T.2: Optical components fabrication and characterization facility at RRCAT

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Abstract
The development of lasers requires a variety of optical components with stringent specifications of form, roughness, etc. to generate, guide, reflect and focus the light beam precisely at an appropriate location. RRCAT is involved in the design, development and applications of variety of lasers. Optical workshop has been involved in indigenous development of specialized optical components for the laser and accelerator programmes. In this article, the infrastructural facilities, the process development for fabrication of the important optical components and optical characterization are discussed.

1. Introduction
RRCAT is involved in the design, development and applications of variety of lasers such as high-power Nd:glass laser, Nd:YAG lasers, CO_2 lasers, copper vapour lasers, ultrafast lasers and x-ray lasers. Such lasers have complex optical systems, which include specialized optical components like laser rods and discs, transmission windows, etalons, non-linear and electro-optical crystals, in addition to mirrors (plane, spherical, cylindrical, toroidal, etc.). These optical components are fabricated using different materials, e.g. Nd:YAG, Nd:YLF, Nd:glass, BK7, fused silica, KDP, KD*P, KTP, $LiNbO_3$, BBO, copper, copper-nickel, stainless steel, molybdenum, CaF_2, KCl, silicon, Zerodur®, etc. The quality of the generated light beam, its transmission, transformation and focusing at the user workstation depend significantly on the performance of these optical components. Wavefront distortions, scattering losses and high intensity modulations are to be minimized at each optical surface to achieve the desired quality of the light beam. Therefore, the optical surfaces of these components have to meet stringent specifications for surface figure typically of the order of $\lambda/10$ over 100 mm of aperture, roughness of the order of ~ 5 Å – 10 Å and minimal slope errors.

RRCAT has indigenously developed processes for the fabrication and refurbishment of the required optical components by establishing the necessary infrastructure consisting of conventional spindle based optical grinding / polishing machines, cylindrical polishing machine, milling machine, centring and edging machine, double side optical polishing machine, etc. Chemical mechanical polishing (CMP) process, in which controlled material removal is achieved by using abrasive slurry on a formed tool, is used to generate and polish the optical surfaces. Bowl feed CMP technique is used for super-smooth polishing of mirror substrates to achieve surface roughness of less than 5 Å. To meet the metrology requirements for the above mentioned fabricated optical components, a number of instruments which include phase shifting Fizeau interferometer, autocollimators, cyclic path-based interferometers, schlieren imaging system, etc. have been developed in-house. The processes for the fabrication of diverse specialized optical components, their testing and evaluation are discussed in the following sections.

2. Fabrication and polishing of laser rods and slabs
2.1 Fabrication and polishing of laser rods
Phosphate glass is the most commonly used host material for high power Nd:glass laser systems, mainly because of its low non-linear refractive index and moderate stimulated emission cross section. Fabrication of laser rods from raw laser glass slab involves a number of operations [1]. Firstly, the cylindrical laser rod blanks (CLRB) are prepared from the slab by the following different machining operations, such as sawing, milling, and rounding/edging. Next, the flat end surfaces of the CLRB are ground and optically polished to required optical finish and parallelism.

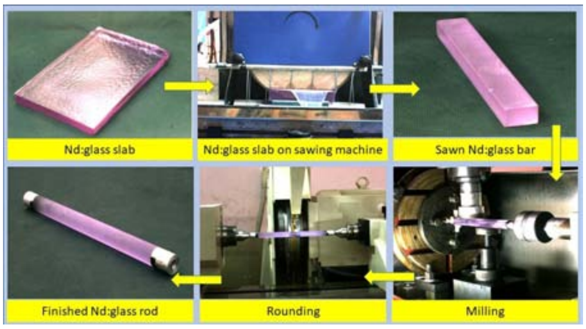


Fig. T.2.1: Fabrication of Nd:glass laser rod from the laser slab.

Custom made indigenous glass sawing, milling and rounding machines are used for the fabrication of the laser rods. Various operations involved in the fabrication of Nd:glass laser rod are shown in the Figure T.2.1. The end faces of the fabricated rod are polished by holding the rod in an appropriately designed fixture. During polishing, the surface figure is tested using a master plate in contact with the surface being polished under sodium lamp illumination. On completion of polishing, the surfaces are inspected with a laser based Fizeau Interferometer. The process for polishing Nd:YAG laser rods has also been established. Nd: Glass laser rods of sizes up to 50 mm diameter × 300 mm length, and Nd: YAG laser rods of sizes up to 10 mm diameter × 160 mm length are being fabricated or refurbished routinely.

2.2 Fabrication of large size Nd:phosphate glass slabs
Nd:glass slabs are used in disc amplifiers of high energy Nd:glass laser systems. The slab has two large faces typically of size 300 mm x 150 mm, two side faces of size 300 mm x 40 mm and the remaining two sides of size 150 mm x 40 mm. The smaller faces of the slab are used for cladding the slab. All the faces have to be optically polished. The larger faces are to be polished to a surface figure of ~ $\lambda/10$ and the smaller faces of the order of ~ λ. The surface figure has been measured using a standard flat surface of 100 mm diameter under sodium lamp.

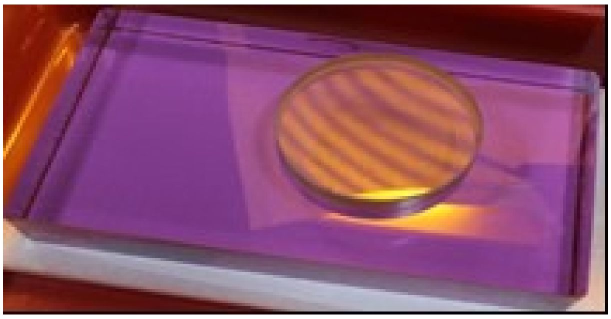


Fig. T.2.2: Photograph of polished Nd:glass slab.

Fig. T.2.3: Double side optical polishing machine.

The raw glass slab is initially sized to the required dimensions using diamond saw. This is followed by grinding the smaller faces and simultaneously making them at right angles along with the larger faces. The slab is held in an appropriately designed fixture, the faces are then polished on a flat pitch lap, or polyurethane pad using recirculating cerium oxide slurry till the required surface figure is achieved. The polished faces are protected by coating of lacquer, which can be easily cleaned using acetone. Subsequently, the larger size (300 mm x 150 mm) faces are polished. Photograph of the polished Nd:glass slab is shown in Figure T.2.2. The process to polish the six surfaces to the desired specifications requires about four weeks of time. To enable faster rate of polishing of the large slabs, double side optical polishing machine has been procured and installed, as shown in Figure T.2.3. This machine can polish both the larger sides of three numbers of 400 mm diameter flat optics simultaneously in about three days. Hence, the complete processing time for the slab is reduced to two weeks.

2.3. Optical polishing of Ti:sapphire crystal

Ti:sapphire crystals (in shape of discs/rods/slabs) are used in ultrafast lasers as active media for the generation and amplification of femtosecond laser pulses. Ti:sapphire being a very hard material, hardness of the order of 9 Mohs, required special process development to achieve the polishing requirements of its surfaces. Polishing technique for Ti:sapphire using diamond paste on tin polishing lap has been developed. Surface figure achieved is of the order of λ/4 at 589 nm. Polished Ti:sapphire crystal (size: 20 mm dia. x 15 mm length) is shown in Figure T.2.4.

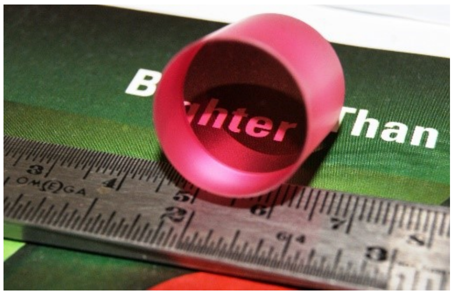


Fig. T.2.4: Polished Ti:sapphire crystal of size dia. 20 mm × 15 mm length.

3. Polishing of metal mirror substrates and ultra-thin glass plates

Metal optics are routinely required for CO_2 lasers, infra-red free electron lasers, etc. Materials include copper, aluminium, stainless steel molybdenum, etc. Polishing of metal optics up to 200 mm diameter are carried out using pitch polisher and Al_2O_3 polishing powder. Surface figure of the order of λ/10 at λ = 589 nm over 100 mm diameter metal optics and λ/8 at λ = 589 nm over 200 mm diameter were achieved. Variety of metal optics fabricated in the optical workshop is shown in Figure T.2.5. Flat mirrors of 100 mm diameter of OFHC copper were fabricated for infra-red free electron laser project at RRCAT. Also, 25 mm diameter molybdenum mirror substrate was polished for CO_2 laser developed at RRCAT.

Next, thin glass/fused silica/crystal quartz plates, pellicles with good surface form and parallelism between the surfaces are required for specialized applications such as substrates for solid etalons, wave plates etc. A technique for fabrication of thin glass plates has been developed. One side of relatively thick plate of the material is polished and attached to a plane parallel base plate of the same material by optical contacting. Thickness of the material is reduced to desired level by grinding the second surface and then polished to good surface figure and finish. Finally, the optical contact is carefully broken to separate the thin plate from the base plate. Thin fused silica plates of diameter 50 mm and thickness of 200 µm with good surface form of ~ λ/4 and parallelism of ~ 10 arcseconds between the plane surfaces have been fabricated. The glass pellicle is shown in Figure T.2.6.

Fig. T.2.5: Polished metal substrates.

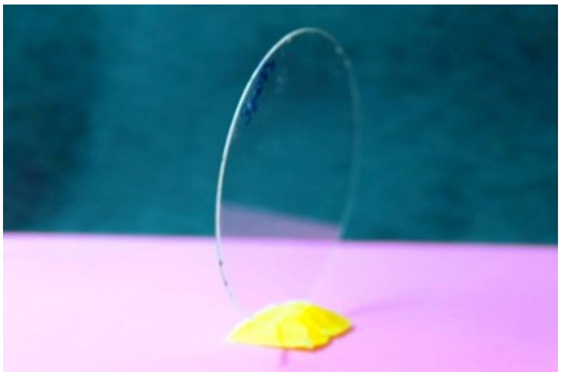


Fig. T.2.6: Thin fused silica glass plate of 200 μm thickness and diameter 50 mm.

4. Polishing of hygroscopic crystal optics

Crystals are used in laser systems for various applications such as harmonic generation, electro-optic modulation, etc. The most important crystalline materials for such devices are: KDP (KH_2PO_4) group of materials such as DKDP (KD_2PO_4), ADP ($NH_4H_2PO_4$), etc. These materials are hygroscopic and also have poor mechanical strength i.e., they are very fragile and sensitive to thermal shock. Because of their hygroscopic nature, polished surfaces of optical components made from these materials are highly sensitive to moisture and tarnishes immediately in moist atmosphere. A technique has been developed for polishing of hygroscopic materials, using ethylene glycol as fluid during grinding and polishing operations. Soft wax polisher/pitch polisher of appropriate hardness are used to polish the crystals. Surface figure of ~ $\lambda/8$ at λ = 633 nm on 25 mm diameter crystals are routinely obtained.

5. Design and development of optical metrology instruments

During fabrication and final qualification of optics, suitable measurements for surface form, angles, parallelism, roughness, etc. are required. These measurements are performed using various optical instruments viz. profilometer, spherometer, autocollimator, test plates for Newton's rings test, Fizeau interferometer, schlieren imaging system, etc. These optical metrological instruments have been developed in-house for characterization of optical components and are described below.

5.1. Laser Fizeau interferometer for surface form measurement of optical surfaces

Fizeau interferometer (FI) is one of the important optical metrology instruments for non-contact surface measurements of polished optical surfaces. FI is a two-beam interferometer, where the interference is formed between the beams reflected, from reference flat surface and test surface. The shape of the interference fringes qualitatively represents the shape of the test surface. For precise quantitative measurement of the surface aberrations and 3-D surface form of the test surface, phase shifting technique is applied [2].

In phase shifting technique, the phase difference or the optical path difference between the interfering beams is modulated in steps by a defined amount using either piezoelectric transducers, that displace the reference flat by a fraction of source wavelength or by using polarization phase shifting in which phase shift is introduced between the orthogonally polarized interfering beams by rotating a polarizer [3]. The advantage of the polarization phase shifting is that, the phase shifting element, i.e., the polarizer, is placed outside the interference cavity and hence the cavity is not disturbed during the measurement. Figure T.2.7, shows the schematic of Fizeau interferometer. The linearly polarized He-Ne laser beam is expanded using microscope objective (MO) and collimating lens (TO). The beams reflected from the reference and test surfaces become orthogonally polarized due to quarter wave plate (Q1) in the interference cavity. The second quarter wave plate (Q2) converts these orthogonally polarized beams into right and left circular polarized beams.

Polarizer (Pol) selects a component of the beams along its pass direction and the two beams interfere forming interference fringes. Rotating the polarizer in its plane by 45 degrees introduces a phase shift of 90 degrees between the beams. Hence, rotating polarizer by 45, 90, 135 and 180 degrees from its initial position, five phase shifted interferograms can be obtained. Applying five step phase shifting algorithm [4], the phase map of the test optics is evaluated. 3-D surface form of the test optics and analysis for aberrations is done using software.

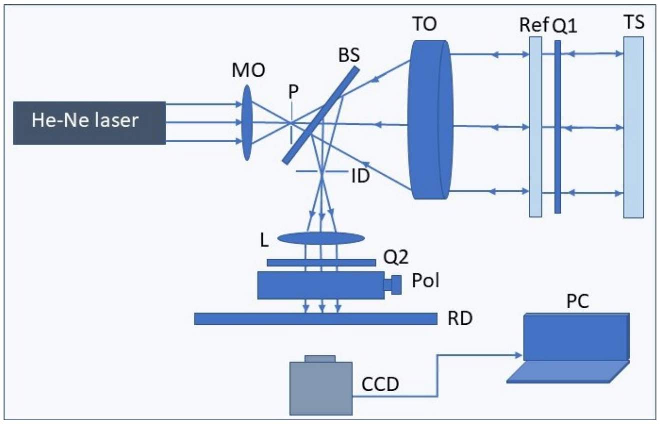


Fig. T.2.7: Schematic of a polarization phase shifting Fizeau interferometer, MO: Microscope objective, P: Pinhole spatial filter, BS: Thin beam splitter, TO: Collimating lens, Ref: Reference flat, Q1: Quarter wave plate, TS: Test object surface, ID: Iris diaphragm, L: Re-collimating lens, Q2: Quarter wave plate, Pol: Polariser, RD: Rotating diffuser screen, CCD: camera.

Figure T.2.8 shows the automated polarization phase-shifting Fizeau interferometer developed for evaluation of surface aberrations and 3-D surface form of polished optical surfaces using polarization phase-shifting [5].

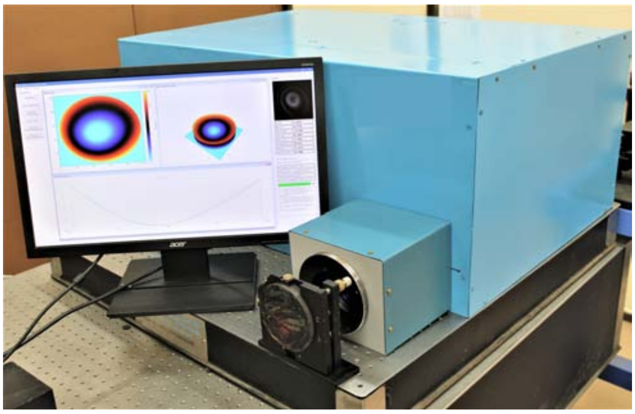


Fig. T.2.8: Indigenously developed laser Fizeau interferometer for measurement of surface flatness of the polished optical surfaces.

The rotation of polarizer is motorized and is controlled using software. Software also provides alignment mode, measurement mode and data analysis both on-line and off-line.

For measurement, the orthogonally polarized laser beams reflected from the reference surface of the instrument and test optics surface are to be aligned to produce interference fringes. Using alignment mode of the software, a focussing lens is introduced automatically between the iris diaphragm (ID) and lens (L). This will focus the reference and test beams on the diffuser screen. The two focussed beams are aligned to coincide with each other for interference, as shown in Figure T.2.9(a) and Figure T.2.9(b), respectively. On removing the focusing lens, interference fringes appear on the screen as shown in Figure T.2.9(c). The images are displayed live on the monitor screen. All these operations are automated.

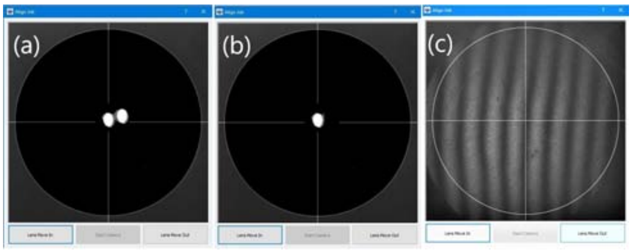


Fig. T.2.9: Screen shot of beam alignment and fringe mode, (a) during alignment (b) after alignment, (c) display of interference fringes.

Once the fringes are formed, after pressing start operation button, the software automatically acquires five phase-shifted interferograms, by rotating the polarizer in steps of 45 degrees, required for phase evaluation. After acquisition, software performs phase wrapping, unwrapping and calculates the Zernike coefficients. GUI displays the 3D surface form, 2D surface map and line profile of the test optics. The individual Zernike coefficients such as X-tilt, Y-tilt, defocus, astigmatism, peak-to-valley and rms values of the test surface are displayed on the monitor screen. Figure T.2.10 shows the screen shot of the GUI displaying the required information. The instrument can measure surface figure of up to λ/10 for the test optics of diameter of 100 mm.

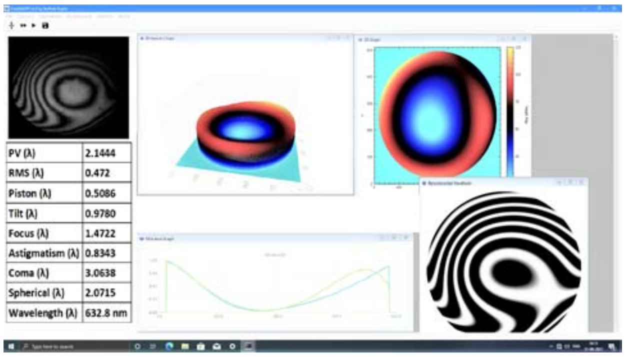


Fig. T.2.10: Screen shot of the GUI showing the measurement results for a test surface.

5.2 Autocollimator

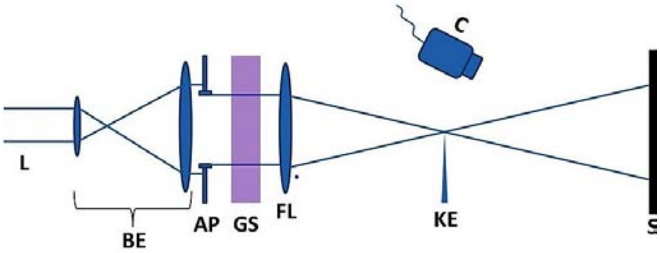
Autocollimator is used for non-contact measurement of angles between the optical surfaces. It is also used for checking the parallelism of polished optical flat surfaces and also for fabrication of wedged optics, prisms etc.

The existing home-made instrument can measure parallelism of the test optics surfaces up to 5 arc seconds. In-house developed autocollimator is shown in Figure T.2.11.

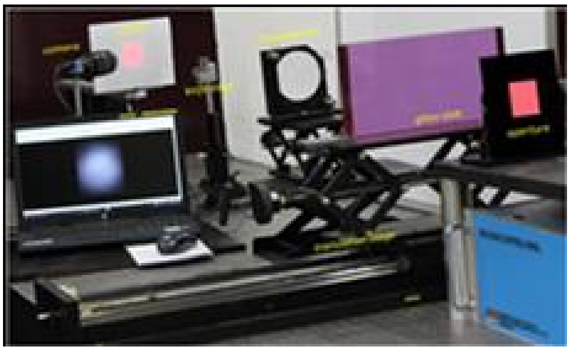
Fig. T.2.11: In-house developed autocollimator.

5. 3 Schlieren imaging for glass homogeneity testing

Setup for schlieren imaging is developed to detect refractive index inhomogeneity in large size (~300 mm × 150 mm × 40 mm) Nd-doped phosphate glass slabs [6]. For high energy operation, laser glass should be homogeneous, free of stress, striae, bubbles and inclusions. The refractive index inhomogeneity should be of the order of 10^{-5} or better to qualify the glass for its use as an active medium of the laser. Therefore, accurate measurement of optical homogeneity as well as striae and bubbles in the doped Nd:glass slab is important. Schlieren shadowgraphy is a simple technique for the measurement of refractive index homogeneity, which does not require a reference beam (unlike the interferometric technique). It provides a good qualitative estimate of the inhomogeneity of the glass medium of ~ 10^{-3}, which is otherwise not observable through visual/naked eye inspection.



(a)



(b)

Fig. T.2.12: (a) Schematic of the experimental setup. L: He-Ne laser, BE: beam expander, AP: rectangular aperture, GS: glass slab, FL: focusing lens, KE: knife edge, S: screen, C: CCD camera, (b) Photograph of the experimental setup.

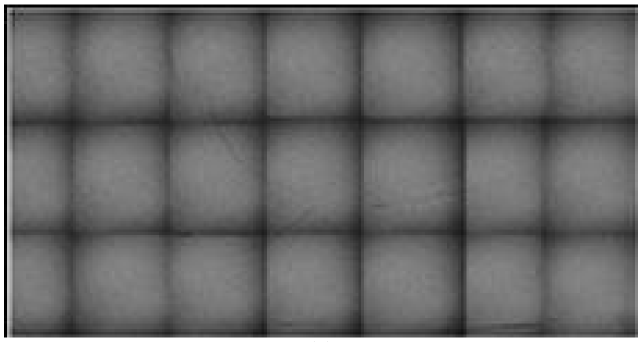
When light rays pass through regions of refractive index inhomogeneities, they are deflected due to refraction. The resultant deflection of the light rays produces intensity changes in the corresponding portions of the light beam. A schlieren image is formed on the screen by focusing the resultant beam, and placing a knife edge at the focus. On removing the knife edge, a shadow-graphic image is formed.

Figure T.2.12(a) shows the schematic of Schlieren imaging setup, and photograph of the instrument developed in the laboratory is shown in Figure T.2.12(b). An expanded, collimated and spatially-filtered laser beam of rectangular cross-section, 50 mm × 60 mm, derived from a He-Ne laser, is passed through the test glass slab. Both entrance and exit faces of this slab are optically polished with surface figure better than λ. The transmitted beam from the glass slab is incident on a spherical convex lens of focal length 500 mm to focus and image it on a screen kept in the far field. The image on the screen is recorded using a CCD camera. A knife edge is placed at the focal position of the focusing convex lens to block the un-deviated light emerging from the homogenous part of the slab. This results in increased contrast of the recorded far-field images.

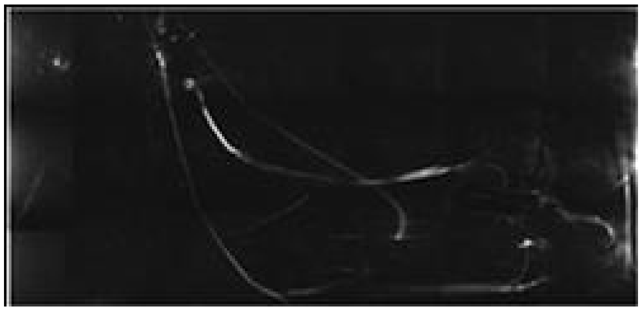
The test glass slab is kept on a motorized translation stage and scanned transversely across the probe laser beam in both horizontal and vertical directions to cover/expose the complete glass slab with the laser beam for its different positions as the size of the test slabs is large enough [~ 300 mm (length) × 180 mm (width) × 50 mm (thickness)] in comparison to the size of the laser beam (~50 mm × 60 mm).

Overlap area of ~10-20 % between adjacent images is kept to perform stitching. For each scanned position of the slab, the images of the transmitted light were recorded. Finally, all the recorded images corresponding to each scanned position of the glass slab are stitched to form one larger image corresponding to the complete slab.

Figure T.2.13(a) and Figure T.2.13(b) show the typical stitched shadowgraphic image and schlieren image, respectively. Nearly one to one correspondence of the observed refractive index inhomogeneity defects in both the images is evident. The schlieren image provides more contrast than the shadowgraphic image. This home-made laboratory setup of schlieren imaging is being used regularly to test the Nd-doped phosphate glass slab samples. For refractive index inhomogeneity better than 10^{-3}, the commercial instruments such as Zygo interferometer should be used to measure the inhomogeneity of the order of 10^{-5} or better.



(a)



(b)

Fig. T.2.13: (a) Stitched shadowgraphic image of the test Nd-glass slab, (b) High contrast stitched schlieren image of the test Nd-glass slab

6. Super-smooth polishing for development of high energy laser and x-ray mirrors

One of the key requirements of high energy lasers are mirrors with very high reflectivity and windows with high transmission, and hence both should also have optical coatings with reasonably high laser induced damage threshold (LIDT).

To achieve this, the substrates should have ultra-low surface roughness with minimum cosmetic defects e.g., scratches, digs and pits apart from a high degree of form accuracy. Ultra-low roughness substrates significantly reduce scattering and absorption of radiation.

The thin film optical coating developed on such surfaces for high reflectivity or antireflection coating should have high LIDT. This calls for super-smooth optical substrate (BK-7, fused silica) fabrication which should typically have rms roughness below 5 Å. Likewise, super-smooth substrates (Zerodur®, fused silica, silicon, etc.) are also required for indigenous development of grazing incidence synchrotron x-ray mirrors, which are fairly expensive. Thus, to cater to the need of super-smooth substrates for in-house development of key optical components for high energy laser and synchrotron x-rays, super-smooth optical polishing facility has been developed, using the existing conventional optical polishing machines, duly supported by metrology and roughness measurement instruments (AFM and x-ray reflectivity).

6.1 Bowl-feed chemical mechanical polishing (CMP) for super-smooth optical substrates

Super-smooth optical substrates are usually produced using various methods, e.g., magneto-rheological finishing (MRF), elastic emission machining (EEM), ion-beam figuring (IBF), float polishing and chemical mechanical polishing (CMP). The first three methods, though give better surface accuracy, are highly capital intensive, while float polishing and CMP are inexpensive. CMP in bowl-feed technique is presently being deployed to generate super-smooth surfaces on large optical substrates.

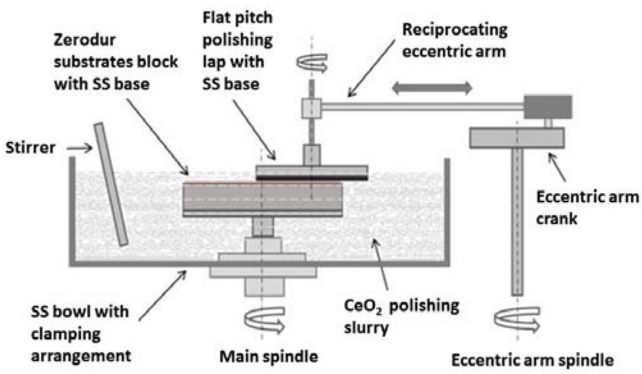


Fig. T.2.14: Schematic of optical polishing using bowl-feed CMP.

Figure T.2.14 shows the schematic of the bowl-feed CMP [7] developed in the laboratory, in which, the pitch lap and the substrate are submerged in a pool of abrasive slurry inside a rotating bowl and the CMP is carried out. A stirrer is used to keep the slurry homogeneous. The concentration of the abrasive particles (0.5-1 µm) in the slurry, it's pH and temperature are maintained at the optimized values during the process to have the desired material removal rate. As the optical polishing in bowl-feed CMP progresses, the abrasive particles break down to smaller sizes (100-50 nm), resulting in the removal of nm-thin layers of the surface. In the final stage, the rotation speed is greatly reduced and the stirring is withdrawn to allow only the smaller abrasive particles at the top layer of the liquid slurry to interact with the surface being polished.

Continuous or intermittent conditioning of the polishing tool is necessary to ensure the accuracy of the surface form. Surface form of the substrate is checked at a regular interval during the process with a reference flat. Bowl-feed CMP is an extremely slow process having a uniform, yet very low material removal rate, thus allowing one to achieve fairly high form accuracy (e.g., flatness) and ultra-low roughness (~ 5 Å or below) or super-smooth surface.

6.2 Roughness measurements

Post CMP, cleaning of substrates is also an important step before the thin film coating is carried out as embedded residual particulate impurities could strongly absorb laser radiation and result in lower LIDT. Thus super-smooth surface is cleaned properly following a laid down procedure before any measurement is carried out. Surface roughness of the substrate is first measured with the atomic force microscope (AFM), which gives a detailed information about the high spatial frequency roughness (rms roughness, average roughness etc.) over a small scan area, typically ranging from 50 µm × 50 µm to 1 µm × 1 µm. High frequency roughness is estimated on large surface area from hard x-ray reflectivity measurements using lab source (Cu-K_α, 8 keV) as well as at energy range of 100-1500 eV in beamline BL-3 at Indus-2 synchrotron radiation source (SRS) at RRCAT. These measurements give ample idea about the high spatial frequency surface roughness of the fabricated super-smooth optical substrates. With these measurements, the surface roughness characterisation at high spatial frequency of the super-smooth optical substrates is complete. Surface form error measurement is carried out using a laser-based phase shifting Fizeau interferometer developed in-house.

6.3 Fabrication of super-smooth BK-7 and fused silica substrates for high energy laser mirrors and windows

Nd:glass disc laser amplifier and spatial filters of the high energy laser chain require large (diameter150 mm) multilayer thin film coated high reflectivity (HR) mirrors and anti-reflection (AR) coated transmission windows with high LIDT. As these large sized HR mirrors and transmission windows with high LIDT are not readily available from the OEMs, indigenous development of super-smooth substrates for these crucial optical components was taken up. Large size BK-7 substrates were optically polished using bowl-feed CMP technique to generate ultra-low surface roughness of < 5 Å, as shown in Figure T.2.15. These substrates have a flatness of $\lambda/10$ at 589 nm over 95% clear aperture, parallelism better than 5 arcsec and a scratch-dig of 20/40. The super-smooth BK-7 substrates have been coated with 25 layers of SiO_2/Ta_2O_5 thin-film to fabricate HR laser mirrors at Optical Coatings Laboratory. The reflectivity of these mirrors has been measured to be 99.8% ± 0.1% over a wavelength band of 140 nm at a centre wavelength of 1053 nm with measured LIDT of 3.9 J/cm^2 at 3 ns.

Similarly, super-smooth fused silica windows of 150 mm diameter for high LIDT transmission were fabricated. Four layers of SiO_2/Ta_2O_5 have been coated on the both sides of the windows.

The developed coatings achieved a total transmission of more than 99.2% at 1053 nm and damage threshold of 4.5 J/cm^2 at 3 ns. Next, super-smooth large size BK-7 substrates were also fabricated for x-ray applications. Figure T.2.16 shows some of these optically polished BK-7 substrates with mounting slots generated using optical milling machine.

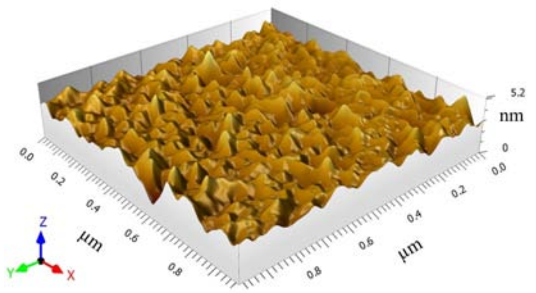
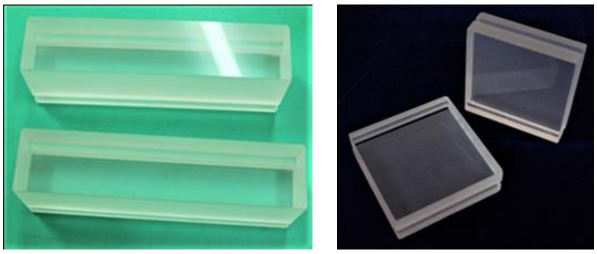


Fig. T.2.15: Roughness measurement in AFM (3D topography).



(a) (b)

Fig. T.2.16: BK-7 substrates with mounting slots, (a) size: 130 mm × 30 mm × 40 mm, (b) size: 100 mm × 100 mm × 25 mm.

6.4 Super-smooth polishing of Zerodur® substrates

X-ray mirrors are required for laser produced plasma experiments, x-ray beam lines of synchrotron, etc. which require an optically polished super-smooth surface coated with a reflecting material for efficient guiding and focusing of the x-ray beam. Large size (170 mm × 80 mm × 20 mm) Zerodur® substrates were optically polished using bowl-feed CMP to generate flat, ultra-low roughness surfaces. Surface flatness better than $\lambda/10$ and an rms surface roughness < 5 Å has been achieved with this technique [8]. The coatings on BK-7 have been optimized and now Zerodur® substrate will be coated with different materials to produce high reflectivity x-ray mirrors.

6.5 Optimization of super-smooth polishing of silicon mirror substrates

Silicon is one of the important optical substrate material used for development of high reflectivity, high damage threshold gold coated mirrors for high power/energy IR lasers and grazing incidence x-ray mirrors. These applications require ultra-low roughness or super-smooth substrates that ensure extremely low scattering losses. Fabrication of super-smooth Si substrates needs a very precise control of the entire polishing process [9]. A number of polycrystalline silicon substrates of 50 mm diameter and 10 mm thickness were optically polished to produce flat, super-smooth surfaces devoid of sleeks, scratches and digs as depicted in Figure T.2.17.

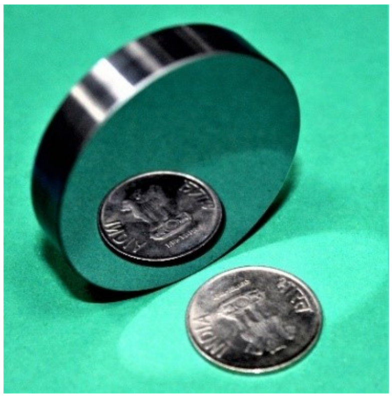


Fig. T.2.17: Super smooth polished silicon substrate.

The surface figure of silicon substrates was measured to be about $\lambda/10$ with 589 nm illumination. The measurement of high spatial frequency surface roughness of silicon substrate is done using AFM and the rms roughness was found to be 3.2 Å. The measurement of roughness over a larger area, using hard x-ray reflectivity measurement at Cu K_α (energy 8.047 keV) were also performed and roughness of 6.3 Å was measured. The technique developed for super smooth polishing of Si was applied to refurbish six laser damaged silicon mirrors used with the galvo scanner of CO_2 laser-based passport printing facility at India Security Press, Nashik. Post polishing, these Si substrates were gold coated and yielded a reflectivity of 95% at 632.8 nm.

7. Conclusions

In conclusion, specialized optical fabrication techniques and facilities developed at RRCAT have been described and discussed. To the best of our knowledge, fabrication of laser rods is being done only at RRCAT in India.

Since characterization of optical components is integral part of optics development activity, non-contact interferometric testing methods have been developed along with the specialized fabrication methods. Fully indigenous machineries and home-built equipment have been used for the R&D activities described here. Apart from meeting the needs of the various laboratories at RRCAT, we have also supported and fulfilled specialized optical fabrications / refurbishments requirements of BARC, IGCAR, VSSC, India Security Press, Nashik, etc.

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