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CRYSTAL QUARTZ WINDOWS FOR FAR-INFRARED INTERFEROMETER OF SST-1

Asha Adhiya* and Rajwinder Kaur

Institute for Plasma Research, Bhat, Gandhinagar- 382 428, Gujarat

ABSTRACT

This paper presents the estimation of power transmission through optical windows for three (vertical, lateral and tangential) views of the far infrared (FIR) interferometer operating at 118.8μm and 432.6μm for plasma density measurement in steady-state superconducting tokamak-1 (SST-1). The lateral and tangential views have fan of beams incident on the optical windows at different angles of incidence. Crystal quartz has been selected as the window material owing to its good optical properties in Far infrared region, in addition to high melting point and very high physical strength. Ordinary and extraordinary modes of propagation inside crystal quartz cuts for incident s and p-polarized light beams have been investigated. z-cut crystal quartz has been selected to get maximum power transmission and reduce the effect of birefringence. The reflectivity of windows for the ordinary mode propagation has been calculated using resonant effect by Fresnal equations for all probing beams and the thicknesses have been optimized corresponding to maximum transmission through the windows. The power transmission of incident beams taking absorption coefficient into account has been given.

Keywords: *Crystal Quartz, Ordinary and extraordinary modes, Quartz cuts, Resonant effect and Fresnal equation*

INTRODUCTION

Interferometry is the principle diagnostics method for density measurement in tokamak plasmas [1-7]. Radiation of suitable wavelength, decided by beam refraction and mechanical stability of the interferometer support structure, is used to probe the plasma. SST-1 is a modest size ($R\sim1.1m$, $a\sim0.2m$, $\kappa\sim1.7$-2, $\delta\sim0.4$-0.7, $B_T\sim3T$, $I_P\sim220kA$) steady state superconducting tokamak designed to operate for stable long pulse duration of 1000 sec. SST-1 plasma will have D-shaped cross-section which limits diagnostics access due to presence of stabilizer and divertor plates. The loss of circular symmetry requires multiview, multichannel density measurements. Optically pumped FIR lasers operating at 118.8μm and 432.6μm have been selected as radiation sources for three views of interferometer being developed for SST-1 tokamak [7]. Far infrared laser beams enter the plasma column through vacuum windows mounted on machine ports.

This paper discusses the criteria for the selection of diagnostic window material for vertical, lateral and tangential viewing of FIR interferometers for SST-1 tokamak. Based on various considerations, crystalline quartz has been found to be the material preferred for vacuum windows in the present case. Section 2 describes lines of sight of vertical, lateral and tangential view FIR interferometers and their orientation at window surface. The selection of window material and possible modes of propagation inside crystal quartz are presented in section 3. The selection of window thickness that corresponds to maximum power transmission through windows for above-mentioned views of the FIR interferometer for SST-1 is presented in section 4. The concluding remarks are made in section 5.

LINES OF SIGHT

In SST-1 tokamak, the density distribution will be measured using a single channel vertical, five channel lateral and six channel tangential view FIR interferometers (Fig.1). For vertical viewing, the beam waist $d_0\sim7mm$ is placed at the midplane and expands to $d_{win}\sim8mm$. The window aperture has been kept to be 63mm to accommodate the refraction due to transverse density gradient as well as to avoid diffraction losses. The lateral and tangential views of the FIR interferometer employ fan beam geometries to cover the plasma cross-section [5]. The pivot points in both the views are kept at window surfaces.

Owing to the fan beam geometries, the laser beams are incident on the windows at different angles. Fig.1b shows five probing beams (l_1-l_5) of the lateral view interferometer and the corresponding incidence angles are 9°, 4°, 0°, -4° and -8°. The beam diameter is $d_{win}\sim32mm$ at the window for lateral viewing and the corresponding clear aperture of the window is taken to be 100mm. Fig.1(c) shows six probing beams (t_1-t_6) of the tangential view interferometer covering whole of the plasma cross-section (plasma major radius R = 0.9-1.3m) at the equatorial plane. The incidence angles of these beams at the window surface are 4.32°, 2.9°, 1.46°, 1.48°, 2.99° and 4.52°. The Gaussian beam waist $d_0\sim24mm$ is located at the retroreflectors mounted on the outside wall of vessel and expands to $d_{win}\sim 26mm$ at the vacuum window. The 63mm clear aperture of the window ensures negligible diffraction losses. The transmissivity of windows will be different for different channels since their angles of incidence are different. The thicknesses of windows have been chosen to maximize power transmission for all lines of sight.

SELECTION OF VACUUM WINDOW

The selected windows should have high transmission in the far infrared region and good optical properties in the visible region for easy alignment with visible light. In addition, the mechanical strength of window material should be sufficient to withstand differential pressure and high baking temperature [8]. The window material should satisfy all these critical requirements. The materials that are transparent at far infrared wavelengths include sapphire, crystal quartz, TPX, polyethylene, mica etc [6]. Plastics are not acceptable for high-vacuum devices; therefore, TPX and polyethylene cannot be used to make vacuum windows. Mica has very high physical strength but its melting point is low, hence cannot survive at high baking temperature. Crystal quartz and sapphire seem to be best suited [5,6] for diagnostics windows of FIR interferometers in

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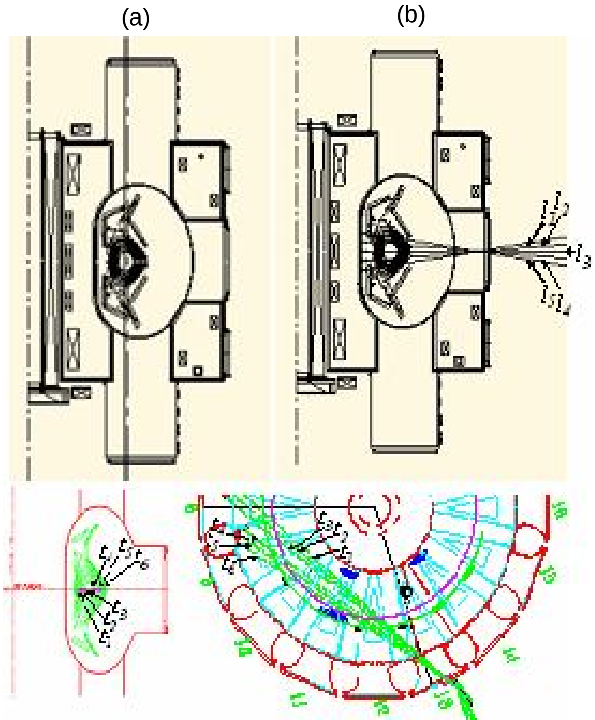
*Corresponding author: adhiya@ipr.res.in

SST-1.We have preferred to use crystal quartz due to its lower absorption coefficient than sapphire.

The vacuum windows for FIR interferometer of SST-1 are plane parallel plates of quartz made from its crystalline form by cutting it at precise orientations with respect to its crystallographic axes. Crystal quartz is an optically active and birefringent medium, i.e., the normal eigen modes for arbitrary angle of incidence (with respect to optic axis) are elliptically polarized. It exhibits optical activity for propagation along optic axis and linear birefringence for propagation perpendicular to optic axis. Hence modes of propagation inside crystalline quartz and the state of polarization of transmitted beam depend on orientation of E-vectors of the incident beam with respect to optic axis. The propagation modes inside quartz crystal with cut parallel to optic axis (x & y -cut) are shown in Fig.2(a) and with cut perpendicular to optic axis (z-cut) are shown in Fig.2(b). For single mode propagation inside above-mentioned crystallographic cuts, the E-vectors of incident beam must be oriented exactly parallel or perpendicular to the optic axis, which, in practice, is nearly impossible to achieve.



(a) (b)

(c) (d)

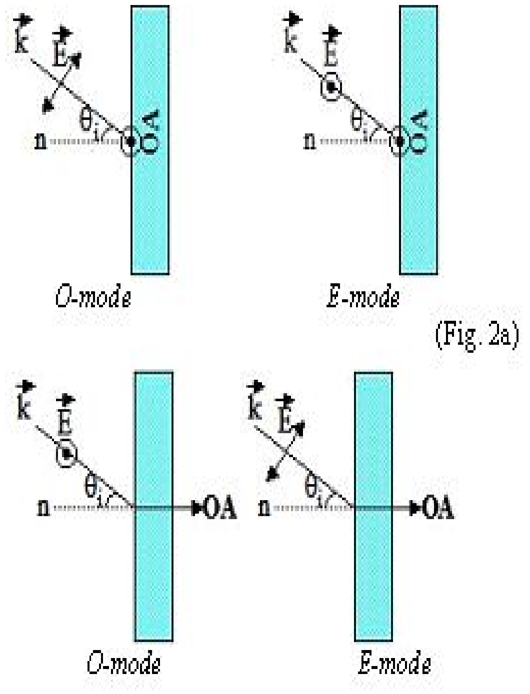
Fig. 1 (a) Vertical (b) lateral (c) tangential probe beams shown in the Cross-section of SST-1 and (d) tangential probing beams shown in the plan of SST-1.

We have selected z-cut quartz crystal for the vacuum windows for all the views of interferometer. The incident beams are arranged such that each fan of beams lies in single incident planes, with E-vectors oriented normal to this plane. This ascertains that the plane of polarization of the incident laser beams is aligned normal to the optic axis (s-polarization), thereby ensuring ordinary mode propagation inside all the crystal quartz windows. The optic axis is further aligned normal to the toroidal magnetic field of SST-1. This arrangement has an advantage that it introduces lesser ellipticity than x & y cuts in the transmitted beams.

RESULTS AND DISCUSSION

The thickness of window is calculated to withstand the atmospheric pressure and minimize reflection losses. The window apertures for vertical and tangential viewing are 76mm and lateral viewing is 114mm. Based on mechanical considerations, the rough estimates of window thickness $d = (1.1PD^2/MR)^{1/2}$, P = differential pressure, D = window diameter & MR = modulus of rupture ~ 6000 psi for crystal quartz) are made. Keeping the safety factor of 1.5-2, the window thicknesses are estimated to be 9.9mm and 6.5mm respectively for lateral and vertical/tangential viewing of FIR interferometer.

Further, a precise calibration of window thickness has been done by considering resonant effect between waves reflected by the parallel surfaces of etalon [9].



(Fig. 2a)

(Fig. 2b)

Fig. 2 Propagation modes (ordinary mode: O-mode & extraordinary mode: E-mode) inside (a) x or y-cut and (b) z-cut crystal quartz with incident planes perpendicular to the window surface.

The refractive index (n = 2.10748 for 432.6mm and n = 2.12033 for 118.8mm) and absorption coefficient (α = 0.1 for 432.6µm and α = 0.55 for 118.8µm) are interpolated from the table given by Russel and Bell [10]. The reflectivity of window has been calculated from [11] .

$$\frac{I_r}{I_o} = \frac{4R\sin^2\frac{\delta}{2}}{(1-R)^2 + \left(4R\sin^2\frac{\delta}{2}\right)} \qquad (1)$$

where, δ is the phase difference caused due to passage through the windows:

$$\delta = \frac{4\pi}{\lambda} nd\cos\theta_r \qquad (2)$$

d is the window thickness, θ_r is the angle of refraction and n is the refractive index of crystal quartz for the selected mode of propagation inside the window.

$$r_s = -\frac{\sin(\theta_i - \theta_r)}{\sin(\theta_i + \theta_r)} \qquad R = |r_s|^2 \tag{3}$$

The reflectivity of z-cut quartz windows has been calculated as function of window thicknesses for vertical, lateral and tangential view interferometers. The reflectivity varies sinusoidally with its thickness at a given incidence angle and for a given wavelength.

Taking power absorption ($P = P_o$ (1-exp ($\alpha/d \cos \theta r$)), P_o = incident power) inside the window into consideration, the power transmissivity of these windows is calculated for all the channels.

The window thickness of 76mm aperture for vertical and tangential viewing of 118.8µm interferometer is 6.502±0.002mm and 114mm aperture for lateral viewing of 432.6µm interferometer is 9.967±0.002mm. The incidence angle for vertical viewing is 3° to eliminate reflection of the He-Ne laser beam [12,13]. The corresponding transmissivity of the window for single pass through two windows is 1.55dB. For double pass lateral and tangential viewing, transmissivity through the windows is plotted in fig.3 as function of window thickness for all channels.

CONCLUSIONS

The vacuum windows chosen for various views of far infrared interferometer are made up of crystalline quartz due to double advantage of having low absorption coefficient and being transparent to both far-infrared and visible radiation. Further, it has high melting point to withstand baking temperature of 250°C. z-cut crystal quartz should be preferred to get maximum power transmission and reduce ellipticity. The thickness, 6.502± 0.002 mm for vertical/tangential and 9.967 ± 0.002 mm for lateral viewing minimizes reflection losses and can withstand atmospheric pressure. The above-mentioned thicknesses provide maximum transmission for all the 12 channels of vertical, lateral and tangential view interferometers.

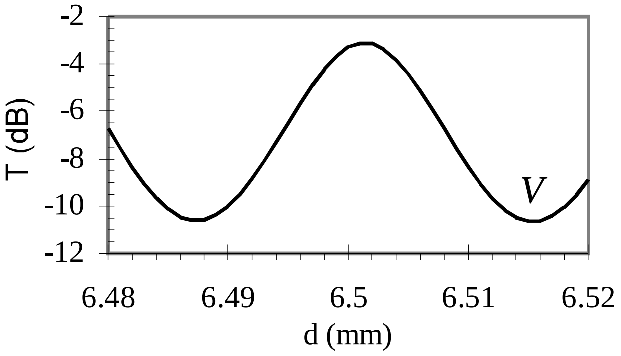


Fig. 3(a)

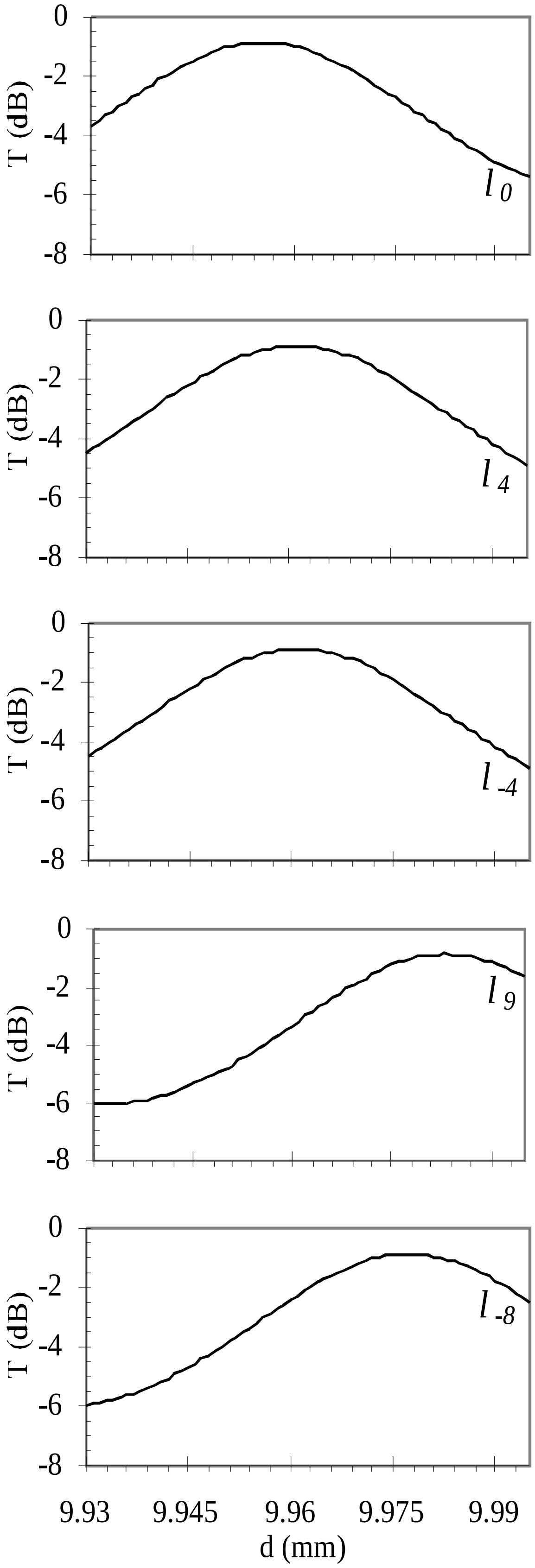


Fig. 3(b)

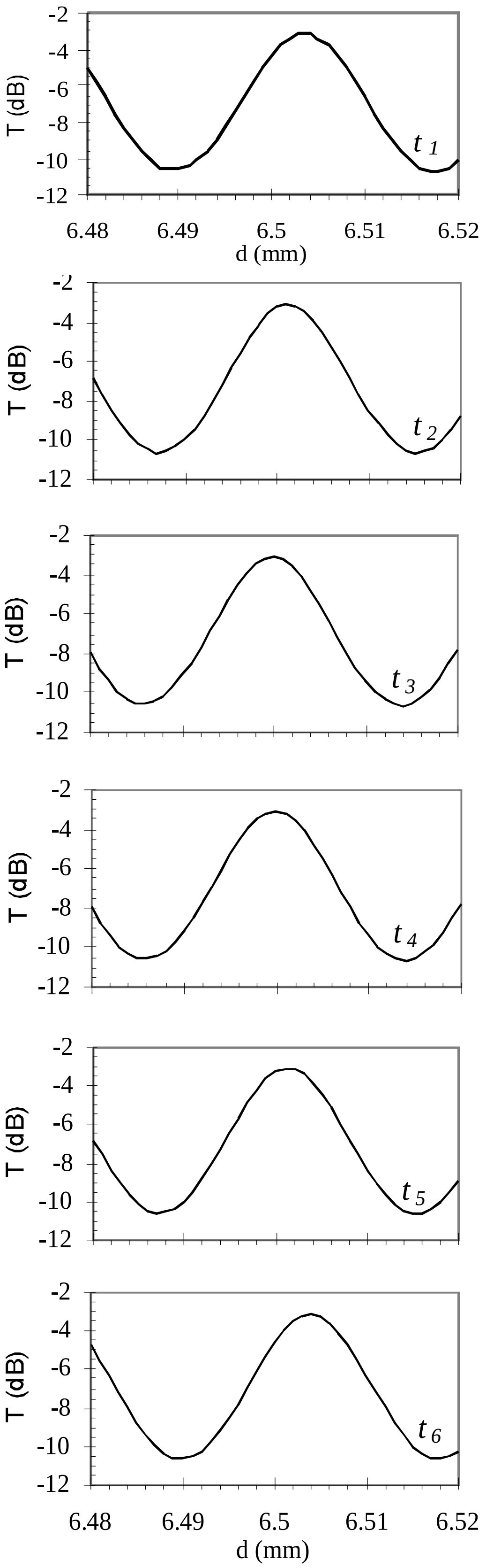


Fig. 3(c)

Fig.3 Transmissivity as function of thickness for (a) single channel vertical (V), (b) five channel lateral *(l_0, l_4, l_{-4}, l_9 & l_{-8})* and (c) six channel tangential *(t_1, t_2, t_3, t_4, t_5 & t_6)* viewing.

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