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Since brazing to diamond can be difficult, time-consuming and expensive, we have designed windows sealed for high vacuum by two Helicoflex® metal seals on opposing faces of a diamond disk. To prevent excessive stress on the diamond, the seals must be well aligned and external forces on the window assembly must not be transmitted to the diamond. We describe the main features of these windows. Calculations of the temperature rises and stresses in the diamond are presented.

Tests with heat sources indicate that the thermal conduction through the seals is very good. A window in 31.75 mm corrugated waveguide with a diamond disk 0.75 mm thick for 84 GHz has been operated up to 300 kW in 3 s pulses. The temperature rise measured in thermocouples touching the edges of the diamond disks was very small. Water cooling channels were provided but have not been needed.

1. Introduction

Vacuum windows are required on high power microwave tubes and also near the end of high power transmission lines to isolate them from plasma devices such as tokamaks.

The advent of large synthetic diamond disks with optical quality has made other window materials generally obsolete for high power applications. Diamond is superior in all of the major properties: low microwave loss, high thermal conductivity, and high strength. Diamond's drawbacks have been high cost and the difficulty of making a vacuum-tight connection to the diamond.

Brazing is generally required for windows on microwave tubes that must be baked to a high temperature. However, the same baking requirement does not apply to windows for waveguide transmission lines. For that application, we can consider braze-less seals such as those made by metal O-rings with internal springs.

This paper considers waveguide diamond windows sealed with Helicoflex® metal seals having a “delta” ridge. Advantages include a structure that is simpler and less expensive than that for brazed windows. In addition, replacement of any damaged diamond disk would be much simpler in a window sealed without brazes.

Section 2 describes calculations of the temperature rises in the diamond. An analytic solution is found for the temperature distribution in a diamond disk across a corrugated waveguide propagating the dominant HE_{11} mode. The estimated thermal conduction through the metal seals is sufficient to avoid the need for direct water cooling of the diamond, even for continuous high-power operation.

Section 3 describes calculations of the stresses in the diamond. The thermal stresses are found to be relatively small, even for continuous operation with 1 MW incident power. Shear stresses due to misalignment of the seals on opposing sides of the diamond disk can be much larger. For thin disks, the seal diameters and locations must be matched quite well to avoid fracture of the diamond. Nevertheless, the required alignment is achievable in practice.

Section 4 briefly describes the structure of waveguide diamond windows fabricated in 31.75 mm corrugated waveguide for use at 84 GHz. While the disk thickness was only 0.75 mm, two of these windows were successfully sealed with Helicoflex® seals. A thermocouple was mounted in each window to monitor the edge temperature of the diamond disk. Provision was made for water cooling of the edge of the diamond, but it is expected that such cooling will not be needed.

In Section 5, some experimental results are described. The measured thermal conduction through the metal seals was found to agree with the calculations described in Section 2. The results of high-power operation at NIFS in Japan are also cited.

2. Theoretical Temperature Distributions

2.1. Distribution Across the Diamond

The total power Q_{TOT} absorbed in a thin diamond disk whose thickness t is an integral multiple of a half wavelength in the dielectric is:

$$Q_{TOT} = \frac{2\pi t}{\lambda}\left(\frac{\varepsilon + 1}{2}\right) P_0 \tan\delta \quad , \tag{1}$$

where λ is the free space wavelength, ε is the relative dielectric constant of the diamond (5.67) and P_0 is the incident power. This expression includes the enhancement due to the standing wave inside the diamond. For example, assume t = 1.11 mm (1.5 wavelengths in the diamond at 170 GHz). When 1 MW is incident on a disk with a loss tangent $\tan\delta = 5\times10^{-5}$, then the total power absorbed is 660 W at 170 GHz. Typical loss tangent values have been significantly lower, around 2×10^{-5} when no brazing is used (from data published by FzK in Karlsruhe, Germany on CVD deposited diamond [1]).

The power absorbed in the disk when the HE_{11} mode is incident in the waveguide varies radially as $[J_0\,(2.405\ r/a)]^2$, were J_0 is the lowest order Bessel function. Here 2a is the inside diameter of the waveguide.

Consider now the rise in temperature from a place near the disk edge where the temperature is fixed to the center of the disk at r=0. Assume that the radius of the fixed temperature is r=b, where b>a. From the solution of the equation for radial heat diffusion with the above radial distribution of absorbed power, we find that the rise in temperature ΔT from r=b to r=0 for a thin disk is:

$$\Delta T = \frac{Q_{TOT}}{2\pi kt}\left[1 + \ln(b/a)\right] \tag{2}$$

where k is the thermal conductivity of the disk, and Q_{TOT} is the total power absorbed. Note from Eq. (1) that Q_{TOT} is proportional to the thickness, so the increase in temperature is independent of the thickness in thin disks.

Consider from the preceding discussion Q_{TOT} = 660 W with t = 0.111 cm. The thermal conductivity k = 19 W/(cm-K) [1]. Assume that the waveguide inside diameter 2a is 3.175 cm, and the diameter 2b of the center of a fixed temperature location is 3.9 cm. This could be approximated by the diameter of a braze or Helicoflex® seal, or by the effective diameter for water cooling. Then Eq. (2) yields ΔT = 60°C, which is rather small.

To find the total temperature rise at the center of the disk, we must add either: 1) the temperature rise of the cooling water plus the temperature rise from the water to the diamond; or 2) the temperature rise of the window housing plus the rise across the braze or seal if there is no water cooling.

2.2. Conductance Across the Seals

The temperature drop across Helicoflex® seals can be estimated from the thickness of the aluminum in the seals, the cross sectional diameter, and the overall diameter of these seals. There are two seals in parallel (one on each side of the diamond). The Helicoflex® seals used for our latest diamond windows have an aluminum jacket and an aluminum lining. The jacket and the lining are each 0.4 mm thick. The cross-sectional diameter d of the seal after compression is approximately 2.2 mm. The path length L from one side of the seal to the other is about 0.5 π d = 3.5 mm = 0.35 cm. To account for conduction around both sides of the cross section, we can model the conduction as two straight aluminum sections of length L each with thickness t = 2×0.4 mm. We can safely assume that the effective contact width for the seal after compression is T = 2t = 1.6 mm. The total area A of heat conduction through the seal is approximately π D T. The average seal diameter D is about 39 mm. Hence A=196 mm^2 = 1.96 cm^2.

The thermal conductance σ is kA/L per seal. Since there is a seal on each side of the diamond, the total conductance from the diamond to the window body is 2 kA/L. Using k = 2.1 W/cm-K for the 1100 alloy aluminum used in the seal, we find that the total thermal conductance is σ = 23.5 W/K. The above calculation did not include any thermal resistances between the seal and the mating surfaces. Nevertheless, the sealing forces are large, so these resistances should be negligible. Furthermore, no conduction through the Inconel spring in the center of the seal was considered.

When 660 W is absorbed in the diamond, the temperature drop across the seals is then 660 W/(23.5 W/K) = 28°C. This is also rather small.

Combining the two calculations above, we find that the peak temperature in the center of the diamond disk is about 90° above the temperature in the bulk metal window housing, when the loss tangent of the diamond is 5×10^{-4} at 170 GHz. These calculations suggest that water cooling of the housing itself, rather than the diamond directly, may be adequate. If some direct cooling of the diamond is desired, helium gas cooling is a reasonably effective alternative to water, particularly if the helium reaches some of the face of the disk near the edge, and not just the edge itself.

3. Theoretical Stress Distributions

3.1. Thermal Stresses

Heating will produce compressive stresses at the center of the disk and azimuthal tensile stress near the edge. If a thin disk is unconstrained at the edge r=b, and has a temperature distribution independent of azimuth, then the azimuthal stresses are [2]:

$$\sigma_\theta(r) = \alpha E\left[-T(r) + \frac{1}{b^2}\int_0^b Trdr + \frac{1}{r^2}\int_0^r Trdr\right] \quad . \tag{3}$$

Here T(r) is to be interpreted as the increase in temperature relative to the edge. The radial stress distribution $\sigma_r(r)$ can be obtained similarly. The coefficient of thermal expansion is α and E is the Young’s modulus. Note from this equation that the maximum azimuthal tensile (positive) stress is at the edge r=b.

The maximum compressive (negative) stresses are at r=0. From the temperature distribution T(r) found in deriving Eq. (2), we obtain

$$\sigma_r(0) = \sigma_\theta(0) = -\alpha E T_0\left[0.25 + 0.5\ln(b/a) + 0.055(a/b)^2\right] \quad , \tag{4}$$

where we have defined

$$T_0 \equiv \frac{Q_{TOT}}{2\pi kt} \quad , \tag{5}$$

At the edge the radial stress is zero, while the azimuthal tensile stress is a maximum:

$$\sigma_\theta(b) = \alpha E T_0\left[0.5 - 0.109(a/b)^2\right] \quad . \tag{6}$$

For diamond, the bulk properties are $\alpha=0.8\times10^{-6}$ per °C at room temperature, and $E=1.05\times10^{12}$ Pa [3]. Using the example of Section 2, we then find T_0 = 50° and $\sigma_r(0) = \sigma_\theta(0) = -16.5$ MPa, while $\sigma_\theta(b)$ = 18 MPa. These stresses are much lower than the fracture stresses measured on CVD diamond with about 1 mm thickness, about 400 MPa [1].

3.2. Stresses caused by the Seals

Calculation of the total stress must also include any stresses induced by the seals. For Helicoflex® seals, the stress of most concern is due to radial misalignment of the seals on opposing sides of the diamond disk. If the radial misalignment of the two opposing seals is Δr and the sealing force required per unit circumferential distance is P, then a moment M = P Δr is produced, and the corresponding radial stress induced in the disk is

$$\sigma_r = \frac{6M}{t^2} = \frac{6P\Delta r}{t^2} \quad , \tag{7}$$

where t is the disk thickness. Note that the stresses decrease rapidly with increased thickness.

Equation (7) assumes that the sealing forces are concentrated at one radial position for each seal. In practice, the forces are spread out over some distance, and so (7) is an upper bound for the stress.

As an example, consider a required sealing force P of 100 newtons per mm, which applies for a typical Helicoflex® seal with aluminum jacket and lining. A radial misalignment of up to 0.2 mm between matched pairs of seals may be expected. Equation (7) then predicts an induced stress of 97 MPa in a disk of thickness 1.11 mm. This is safely below the 400 MPa fracture stress.

3.3. Bending Stresses

When a pressure differential exists across the window, there will be bending stresses in the diamond. When the diamond disk is simply supported by the seals near its edge, the maximum tensile stress is at the center of the disk. For a differential of one atmosphere, and a Poisson's ratio of 0.2 [3], the calculated maximum stress is about 80 MPa in a disk of 0.75 mm thickness. In general, the bending stresses are inversely proportional to the square of the thickness.

4. Actual Window Construction

A window in 31.75 mm corrugated waveguide fabricated for 84 GHz is shown in Fig. 1. The main features of the construction are:

- The region around the diamond has a large diameter, so that forces applied to the assembly will not be transmitted significantly to the diamond.
- The waveguide ends are machined to accept standard vacuum-tight couplings.
- The opposing halves of the aluminum housing are well aligned to each other.
- The opposing seals are precisely aligned.
- A thermocouple with fast (3 s) time response is provided to monitor the diamond edge temperature.
- The diamond disk is centered in a cooling cavity. Water or gas cooling can be used.

Two windows were made with 0.75 mm thick diamond disks polished on both sides to better than a 200 nm roughness average (Ra) finish. Both windows sealed with He leak rates less than 10^{-9} Torr-ℓ/s.

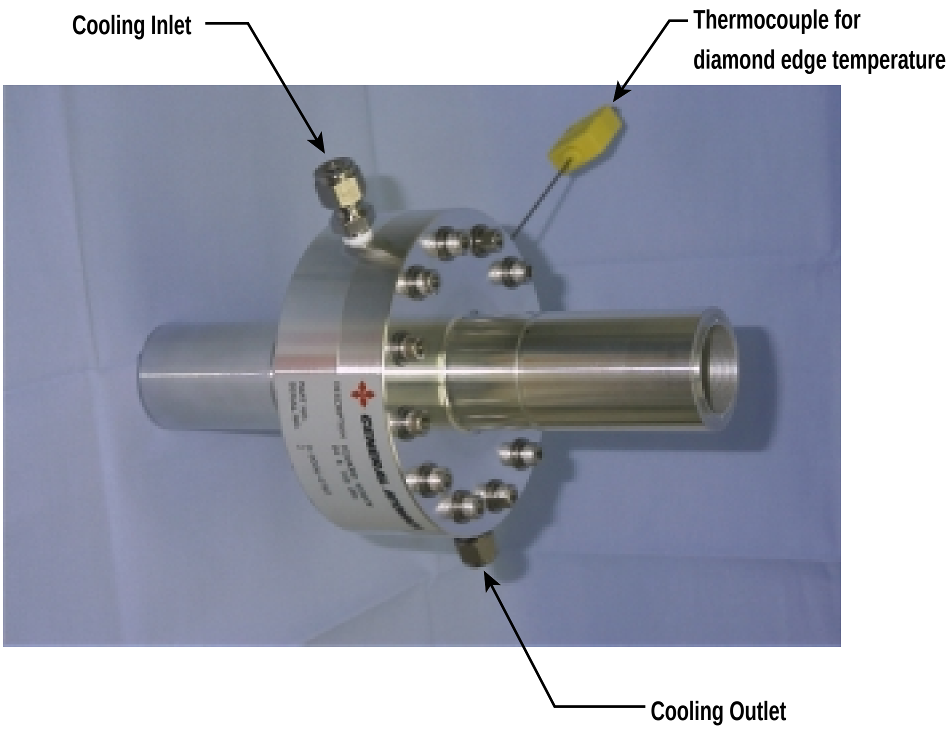

Fig. 1. 31.75 mm waveguide diamond vacuum window with Helicoflex® metal seals.

Both windows used Helicoflex Delta® seals with a ridge. The seals in the first window had an aluminum jacket but Inconel lining. Since the nominal sealing load P for these seals is 140 newtons per mm, the seals were compressed about 0.4 mm instead of the nominal 0.7 mm in order to keep P below about 100 newtons per mm. The second window used seals with aluminum lining and jacket, with a nominal P of about 100 newtons per mm. These seals were compressed about 0.55 mm instead of the nominal 0.7 mm. Opposing seals were selected to minimize the radial offsets Δr. The estimated maximum radial offsets for the two windows were about 0.1 and 0.15 mm, respectively. The maximum stresses calculated according to Eq. (7) were then slightly above 100 MPa.

The disadvantage of compressing seals less than their nominal value is that the seals may not hold at high temperatures. Since the expected temperatures at the seals are not high, however, no problem is expected. The maximum operating temperature of the assembly is estimated to be about 150°C.

5. Experimental Results

One of the windows has been used at NIFS on an 84 GHz transmission line for ECH on LHD. As of early 2002, 300 kW in pulses up to 3 s had been transmitted through this window [4]. No cooling was used, except for normal free convection.

Thermocouple measurements were made of the edge temperature of the diamond with no cooling of the window assembly except free convection of the outside. After several hours of 300 kW 0.6 s pulses repeated every 3 min, the edge temperature rise saturated at about 3°C [4]. The observed time constant for the rise was consistent with the calculated thermal constant of about 2 h for the window assembly. The calculated thermal resistance of the assembly due to free convection of the external surface is about 5.3°C/W, assuming a convective heat transfer of 5 W/m^2 K. A 3° temperature rise then implies that the average power absorbed in the window is about 0.5 W. Since the average incident power in these pulses was 300 kW $\times$ 0.6 s/180 s = 1.0 kW, this absorption would be consistent with Eq. (1) if the loss tangent was about 1×10^{-4}.

In addition, a test was made of the thermal conductance of the seals. For this test a third window housing was made, and an aluminum disk was used instead of diamond. The seals with aluminum jacket and lining were used, and a vacuum-tight seal was made. Kapton film insulated 5 W heaters with pressure sensitive adhesive were applied to both faces of the aluminum disk. Each heater had an area of 25×25 mm.

Besides the thermocouple measuring the edge temperature of the aluminum disk, another thermocouple was attached to the housing of the window near the disk. The extra thermocouple was inserted into one of the cooling channel ports. The observed time constant was consistent with the calculated value. The steady-state difference between the measured thermocouple temperatures was 0.5°C. Since the input power was 10 W, and there was no other significant path for the heat to flow from the aluminum disk to the window housing, we conclude that the effective conductance of the seals was about 10 W/0.5°C = 20 W/°C. This is quite close to the estimated value cited in Section 2.2.

Acknowledgments

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