T.2: Optical thin film coatings and characterization facility at RRCAT

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Abstract
Ever since the advent of lasers, applications of lasers in various diversified fields have increased by many fold and lasers have been used in innovative ways. The development of laser systems and laser application setups require a wide range of optical components with high-performance optical thin film coatings e.g., high reflection (HR) coatings and antireflection (AR) coatings on lenses, windows, crystals, laser rods and polarizing optical components. The rapid developments in laser technology have put enormous technological challenges on thin film coatings. RRCAT is involved in the design, development, and applications of various lasers. With a view to cater to these requirements, specialized optical coatings, state-of-the-art technology to produce multilayer optical thin film coatings with excellent spectral performance, laser damage threshold, durability, and thin film characterization facilities have been established. The very basis of these coatings is nano-metric thin film layers of dielectrics with defined microstructures, or their stacking as multilayers that utilize the principle of interference, governing the amplitude, phase, and polarization of the electromagnetic radiation. Both material and geometric parameters are equally important in the description of optical coatings. In this article, the thin film deposition facilities, the process development for fabrication of important optical components and different characterization techniques are discussed. An overview of various specialized and challenging optical coatings developed in Optical Coating Laboratory (OCL), RRCAT and their characteristics is presented in this article.

1. Introduction

Optical thin film coatings are all around us - on Earth and in Space - working in innumerous essential products that better our lives. Technological and scientific applications linked to interference coatings especially lasers are enormous and are continuing to grow. The very basis of these coatings is nanometric or sub-nanometric thin film layers of metals, ceramics, dielectrics, composites with defined microstructures or their stacking as multilayers that utilize the principle of interference governing amplitude, phase and polarization of the electromagnetic radiation.The beautiful natural phenomena and vivid spectral colorful creations of the nature are the outcome of the optical interference and are fascinating over the ages. The rainbow, the colorful birds, insects, bugs, sun light-lit waterfall are the prominent examples as shown in Figure T.2.1.

Fig. T.2.1: Natural optical interference phenomena [1].

Optics and optical components with specialized optical coatings are important for laser based R&D and spectroscopic studies and also help in considerably enhancing the efficiency of various industrial and high power laser systems being developed at RRCAT. These components are very expensive, not readily available as and when required and are mostly being imported. Development of large area optical coatings with high performance uniformity and high damage threshold is required for the development of high energy lasers.

It is well known that a stack of thin layers of optical materials can preciously control the flow of light through the surface of a transparent solid on which layers are deposited. The behavior of the coating depends on the optical properties of the material together with interference effects, which vary with wavelength, angle of incidence and polarization. Only specular component of light is considered. As the incident light enters the system of optical thin film coatings, it suffers multiple internal reflections at each interface. All the reflected/transmitted component waves having a distinct amplitude and phase as decided by the multilayer stack interfere either constructively or destructively to produce the resultant reflected/transmitted wave as desired [2]. Such calculation is well organized and understood. However, the inverse problem is rather complicated with no unique solution. The success depends equally on powerful theoretical tools, experience and skill. Design has to be finalized based on the practical problems faced in depositing and the limitations of the deposition and monitoring systems. The problem is compounded by the fact that properties of materials in thin film form vary on their own and also in the vicinity of another material.

2. Antireflection coating- Destructive interference

To understand the performance of thin film coating we need to accept following statements. First is that the amplitude reflectance of light at any boundary between two media (e.g., air and glass) at normal incidence is given by $(1-n_2)/(1+n_2)$, where n_2 is the refractive index of glass. The second is that there is a phase shift of π (i.e. $\lambda/2$) when the reflection is backed by a denser medium. The third is that light splits into two components, one at the top and the other from the bottom surface of a thin film. The incident ray is shown in black color. The thickness and refractive index of the film (blue) are such that the reflected beams (blue and red) from the 1st and 2nd interfaces have a phase difference of π and also their amplitudes are almost equal. Therefore, they recombine destructively producing low reflection and is known as antireflection (AR) coating [2]. This is described in Figure

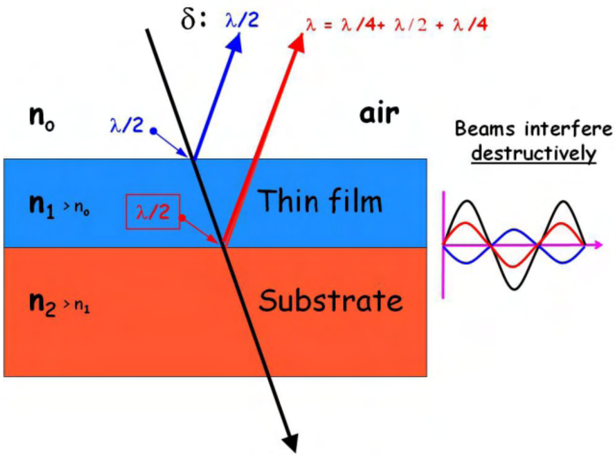


Fig. T.2.2: Principle of antireflection (AR) coating.

3. High reflection coating- Constructive interference

The basic high reflectance (HR) thin film structure consists of a stack of alternate high and low refractive index layers, starting and ending with high index layers and all the layers are one quarter wave thick at the centre of the desired wavelength range. Under such condition all the reflected rays meet constructively and result in high reflectance. The reflectivity can be made very high simply by increasing the number of layers. One of the most important requirements of all these coatings is that the films have very low absorption in the wavelength range of interest. Figure T.2.3 shows the principle of such a stack.

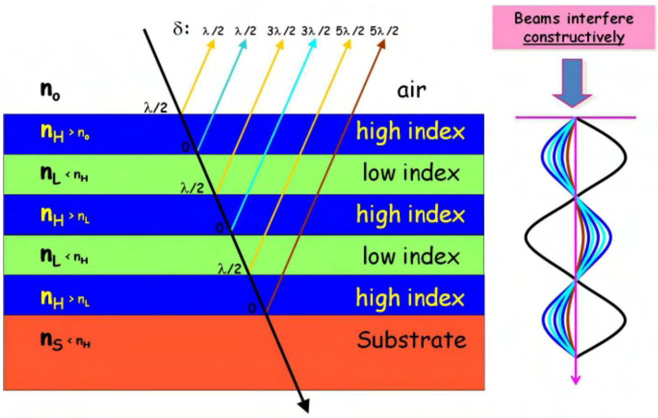


Fig. T.2.3: Principle of high reflection (HR) coating.

4. Multilayer coatings: Design & optimization

The computation of multilayer assembly, with large number of layers, is a complex task. One possibility is to use matrix formalism. This is based on the fact that tangential component of electric and magnetic fields are continuous across a boundary between two layers of different refractive indices. In this approach each layer is represented by a 2x2 characteristics matrix and multiplication of large number of such matrices provide the final equivalent layer matrix (2x2). Often the practical requirements are more demanding, complex and difficult to attain by a conventional design approach. Hence, there has been an extensive role of computer-aided-design for such multilayer stack. A giant step in coating design was taken by P. Baumeister [3,4]. He introduced the merit function for estimating the closeness between designed and target spectral performance. An automatic process that involves an element of design construction is usually known as synthesis. An automatic computing/numerical process that makes adjustments to an already existing design without making major changes is known as refinement. The term optimization simply means improving performance and includes both refinement and synthesis. A good starting design is important for this. In 1982, the needle optimization technique was invented and is used in all commercial thin film softwares [1].

5. Optical thin film materials- Dielectric materials

A typical transmission characteristic of an optical thin film material is presented in Figure T.2.4. Every material, because of its structure, has a characteristic transmission spectrum that can be split into three parts: (i) the high-frequency electronic absorption region, (ii) a transparent region, and (iii) a region dominated by the low-frequency lattice vibration. The transparent region, merely the region in between the electronic absorption and the lattice vibration, and as such is particularly influenced by impurity and free-carrier absorption [5].

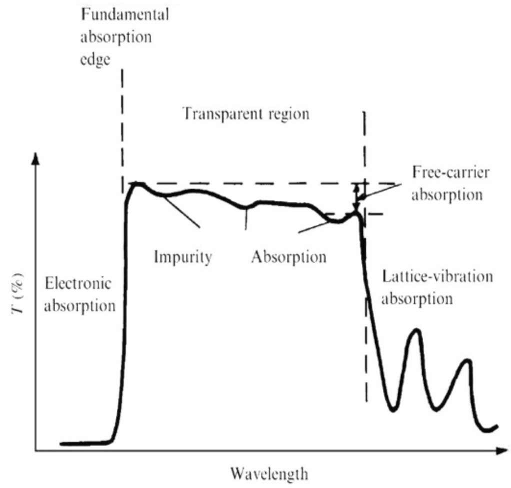


Fig. T.2.4: Wavelength dependent characteristic of a typical optical material used for interference coating [5].

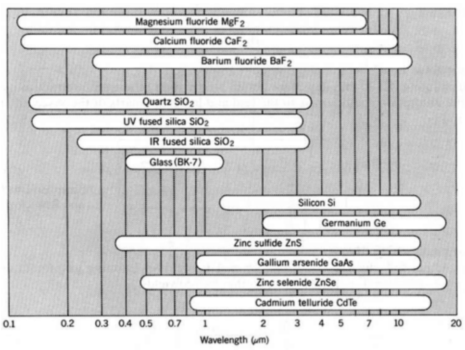


Fig. T.2.5: The spectral band in which optical substrate materials are transparent [6].

As it can be seen in Figure T.2.5, there are a very limited number of substrate materials available for optical coating applications. Out of these, a handful of materials are available for UV lasers such as excimer lasers. Refractory oxides are the most favourable materials for multilayer laser coatings and a list of popularly used coating materials is presented in Table T.2.1.

Table T.2.1: Refractory oxides for multilayer laser coatings.

Metal Oxide	Refractive index at 550 nm	Transparency range (nm)	Melting point (°C)
TiO_2	2.31	450 – 10000 nm	1850
Nb_2O_5	2.25	400 – 10000 nm	1460
Nd_2O_3	1.79 – 2.15	400 – 2000 nm	2300
HfO_2	1.93 – 1.97	250 – 10000 nm	2800
ZrO_2	2.05	270 – 7000 nm	2700
Sc_2O_3	1.85 – 1.90	220 – 10000 nm	2300
Ta_2O_5	2.05 – 2.10	400 – 10000 nm	1800
SiO_2	1.40 – 1.45	185 – 5000 nm	1710

6. The coating process

Modern thin film multilayer optical coatings are usually fabricated by physical vapour deposition techniques in a vacuum chamber. Prior to deposition, necessary substrates are polished and thoroughly cleaned by multi-frequency ultrasonic cleaning, which is followed by hot air drying [7]. The vacuum chamber is also cleaned from residues of previous deposition runs. The substrates on which the thin films are to be deposited are mounted on a flat or a hemispherical plate called calotte. Deposition chamber is evacuated to a low pressure of 10^{-7} to 10^{-8} mbar. A small amount of oxygen is added into the chamber during deposition of refractory oxide materials. The substrates may be at room temperature or they may be heated say upto 300 °C. To ensure uniformity of the deposited film thickness over the coated area, the calotte is usually rotated about a central vertical axis, and the relative geometry of the source and substrates is carefully chosen [1,2,8]. Various coating processes include: (i) Ion-assisted e-beam evaporation, (ii) Magnetron sputtering, (iii) Ion beam sputtering and so on.

6.1. Deposition by electron-beam evaporation

Traditional electron-beam (e-beam) evaporation is one of the most widely employed methods for producing thin films. Here, a coating material is heated through electron beam bombardment (for dielectrics) within a high vacuum chamber until it vaporizes. This method of evaporation is a relatively low energy process, and as a result, the dielectric films it produces are porous, of relatively low density, and exhibit a columnar structure [9]. Typically, the substrate is heated to several hundred degrees Celsius during coating to mitigate this effect, but it is by no means eliminated. The problem with these porous films is that they can subsequently absorb moisture, which changes the refractive index of the layers.

6.2. Ion Assisted e-beam deposition (IAD)

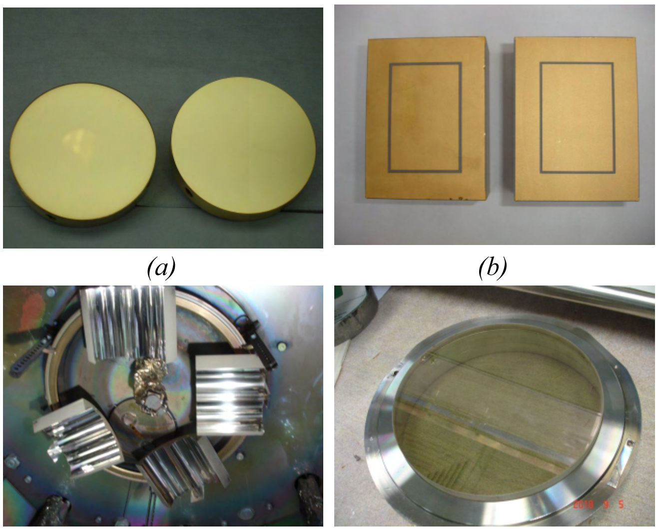
IAD is a variant of the e-beam evaporation process, which adds a high energy ion beam that is directed at the part to be coated. These ions act almost like an atomic sized hammer, producing a higher film density than evaporation alone. The ion beam can also be used to pre-clean the substrate, which can improve film adhesion. IAD results in higher coating density, improved mechanical durability, greater environmental stability and lower scatter as compared to e-beam evaporation [10]. It also enables the intrinsic stress to be modified during deposition, i.e., changing the overall film stress from tensile to compressive [11]. The deposition facility is shown in Figure T.2.6.

Fig. T.2.6: Ion-assisted e-beam deposition facility at RRCAT.

6.3 Magnetron sputtering

At present, the sputtering of metals and dielectric is carried out in the in-house developed sputtering system as shown in Figure T.2.7. The system is computer controlled. The sputtering system is established to meet many metal deposition requirements. Co-sputtering of two different targets using DC, pulsed-DC and RF plasma can be done. Film thickness monitoring can be performed with multiple quartz crystal monitors. An ion source is fitted for ion-assisted deposition. The chamber can be baked out, and elevated deposition temperatures of ~400 °C can be maintained. A provision is also made for low substrate temperature (LN_2) deposition. Flat sample rotation provides better film thickness uniformity than stationary substrate holder. Samples up to 150 mm in diameter can be coated with <5% uniformity. Many challenging coatings e.g., FEL mirrors, TMT edge sensors, mirrors for underwater reactor tube cutting, large beam splitter for sag measurement of reactor tubes, WS_2 coating on bearings for RF tuners, HR coating on large size involute reflectors have been made and are shown in Figure T.2.8.

Fig. T.2.7: Magnetron sputtering deposition system at RRCAT.



(a) (b) (c) (d)

Fig. T.2.8: (a) FEL mirrors, (b) TMT edge sensor, (c) involute reflectors, and (d) beam splitter for sag measurement of reactor tubes of KAPS reactor.

6.4. Dual ion beam sputtering

Dual ion beam sputtering (DIBS) is remarkable to deposit thin films with better compositional stoichiometry and film adhesion even for films grown at room temperature. A few other unique features of the DIBS system are high-quality growth with reduced surface roughness and increased growth uniformity on a larger substrate area, and in-situ substrate pre-cleaning before growth [12]. There are two ion sources in a DIBS system, a primary radio frequency (RF) ion source is used for sputtering of materials from a multiple target assembly. A RF secondary assist ion source had dual roles to play. Before actual film deposition, assist source was turned on for substrate pre-cleaning with Ar bombardment. During material growth, assist ion beam, composed of Ar/O_2 ions, helps in the reduction of columnar growth and thereby enhances growth uniformity and film adhesion to the substrate [12]. Moreover, the assist ion source hinders island formation and removes weak dangling bonds during the actual sputtering process [13]. Four oxide targets each of 350 mm diameter are used to grow multilayer oxide coatings. Four substrates, each of 150 mm diameter can be accommodated and are rotated at 120 rpm (max.) in a planetary configuration. The DIBS facility is shown in Figure T.2.9.

Fig. T.2.9: Dual ion beam sputtering deposition system at RRCAT.

6.5. Thickness monitoring during deposition

Precise control of film thickness (to within 1% of the desired value) and controlled film deposition rate are essential during the fabrication process. The most common method for controlling the film thickness during deposition is by the optical interference method, where a chopped beam of light is allowed to fall on a witness substrate. As the film grows on the substrate, the transmitted or reflected light intensity at a particular wavelength is monitored by the optical thickness monitor. The measured transmittance or reflectance goes through a series of maxima and minima, and extrema being reached when the optical thickness is an integral number of quarter waves of the monitoring wavelengths [14]. Alternately, the physical thickness of the film is measured by a quartz crystal monitor, where an oscillating quartz crystal is exposed to material vapour, and as the film grows on it, its oscillating frequency changes. This change in frequency is used to determine physical thickness of the deposited film.

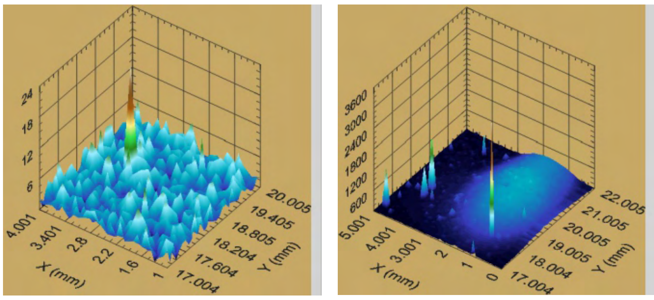
7. Damage threshold testing of multilayer coatings

Laser induced damage threshold (LIDT) of coated optical components is a critical quality parameter for laser systems operating at high power/high energy [15]. As per ISO standard procedure (ISO-11254-1), a laser beam is directed towards optics at different locations and optics is observed carefully for any damage under microscope. This LIDT test setup consists of a pulsed Nd:YAG laser, which can give up to 0.5 J per pulse with 1-10 Hz repetition rate at 1064 nm and a typical pulse width of 5-6 ns (FWHM). Damage morphology is recorded with Nomarski DIC microscope.

If damage is not found, energy/power is increased and the exercise is repeated until damage is observed by a visible spark. This is repeated for more than 100 sites, followed by plotting the probability of damage versus fluence [16]. This is a unique facility in the country.

8. Ultra low absorption coefficient measurement

The absorption coefficient is measured by photo-thermal common path interferometer (PCI) technique. The main purpose of the system is characterization of absorption for different optical elements: coatings, substrates, crystals, interfaces, etc. The setup is of a pump/probe type, based on the thermal lensing effect. Absorption is tested at the wavelength of a "pump" laser (532 nm & 1064 nm). For better sensitivity, the pump is chopped to provide periodic heating of a tested object. The probe beam (He-Ne laser) senses the heating effect of absorbed pump. Intensity change is detected by a detector, which relies on phase distortion, which in turn relies on pump beam absorption [17]. This is a unique facility in the country and caters to the requirements of high energy laser program of RRCAT and other national institutes. The lowest absorption of 1 ppm can be measured. Figure T.2.10 shows the 2D absorption map of fused silica sample before and after prolonged exposure of laser plasma.



(a) *(b)*

Fig. T.2.10: 2D absorption map of fused silica sample (a) before and (b) after prolonged exposure of laser plasma.

9. Laser resistant coatings

Development of optical components for lasers operating at very high power levels (terawatt level in pulsed systems and multi-kilowatt range in CW) at various wavelengths is a challenging task. This power handling capability of optical coatings is a major limiting factor. Today thin film laser damage research continues to focus on reducing absorption and coating defects. Telecommunication optics are being limited by laser damage issues as larger number of photons are being injected into small fibers. The need of semiconductor lithography industry for short wavelength coatings requires development of low absorbing materials in deep and extreme UV region. Mega projects like inertial confinement fusion, free electron lasers, air borne lasers have extremely high energy levels over large size optics. Short pulse lasers require coatings capable of withstanding pico-second and femto-second pulses. Coating design strategies such as standing wave electric field (SWEF) reduction technique and thick silica overcoat also improve laser resistance. SWEF reduction technique have immensely helped in using materials of different refractive index by reducing the SWEF peaks in the high index materials and also by shifting the peaks away from the interfaces. Reproducible and reliable measurements of LIDT are essential for optimization of laser components [18]. Damage in ultra short pulse region has been demonstrated to be mainly driven by direct electronic interaction of the material with intensive laser radiation involving tunneling, multi-photon and avalanche mechanisms. Films with pores, cracks, columnar microstructure, multiple crystalline phases, and lack of stoichiometry leads to intrinsic defects. On the contrary extrinsic defects occur due to foreign defect seeds created during the coating process and due to surface contaminants present on the substrate. Therefore appropriate substrate and deposition system cleaning methods must be adopted to avoid such defects [5,18].

10. Development of AR coating on end faces of Nd:YAG, Ti:Sapphire and Nd:glass laser rods

10.1. For Nd:YAG laser rod, single quarter-wave (1064 nm) MgF_2 layer perfectly serves the purpose. Such a layer was deposited on both the end faces of 5-10 mm diameter and 100-150 mm long Nd:YAG rods. End faces of damaged rods were optically polished at Optical Design and Development Lab, RRCAT and subsequently AR coating was done. Rods were held vertically and rotated during deposition at 5 rpm. MgF_2 coated Nd:YAG laser rods are shown in Figure T.2.11. Optimized deposition parameters to grow dense film with the required refractive index were used. For this, special rod holder was developed. Deposition was carried out at 125 °C under Ar ion assisted environment. AR coated rods yield 300 J pulse energy (2-40 ms, 1-100 Hz rep. rate, 10 kW peak power).

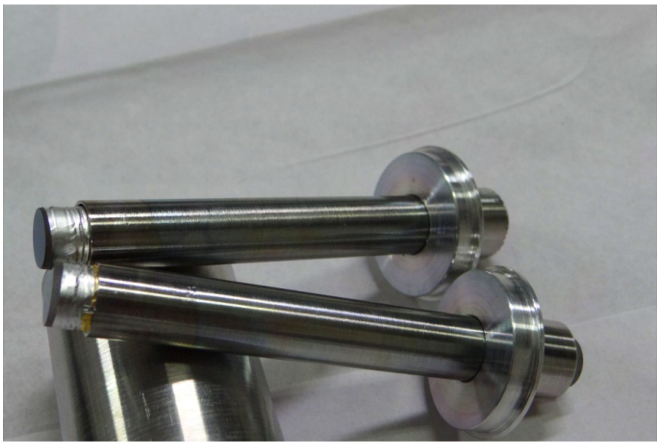


Fig. T.2.11: MgF_2 coated Nd:YAG laser rods in specialized fixtures.

AR coated rods were also tested in the amplifier cavity. Each rod was pumped up to 85 J and no lasing was observed. This shows that the quality of the coating is excellent and comparable with that of the coating, which was initially on the laser rods. Though the reflectivity of the coating was measured quantitatively on a dummy substrate and was <0.2%, it is obvious from its performance that the coating's residual reflectivity is comparable to the original coated rods. Coating did not develop any damage and delivered 1.5 J in <10 ns [19].

10.2. For complex requirement such as Ti:Sapphire laser rod, a single layer approach is insufficient, hence multilayer thin film structure is required to achieve low reflection loss both at pump (532 nm) and lasing (800 nm) wavelengths. Non-quarter-wave layers are required for achieving such high optical performances. We have optimized a four layer structure SUB/0.25H/0.35L/2.1H/1L/AIR, where H and L represents one quarter-wave HfO_2 and SiO_2 layers, respectively. SiO_2 as low index and HfO_2 as high index material are chosen due to their very low optical absorption and high laser damage threshold. This layer structure yielded a very low residual reflection loss at 532 nm and 800 nm on a dummy sapphire substrate. Finally, this 4 layer structure was deposited on both the sides of a polished Ti:Sapphire laser rod (20 mm dia., 20 mm long). Residual loss of ~1.0% is measured at 532 nm and ~ 0.9% at 800 nm as shown in Figure T.2.12. This AR coated rod is used as a four pass amplifier in a Ti:Sapphire laser (650 mJ, 0.2 ns, 10 Hz). No coating damage is observed even at maximum laser power level [20].

10.3. High energy lasers are increasingly used in study of equation of state of materials at high temperature and pressure, high density shock, implosion physics, etc. One such laser is Nd:glass. Besides, high transmittance, high laser induced damage threshold (LIDT) and durability are important for such applications [3]. Laser induced damage in optical materials remains a limiting factor in the development of high power laser systems. Large size e.g., 300 mm long, 50 mm dia. Nd:glass rods are polished and AR coated indigenously at RRCAT. Five Nd:glass rods fitted in the deposition system is shown in Figure T.2.13.

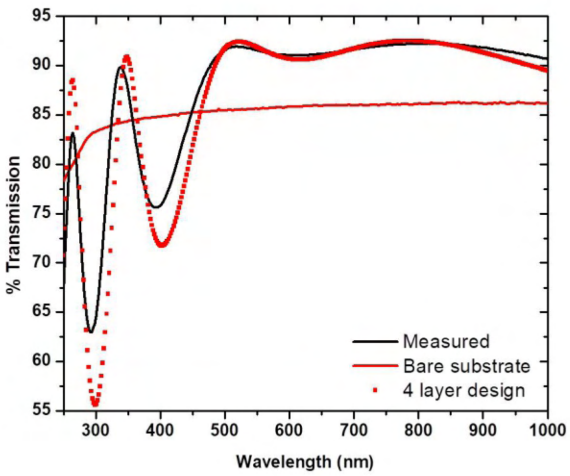


Fig. T.2.12: Transmittance of AR coated sapphire substrate.

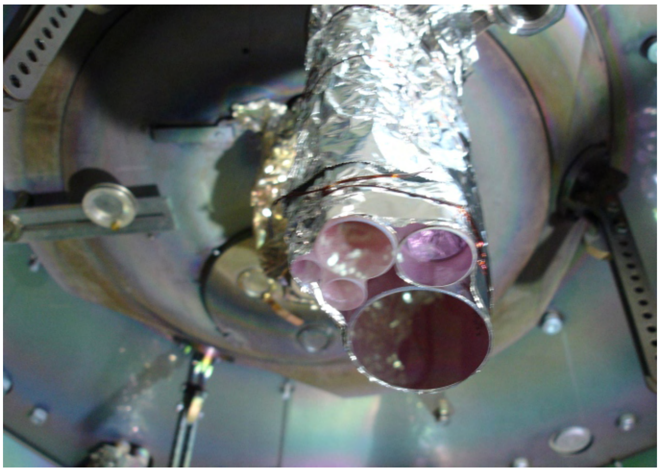


Fig. T.2.13: Five Nd:glass laser rods of different sizes fitted for coating.

We have studied two, three and four layer structures: SUB/0.5H/1.3L/AIR, SUB/2L/0.5H/1.3L/AIR and SUB/0.35H/0.3L/1.09H/1L/AIR, where H and L represent one quarter-wave HfO_2 and SiO_2 layers, respectively. The design wavelength used are 995 nm, 995 nm and 1054 nm, respectively. We have chosen HfO_2 as high-refractive index optical material with very high damage threshold. This layer structure yields a residual reflection loss nearly 0.25% per surface on a wavelength range over 165 nm, 165 nm and 325 nm, respectively. Four layer design (blue curve) is superior in its broad wavelength band. For these calculations, wavelength dispersion data of both the materials is taken into consideration. Electric field intensity profile along the depth of each multilayer is calculated and shown in Figure T.2.14. Electric field intensity profile provides insight into the laser damage phenomena. Transmission of more than 99.5% at 1054 nm is achieved. High LIDT of >21 J/cm^2 for 5.2 ns pulses is achieved in 3 layer AR coating after annealing at 450 ^{0}C for 4 hours. This is associated with 60% improvement in absorption coefficient. The large size AR coated Nd:glass laser rod delivered pulse energy of 15 J at 1.5 ns duration [21].

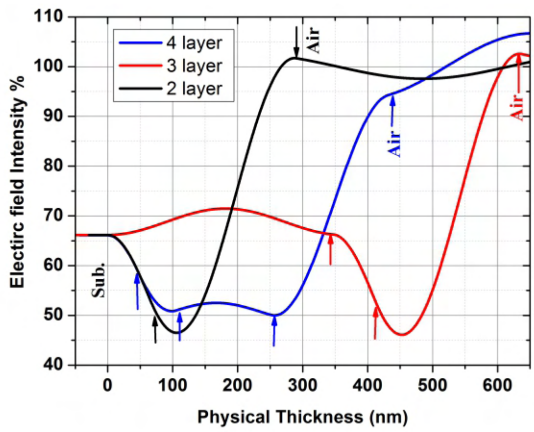


Fig. T.2.14: Calculated electric field intensity profile along depth of the multilayer for 3 different layer structures.

11. Large area AR and HR coating on super smooth fused silica optics for Nd:glass laser

Nd:glass disk laser amplifier of the high energy laser chain requires large size (150 mm) multilayer thin film coated anti-reflection and high reflectivity (HR) mirrors 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 at RRCAT.

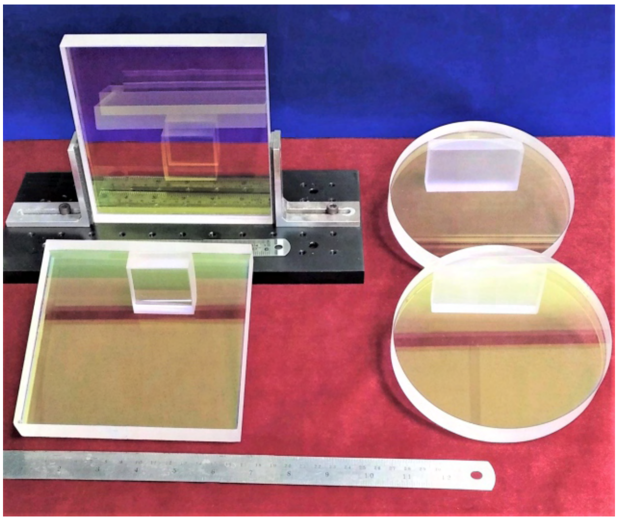


Fig. T.2.15: AR coated, 150 mm dia. & 150 x 150 mm optics.

Fused silica substrates were optically polished using bowl-feed CMP technique to generate ultra-low roughness (<5 Å) with flatness of λ/10 at 589 nm over 95% clear aperture, parallelism better than 5 arc sec and a scratch-dig of 20/40. Three layer AR coating design was optimized while using HfO_2 as high index layer.

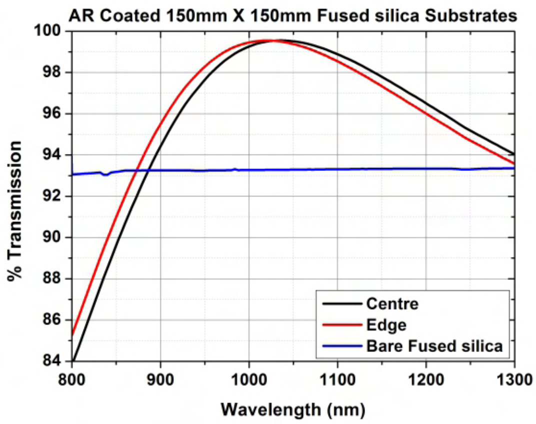


Fig. T.2.16: Transmission spectra of AR coated (red & black) and uncoated optics (blue).

Multilayer design is Sub/2L/0.46H1.26L/Air, where H & L correspond to single quarter-wave layers of HfO_2 and SiO_2, respectively.

The half-wave layer, adjacent to the substrate helps to minimize the standing wave electric field at the remaining imperfections on the substrate. AR coated optics are shown in Figure T.2.15. Transmission of 99.4% at 1054 nm, and 99.2% over wavelength band of 60 nm is achieved (Fig. T.2.16). Laser damage threshold of 13 J/cm^2 for 5.2 ns pulse at 1064 nm for un-annealed samples were recorded. Nearly 100% improvement in LIDT is noticed with respect to samples without half-wave SiO_2 layer adjacent to substrate. It is also to be noted that these substrates are having very low roughness and low scratch/dig. These two factors contributed to the improvement of LIDT [22].

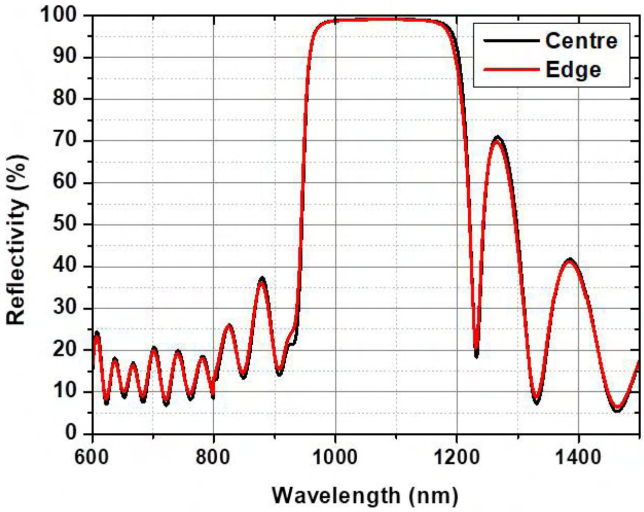


Fig. T.2.17: Reflectivity spectra of HR coated optics of size 150 x 150 mm.

The super-smooth substrates have also been coated with SiO_2/Ta_2O_5 multilayer thin-film to fabricate HR laser mirrors. 25 layers were deposited. It took 25 hrs. to grow the entire HR coating. The reflectivity of these mirrors has been measured to be 99.5% ± 0.1% over a wavelength band of 140 nm at a centre wavelength of 1054 nm, with a measured LIDT of 5.7 J/cm^2 at 5 ns as shown in Figure T.2.17 [23]. HR coated optics of sizes 150 mm x 150 mm and 90 mm x 90 mm are shown in Figure T.2.18.

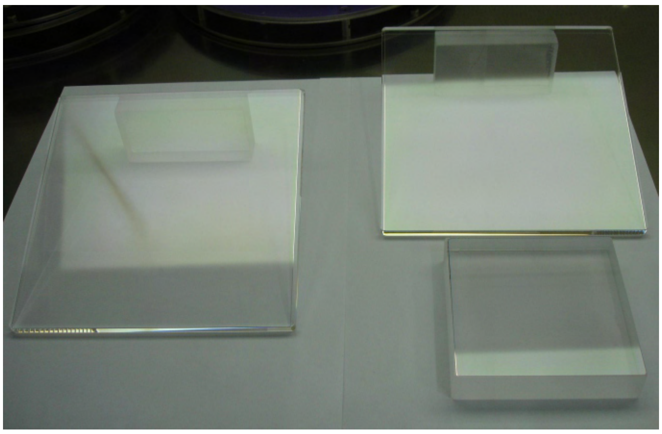


Fig. T.2.18: HR coated 150 mm x 150 mm & 90 mm x 90 mm optics.

12. Development of tunable Fabry-Perot (F-P) filter

Wavelength division multiplexer/demultiplexer (WDM/WDDM) is the key component in optical communication. Using thin film Fabry-Perot filter wavelength demultiplexing/tuning can be achieved by varying the spacer layer thickness. The spacer layer thickness was varied from 125 nm to 160 nm across a 25 mm dia. substrate. Nine channels each of FWHM = 3 nm can be placed each, 2 mm apart from the previous channel on the substrate along the direction of shutter motion. Tuning of 21 nm is achieved. Figure T.2.19. shows the transmission spectra of a 17 layer F-P filter with high refractive index spacer layer (thickness = 4*λ/4 at 465 nm plus a tapered layer varying from 0 to 33 nm) [24].

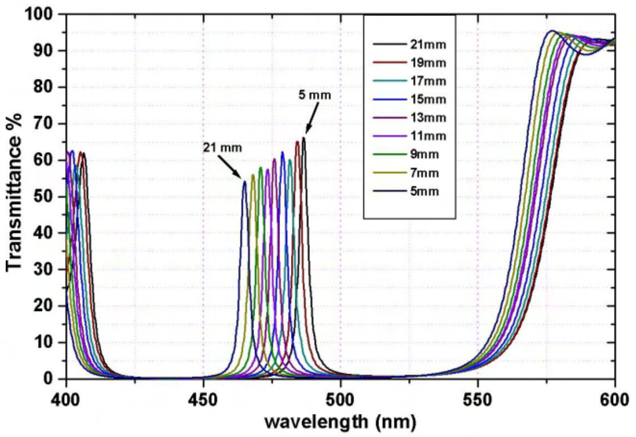


Fig. T.2.19: Transmission spectra of 17 layer F-P filter with a graded spacer thickness varying from 0 to 33 nm.

13. Recent developments in heterogeneous coatings

Any optical coating with a refractive index that depends on the spatial coordinates is considered as heterogeneous coating. Grating – waveguide structure / guided-mode resonance (GMR) filter is one such structure. A three layer GMR filter consists of top grating layer, a waveguide layer and a sub-waveguide layer coated on the substrate. The remarkable property of a grating waveguide (GWG) is that it can show a reflectivity of 100% for a given optical wavelength despite its thickness of typically less than a wavelength. This makes GWG a promising candidate for test mass coatings in gravitational wave detectors, because only a very small amount of dielectric coating material is required with a corresponding considerable reduction in coating thermal noise. Raman notch filters can also be made using such structures [25].

Meta-materials: The development of electromagnetic, artificial-lattice structured materials (photonic crystals), termed meta-materials, has led to the realization of phenomena that cannot be obtained with natural materials. The meta-material coating consists of a mesh and an electric split-ring resonator array separated by a dielectric spacer layer (~10 µm). Structured meta-materials can achieve negative refraction using nano-fabricated materials in terahertz region [26].

14. Conclusion

Specialized optical coating and characterisation facilities developed at OCL, RRCAT to meet the demands of the laser programmes at RRCAT and other institutions have been discussed. To the best of our knowledge, high damage threshold coatings, on large area optics and laser rods are being done only at RRCAT in India. State of the art characterization facilities e.g., laser damage threshold testing and ultra-low absorption measurement facilities, which are unique in the country have been established. Multilayer antireflection coatings have been designed and optimized for achieving very low reflection loss for high energy Nd:glass laser on large area super-smooth optics (150 mm x 150 mm). 99.4% transmission and LIDT of 13 J/cm^2 for AR coated optics are achieved. Such coated optical components are deployed in high energy Nd:glass laser being developed at RRCAT. 25 layer high reflection coatings have been designed and optimized for achieving very high reflectivity for Nd:glass laser. 99.5% reflectivity and 5.7 J/cm^2 LIDT have been regularly obtained for HR optics. Large size (300 mm long & 50 mm dia.) Nd:glass rods are AR coated indigenously at RRCAT. Transmission > 99.5% at 1054 nm is achieved. High LIDT of > 21 J/cm^2 at 5.2 ns is also achieved. Apart from meeting the needs of the various laboratories at RRCAT, OCL has also supported and fulfilled specialized optical coating requirements of BARC, VSSC, IIT Indore, India Security Press, Nasik, etc. and also collaborated with LEOS, VSSC, ISRO, etc. In future, it is planned to upgrade the optical coating facilities by including plasma-enhanced chemical vapour deposition (PECVD) based coating on KDP crystals, dip coating facility and develop synchrotron mirrors (500 mm x 50 mm) on super-smooth cylindrical and toroidal fused silica optics.

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