the circular window case. The reason will be clarified by the comparison of FEM analysis. Uniformity of cooling effect is within 5–10% even for only nine nozzles.

(3) On the basis of the results of the simulation experiments, we fabricated prototype (SN-220) and real (SN-287) Brewster windows and gas-cooling structure. The circumference of the disk can be water-cooled. The disk surface is cooled by gas jet ejected from the nozzles drilled on the waveguide wall.

We have just prepared to test it by high CW power transmission to evaluate the widow ability and cooling performance.

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