JET–P(93)83

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Antireflection Treatments for JET Millimetre Wave Diagnostic Windows

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Preprint of a paper to be submitted for publication in
Int. J. of Infrared and Millimetre Waves
October 1993

ABSTRACT

When tritium is used as a fusion fuel in the JET tokamak it will be necessary to use double, interpumped windows on the vacuum vessel. Methods are discussed for reducing the frequency dependence of the transmission of double windows to be used for various millimetre wave diagnostics, over the appropriate frequency ranges.

1. INTRODUCTION

Vacuum windows for diagnostics on the JET tokamak must provide reliable high vacuum seals and satisfy stringent safety criteria. They must withstand atmospheric pressure and mechanical shocks with a substantial safety margin, and be capable of repeated cycling from room temperature to about 250° C. If they are near the bottom of the torus they may have to resist exposure to water during a preliminary cleaning process. Double, interpumped windows are required as an additional precaution against leaks when tritium is used as a fusion fuel.

Even with a single plane parallel window in a collimated beam multiple reflections cause the millimetre wave transmission to be significantly frequency dependent; Figure 1(a) shows the calculated intensity transmission spectrum for a single 6 mm crystal quartz window at normal incidence, assuming the refractive index N is 2.108 over the frequency range.

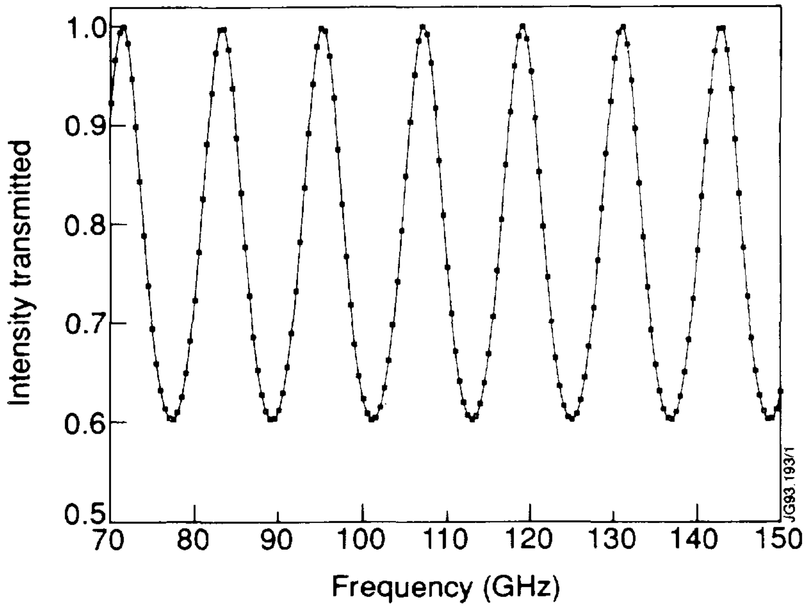

Figure 1(a). Transmission of a single 6 mm quartz window at normal incidence.

With a double window the multiple reflections from the four window surfaces can cause the transmission to be very strongly frequency dependent. Figure 1(b) shows, for example, the irregular intensity transmission spectrum for two 6 mm quartz discs separated by 5 mm.

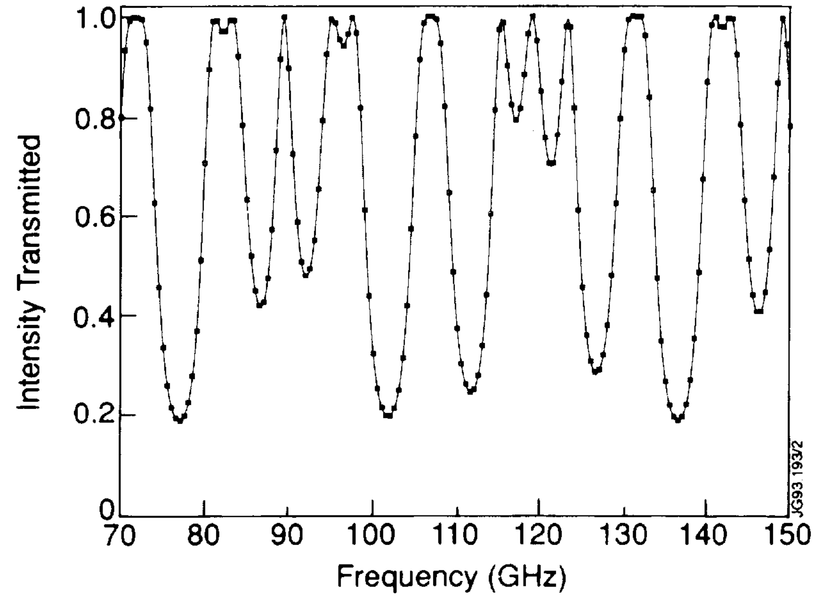

Figure 1(b). Transmission of two 6 mm quartz discs separated by a space of 5 mm.

JET has several millimetre wave diagnostic systems, which may be divided into two categories, those which measure phase shifts at fixed frequencies, and those which measure spectral intensities. The phase measuring diagnostics (plasma reflectometers and density measuring interferometers) are not very sensitive to changes in window transmission, although reflections can cause problems. On the other hand the spectral intensity measurements made by the heterodyne ECE radiometer, the Michelson Fourier spectrometer and the collective scattering diagnostic are directly affected by the window transmission. If the slope of the window transmission is steep, as in Figure 1(b), changes in temperature or mechanical movements of the discs of a double window may severely affect the calibrations of these instruments. It is necessary to design a window with as flat a spectrum as possible over the frequency range of the measurements.

In this paper we discuss methods for reducing the undesirable effects of window reflections on the spectral intensity-measuring diagnostics, which operate over different frequency ranges, with different resolving powers, and require different solutions. The method of calculating the transmission of a plane parallel multilayer structure is described in Section 2. In Section 3 we discuss window materials and their properties. The bending of a vacuum window is considered in Section 4. In Section 5 we discuss the behaviour of several possible low power double window structures, and in Section 6 we assess their suitability for the various JET diagnostics. The conclusions are summarised in Section 7.

2. CALCULATION OF THE INTENSITY TRANSMISSION OF A DIELECTRIC MULTILAYER STRUCTURE

A simple double window may be regarded as three plane parallel dielectric layers. The number of layers increases if any of the surfaces are coated to reduce the reflectivity. The many reflections may be treated as being coherent if the thickness of the window assembly is small compared to the longer of the coherence lengths of the radiation source, or of the detector channel. This is true for those of the JET diagnostics in which the bandwidth of the detector channels is less than 1 GHz, because then the effective coherence length is greater than 300 mm, while a typical double window assembly is only ~20 mm thick

We make use of the matrix method for calculating the behaviour of thin dielectric multilayers, developed by Abelès, as described by MacLeod [1969]. The calculations are strictly valid only for infinitely wide plane wavefronts, so at oblique incidence the effects of "walk-off" on a Gaussian beam are not included. We shall assume that the refractive index of air is unity, and that the dielectric materials are non-absorbing. A characteristic matrix is associated with each layer, of the form

$$\begin{bmatrix} \cos\delta_j & (i\sin\delta_j)/\eta_j \\ i\eta_j\sin\delta_j & \cos\delta_j \end{bmatrix} = \mathrm{M}_j \tag{1}$$

Here

$$\delta_j = 2\pi N_j d_j \cos\theta_j / \lambda, \tag{2}$$

where λ is the free space wavelength, N_j is the refractive index of the jth layer, d_j its thickness and θ_j the angle of propagation in the layer relative to the surface normal, and $\eta_j = N_j \cos\theta_j$ for radiation polarised with the E vector parallel to the surface, or $\eta_j = N_j / \cos\theta_j$ for the orthogonal polarisation. If the angle of incidence from the normal in air or vacuum is θ_o, then from Snell's law

$$\sin\theta_j = \sin\theta_0 / N_j . \qquad (3)$$

If there are n layers, including the air or vacuum spaces between the solid discs, we may write

$$\begin{bmatrix} B \\ C \end{bmatrix} = \left\{ \prod_{j=1}^{n} \left[\mathrm{M}_j \right] \right\} \begin{bmatrix} 1 \\ \eta_{j+1} \end{bmatrix} . \qquad (4)$$

It may be shown that the intensity reflectivity of the structure is given by

$$R = \left(\frac{\eta_0 B - C}{\eta_0 B + C} \right) \left(\frac{\eta_0 B - C}{\eta_0 B + C} \right)^* \qquad (5)$$

and since there is no absorption the intensity transmission is

$$T = 1 - R . \qquad (6)$$

At non-normal incidence it is necessary to carry out the calculation of reflectivity twice, once for each polarisation.When a window material is anisotropic, as is the case for crystal quartz, the values of η_j must be determined using the ordinary index N_o for the ordinary polarisation, and the extraordinary index, appropriate to the direction of propagation in the medium, for the extraordinary polarisation. If the direction of propagation makes an angle ψ with the optic axis and the extraordinary index is N_e, then

$$N_e(\psi) = 1 / \sqrt{\frac{\cos^2 \psi}{N_o^2} + \frac{\sin^2 \psi}{N_e^2}} \qquad (7)$$

For normal incidence in air or vacuum $\eta_0 = \eta_{n+1} = 1$, so the reflectivity will be zero when $B = C$.

In the special case of a double window consisting of two discs of equal thickness d_{disc} with an air space of thickness d_{space}, at normal incidence, the condition B=C for zero reflectivity can readily be shown to be satisfied if either

$$\sin \delta_{\mathrm{disc}} = 0 \qquad (8a)$$

or

$$\tan \delta_{\mathrm{disc}} \tan \delta_{\mathrm{space}} = 2(\mathrm{N} + 1/\mathrm{N}). \qquad (8b)$$

In this case, if at some frequency ν_o (and for a defined polarisation) the optical thickness of each disc, $d\ N_{\mathrm{disc}}$, is some whole number of half wavelengths, and the thickness of the space is also any whole number of half wavelengths, the reflectivity will be zero at ν_0 and also at a pair of frequencies equally displaced on either side of ν_0.

Experimental measurements were made of the transmission of a number of window structures and the results were compared to the theoretical predictions. Figure 2 shows the good agreement obtained, in the frequency range of the tunable narrow band source, for two crystal quartz discs each 5.105 mm thick, separated by a space of 0.97 mm. The window was near the Gaussian waist between two lenses, so the wavefronts were almost plane, but the additional reflections caused the slight ripple seen on the measurements.

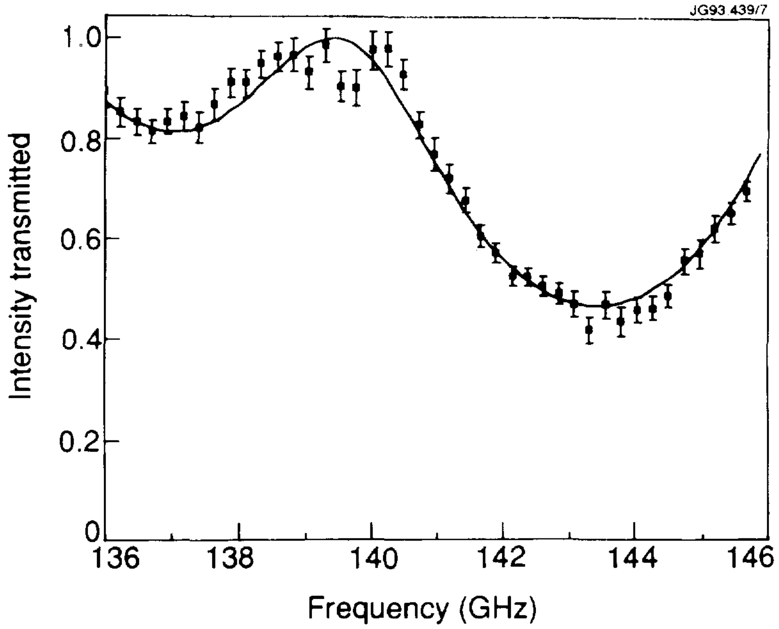

Figure 2. Measured and calculated transmissions of two 5.105 mm quartz discs, separated by 0.97 mm.

3. MATERIALS FOR JET WINDOWS

The three materials most commonly used for low power millimetre wave windows on JET are crystal quartz, fused silica and sapphire, all of which have low absorption. The problem of bonding the window to a metal ferrule, suitable for the JET vacuum, so as to be capable of withstanding thermal cycling has been solved for each of these materials. Fused silica and sapphire are aluminium bonded, but crystal quartz is gold bonded to stainless steel, and because this bond withstands moisture well crystal quartz is the preferred material, especially at the bottom of the torus. Our calculations of window characteristics are therefore based on crystal quartz.

3.1 Properties of crystal quartz

Crystal quartz windows for JET are cut with the faces perpendicular to the optic axis (z-cut) so at normal incidence radiation propagates parallel to the axis and both polarizations experience the same refractive index N_o. Several room temperature measurements of refractive indices N_o and N_e as functions of frequency have been reported [Birch (1991)]. The temperature dependence has been measured at temperatures below room temperature [Heidinger (1992)] and more recently at temperatures up to 400°C [Birch (1993)]. Some values for the refractive indices, together with the linear thermal expansion coefficient, Young's modulus and Poisson's ratio are listed in Table 1.

Table 1 : Some properties of crystal quartz

Real refractive indices at 293° K, for 140 GHz radiation
[Birch et al. 1991]:

$$N_o = 2.106 \pm 0.001$$
$$N_e = 2.154 \pm 0.001$$

Linear thermal expansion coefficients at specified temperatures [Kaye and Laby 1986]:

T (K)	100	293	500
Parallel to axis	4	6.8	11.4 x 10-6
Perpendicular	9.1	12.2	19.5 x 10-6

Hence parallel to the axis the length $l(T^oK) \approx Fl(293^oK)$, where

$$F = 1 + [3.117(T - 293) + 3.45\mathrm{x}10^{-3}(T^2 - 293^2) + 6.43\mathrm{x}10^{-6}(T^3 - 293^3)\,]\mathrm{x}10^{-6}$$

Young's Modulus [ICT, 1928]: (⊥ axis) 77 GPa, (| | axis) 101 GPa
Poisson's Ratio: approx. 0.2

4. BENDING OF VACUUM WINDOWS

If the interspace is evacuated then only the outer disc will experience a pressure difference. Assuming the disc of thickness t is simply supported at an effective radius a, the centre of the disc will be pushed inwards by a distance given by [Roark and Young 1975]

$$d = \frac{3Pa^4}{16Et^3}(1-\sigma)(5-\sigma). \tag{9}$$

Here P = atmospheric pressure (105 Pa),
σ = Poisson's ratio,
E = Young's modulus.

For example, for a crystal quartz window with a = 24 mm and t = 5 mm, d = 2.5 microns.

If, instead, the interspace is maintained at a pressure of half an atmosphere then both discs will experience the same reduced distortion, and although the discs will be slightly curved their spacing will be approximately constant over the radius.

5. SOME DOUBLE WINDOW STRUCTURES

5.1 Wedged windows

A wedged window is often used to overcome problems with surface reflections, which are deflected out of the main beam. It has the advantage of an almost frequency-independent transmission, but it causes deflection and wavefront distortion of a Gaussian input beam, making alignment difficult and slightly polarisation dependent. These problems are more severe and the power loss greater with a double wedged window, so this is not a very satisfactory solution.

5.2 Anti-reflection coatings

A layer a quarter of a wavelength thick of a material with refractive index close to $\sqrt{(N_{window})}$ will greatly reduce the reflectivity over a limited bandwidth near the selected wavelength. This may be seen in Figure 3, which shows the intensity transmission of a double window with ideal quarter wave layers, designed for 140

GHz, on all but the first surface (the surface facing the JET vacuum will probably have to be left uncoated).

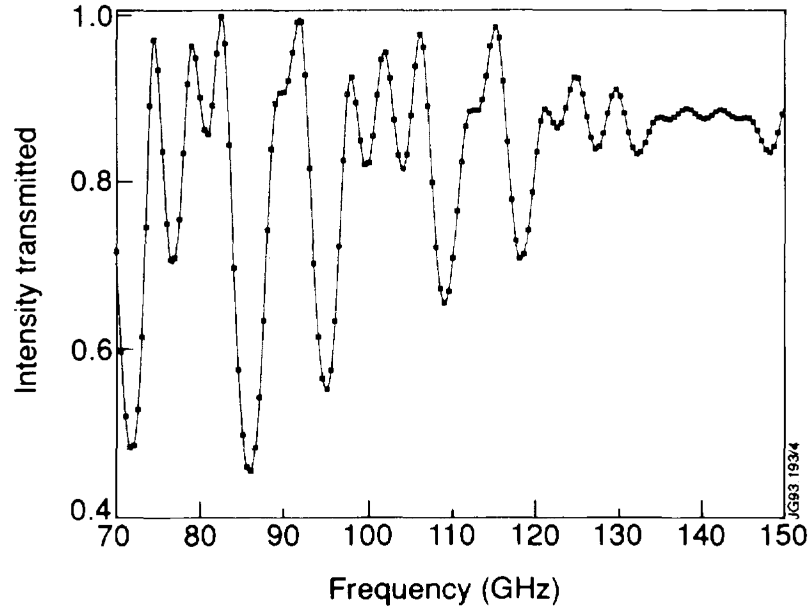

Figure 3. Transmission of two quartz discs, 6λ thick at 140 GHz, with λ/4 layers on all but first surface, separated by $2\frac{1}{2}\lambda$.

The requirements of a low index and high transmission appear to limit the choice of materials to plastics, and the need to operate at up to 250°C further restricts the choice. PTFE or a polyimide are possible candidates, with measured room temperature indexes of about 1.43 and 1.67 at 140 GHz. Machined quarter wave discs can be prepared from both these materials, but unfortunately they have much larger thermal expansion coefficients than quartz, and also they have poor adhesion, so permanent attachment would be difficult, especially under vacuum conditions. The consequences of even a slight detachment would be unacceptable, so this approach is not being actively followed at present.

It may be possible instead to machine fine grooves into the surface of a window to form a quarter wave layer of lower index, and this possibility is being investigated at JET [Porte 1993].

5.3 Separated, tilted plane parallel windows

Suppose two plane parallel window discs are tilted and separated sufficiently so that no reflection from the second disc reaches the first. Assuming wide, plane wavefronts the two discs may be regarded as independent etalons and the overall power transmission is the product of their individual transmissions. If one disc is designed to have a transmission maximum and the other a minimum at a selected frequency, the result is a fairly smooth transmission spectrum over an extended frequency range, but with some polarisation dependence and the loss of up to half the power.

Figure 4 shows the calculated result for two quartz discs, thicknesses 6.051 and 6.315 mm, with their surface normals inclined at 20° to the beam axis.

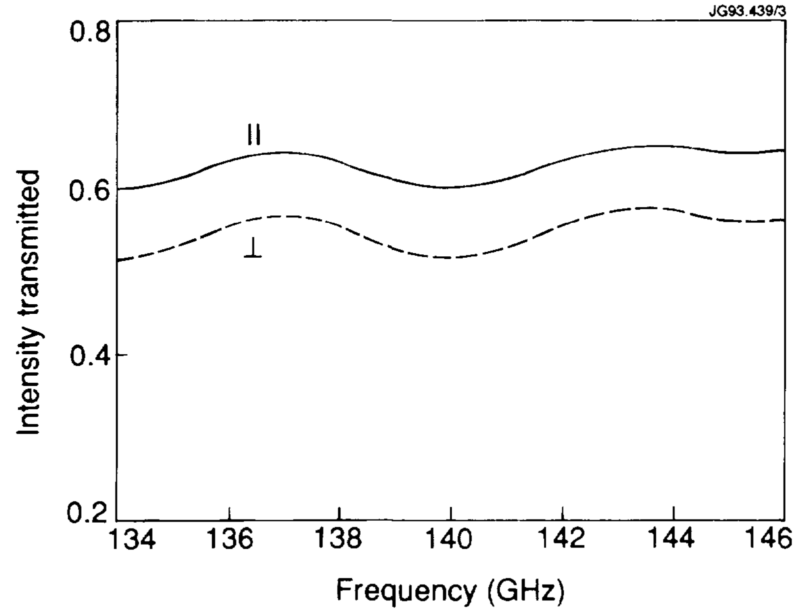

Figure 4. Transmission of two well separated quartz discs 6.051 and 6.315 mm thick, with normals at 20° to beam axis.

In any real millimetre wave system the spatial mode patterns of the input beam and of the antenna or waveguide collecting the output from the window will have to be taken into account and may greatly modify the results of Figure 4. For example, if the input radiation is in the fundamental Gaussian mode, the lateral displacements of the multiply-reflected beams could prevent more than a small fraction of any of them from being accepted by a single mode optical system collecting the output, so the unreflected power would be transmitted, with virtually no interference effects.

5.4 Thick, widely-spaced windows

For a diagnostic which covers a wide frequency range with low resolution, such as the Michelson interferometer, a pair of very thick, widely-spaced plane parallel discs might be used. If, for example, a window is constructed from two plane parallel, 100 mm thick quartz discs separated by 210 mm, the transmission spectrum for radiation with a coherence length of a metre or more varies very rapidly with frequency, as shown in Figure 5(a).

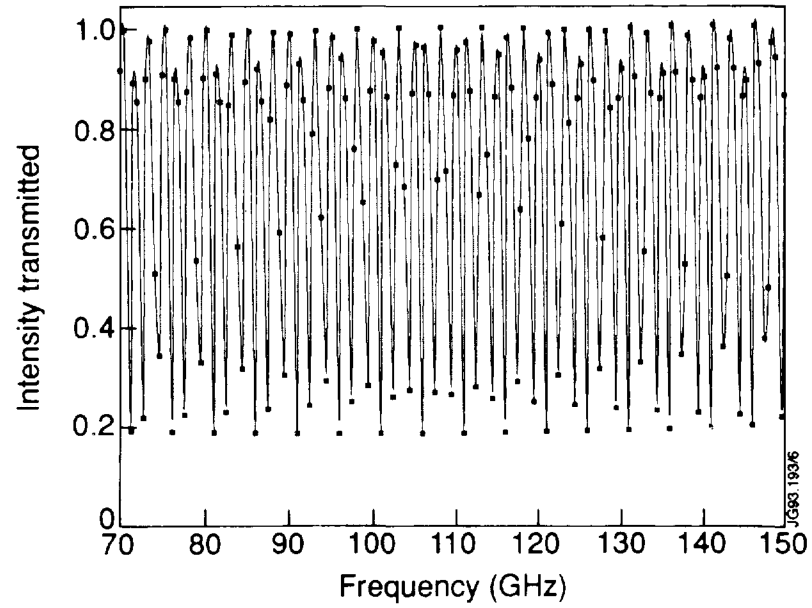

Figure 5(a). Transmission of two quartz windows 100 mm thick, separated by 210 mm (for coherent radiation).

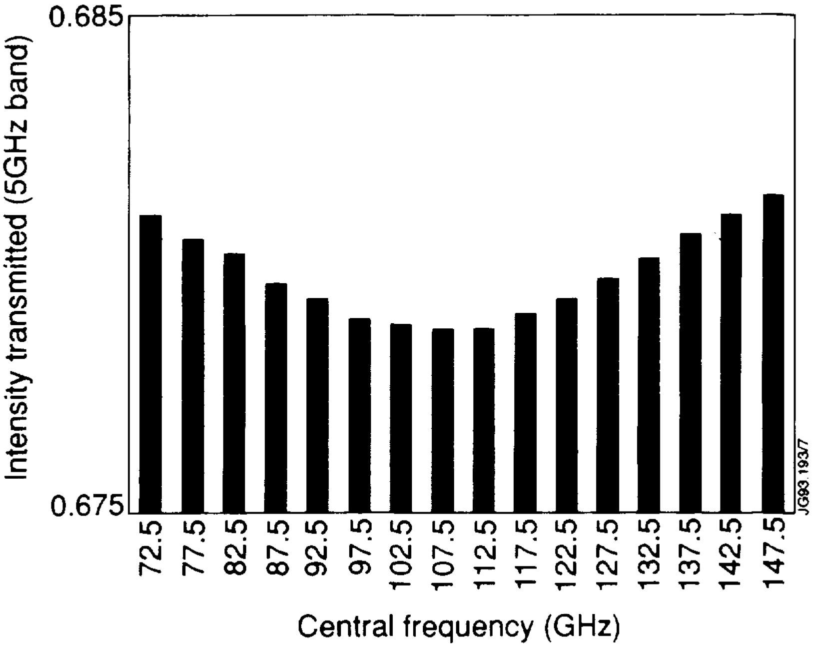

Figure 5(b). As for Figure 5(a), but with the transmission averaged over 5 GHz bandwidths.

However, when averaged over 5 GHz frequency intervals, as in Figure 5(b), the fine structure disappears and the average transmission is almost independent of frequency. There is a power loss of about 32 %.

Such an assembly would be difficult to arrange quasi-optically, but might be constructed using quartz rods within a waveguide.

5.5 Tuned windows

It is possible to obtain 100% transmission at a single frequency with two plane parallel discs, by making both disc thicknesses equal to an integer number of half wavelengths. The shape of the broader transmission spectrum depends on the thicknesses of the discs, and that of the space between them. By using the thinnest mechanically acceptable discs and optimising the space, the transmission can be kept high over a usefully wide frequency band near the resonant frequency. In designing such a double window an accurate knowledge of the refractive index at the working temperature is necessary, together with the thermal expansion.

Figure 6 shows the transmission spectra, over the frequency range of interest for the collective scattering diagnostic, for two 5.079 mm thick crystal quartz discs

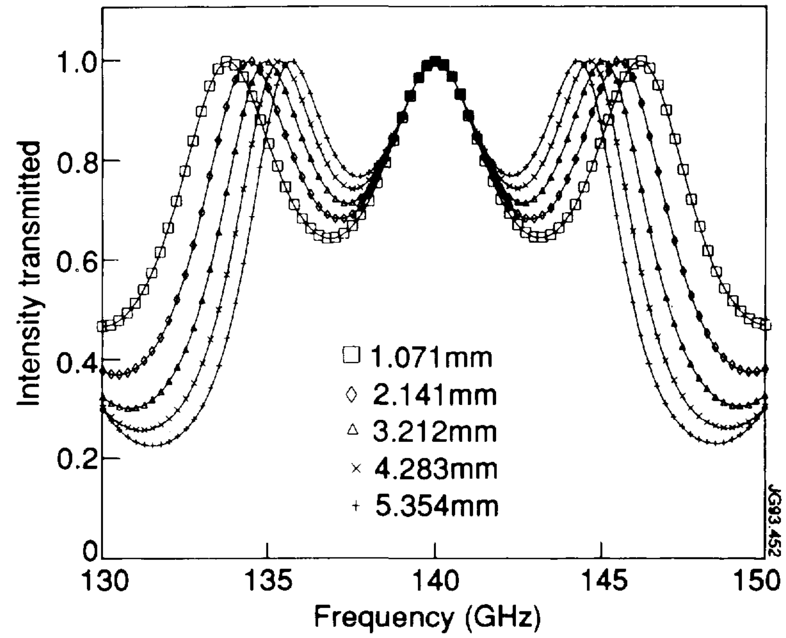

Figure 6. Transmission of two quartz discs 5.079 mm thick (i.e. tuned for 140 GHz) with various tuned separations.

(with N taken to be 2.108) with various spacings, all of which are integer half wavelengths at 140 GHz. The frequencies of the maxima on each side of 140 GHz are given by expression 8(b). If the spacing of the discs (and hence the frequency interval between maxima) is increased the minimum transmission falls.

5.6 "Moth eye" surfaced windows

It is possible to reduce the reflectivity of a window surface by tapering the refractive index to unity over a depth of about a wavelength. This can be done by creating a regular array of protruberances, as is found on the cornea of a moth. Surface structures suitable for millimetre wavelengths have been fabricated by Ma and Robinson (1983) on fused quartz with encouraging results. Further work is needed to establish manufacturing methods for applying the technique to crystal quartz windows for JET and to assess their performance, including any reduction in the mechanical strength, but this method offers the hope of achieving low reflectivity over a wide bandwidth in the future.

6. CHOICE OF WINDOW STRUCTURES FOR JET DIAGNOSTICS

6.1 Collective scattering diagnostic

The collective scattering diagnostic operates near 140 GHz. The 32 receiver channels cover the frequency range between 134 and 146 GHz, with individual bandwidths which vary between 20 and 1100 MHz, so the coherence lengths are between 0.3 and 15 m. and the theory of Section 2 applies. At present the most suitable double window is a tuned window. The beam diameter fixes the minimum window aperture and the strength requirement then determines the minimum thickness, which is 5 mm. The necessary disc thickness is thus 5.079 mm, as assumed for Figure 6. The curves in this figure indicate that a spacing of 3.212 mm will give the best performance over the required frequency range, with transmission varying slowly between about 70 and 100 %.

In the future quarter wave grooved windows may be preferable. If satisfactory moth eye surfaced windows become available, these should give even better transmission over the frequency range of interest.

6.2 Michelson interferometer

Michelson interferometers are used at JET for relatively low resolution (~ 5 to 10 GHz) millimetre wave Fourier spectroscopy. If the moving mirror of the interferometer scans over a distance l from the zero path difference position, the instrument can only resolve frequencies separated by more than $c / 2l$ Hz. If the double window through which the radiation is received is designed so that the smallest optical distance between any two surfaces, Nd, is greater than l, the interferometer will not resolve the structure in the transmission spectrum of the window. For an interferometer with a typical scan of 15 mm the resolution is ~10 GHz, so the thick,widely spaced double window discussed in Section 5.4 seems a promising solution if it can be sealed into a waveguide. A double wedged window, or a double tilted window with careful mode selection, are simpler alternatives. Moth eye windows will be far more effective than any of these if and when they become available.

6.3 ECE heterodyne radiometer

The most difficult problems arise with this instrument, which has high resolution (250 to 500 MHz) over a wide frequency range (70 to 140 GHz). The development of moth eye windows seems to be the only satisfactory long-term solution. A double wedged window or a mode-selected double tilted window can be used for the present.

7. CONCLUSIONS

Although a number of methods are already available to reduce the problems caused by reflections from the surfaces of double windows, none of them are entirely satisfactory.

The most promising approach for the future is the development of moth eye surface structures, which if successful will enable wide bandwidth, low reflectivity windows to be constructed suitable for all the JET millimetre wave diagnostics. Grooved quarter wave layers may also be useful for the collective scattering diagnostic.

The quasi-optical or waveguide components determining the beam input and output wavefronts should be designed with the window.

ACKNOWLEDGEMENTS

We are grateful to Dr J R Birch (NPL); Dr A E Costley, Dr J A Hoekzema and Dr L Porte (JET); and H J Milton (Special Techniques Service, AEA Culham Laboratory) for helpful discussions.

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