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Technology
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focus

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Optics Technology

From the Desk of Guest Editor

Dr. S.S. Negi
OS & Director

Vision is our most important sense. We perceive upto 80 per cent of all impressions by means of our sight. In a battlefield scenario, reconnaissance alone can make a defining statement. During warfare, the night and low light vision provide a great leverage over enemy. Night vision devices, both image intensifier tube based and thermal imagers are true force multipliers as they allow weapons and equipments to be used during day and night in fair and bad weather conditions. With sufficient exploitations of these devices on ground, focus is towards the militarisation of space by deploying multi/hyper spectral imagers for better target discrimination. Instruments Research and Development Establishment (IRDE), a premier establishment of DRDO is engaged in the research, design, development and technology transfer of these key technologies. Working in the field of electro-optics instrumentation, IRDE is able to provide complete solution related to electro-optical surveillance and fire control systems, from design to product realisation. Over the years, IRDE has designed and developed state-of-the-art products such as Integrated Multi-function Sight, Light Weight Portable Laser Target Designator, Holographic Sight, Stabilised Electro-optical Payload Surveillance System with continuous development of Thermal Imagers, Laser Range Finders and Target Designators and Fire Control Systems. IRDE has worked towards the indigenisation of such products and has taken a big leap towards self-reliance in this field.

The heart of any optical or electro-optical sensor consists of precisely made and meticulously assembled optical components in the form of an optical system. IRDE has created a state-of-the-art infrastructure for fabrication and testing of these optical components and developed various process and methods for realisation of such optical components. Under the domain of Optics Technology, IRDE had developed an expertise related to fabrication, testing and assembly of optical systems required for visible, infrared and laser based applications. This issue of *Technology Focus* is dedicated to Optics Technology.

As a Guest Editor, I convey my sincere thanks to DG (ECS) for encouraging me to take up this task. I am thankful to the editorial team of *Technology Focus* for devoting the issue to Optics Technology and inviting me as a Guest Editor. I hope this issue of *Technology Focus* will provide a good overview on this subject.

Optics Technology

Instruments Research and Development Establishment (IRDE), one of the constituent establishment of Defence Research and Development Organisation (DRDO) is devoted to research, design, development, and technology transfer in the field of sophisticated optical and electro-optical instrumentation. IRDE has designed and produced a large number of products to meet various system requirements of vital interest to the Defence Services. IRDE has in-house capability for the design, fabrication, assembly and testing of optical systems for visible as well as infrared region of spectrum. Precision optical components in diverse materials like glass, silicon, germanium, ZnS, ZnSe and various shapes and sizes are realised using state-of-the-art fabrication and testing facilities and decades of experience.

The role of optical design is to conceptualise diffraction limited optical system. Optics technology is the branch of precision manufacturing which brings such an optical design in to realisation. Under the domain of optics technology, precision optical components are fabricated from optical materials. These components are tested for their specifications and then assembled according to the design. The final system is then evaluated for its designed performance. The field of optics technology poses very challenging fabrication and testing problems as angular tolerances of few seconds of an arc and figure tolerances of a fraction of wavelength of light has to be met. This is achieved by combining mechanical, optical and instrumentation engineering with the skilled craftsmanship. Optics technology has been highlighted in this issue of *Technology Focus*.

Optical Fabrication at IRDE

IRDE is a premier lab of DRDO with a vision to achieve excellence in the fields of optics and electro-optics instrumentation. State-of-the-art night vision devices, thermal imagers, laser based instruments and electro-optic surveillance systems are being continuously developed at IRDE. The eye of any optical system is the precisely made optical components. To fulfil the requirements of the critical optical components, IRDE has developed an expertise in the field of optics fabrication and testing. IRDE has decades of experience in conventional optics fabrication techniques. This experience is now coupled with modern computer controlled CNC machines. Using these techniques, flat, spherical and aspheric optics in various geometries and in diverse materials are being realised. The optics fabrication and testing centre at IRDE has readily available solution for fabrication and testing of flat, spherical and aspheric optics up to 300 mm diameter using computer controlled grinding and polishing machines, automated interferometers and profilometer. The infrastructure facilities are being upgraded and very soon centre will increase its fabrication facilities upto 1200 mm diameter optics.At IRDE, both conventional and modern fabrication techniques are used to fabricate critical optics.

Conventional Optics Fabrication

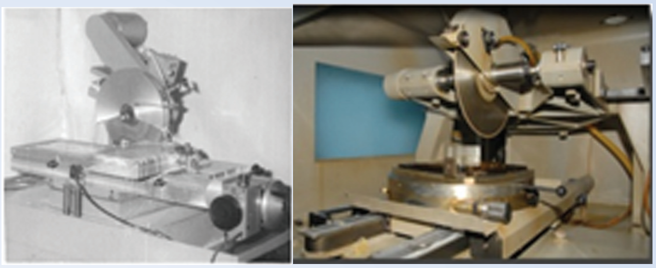
Conventional optics fabrication techniques rely heavily on the skills of optical technician. These fabrication techniques require a high level of expertise that takes years to develop. In this technique, surfaces are generated on machines and then smoothing is done on cast iron tools. For polishing, pitch polishers with metal oxide polishing compounds are used. The use of pitch polishers gives very smooth surfaces and surface roughness of the order of 1 nm is routinely achieved. Using optical contacting techniques, angles are made with in ± 5" accuracy. This fabrication method is most suitable for spherical and flat optics. Ultra precise prisms such as TIR prisms, roof prisms, Z-prisms, etc. where angular tolerances are of the order of few arc seconds are required, are fabricated only by this method.

Conventional optics fabrication is a typical optics fabrication process starts with selection of glass. The glass is generally provided in forms of raw blanks.

These blocks are inspected for inclusions, straie, etc. Refractive index and Abbe value of glass are also measured using Abbe refractometer.

Slicing

After inspection, blanks for the optics are sliced, typically within a few millimeters of final dimensions. This operation can be performed on a NC sawing machine or using a hand saw equipped with diamond impregnated disk tools.



Manual and NC Slicing Machine

Trepanning/Shaping

In this process a circular disc is obtained from a glass blank. Alternatively, other shapes can also be generated by slicing or by means of an edging machine.

Trepanning Machine and Tools

Generating

In this process, optics is grinded with diamond impregnated tools. This process quickly brings the glass disk in to near final specification of thickness, radius of curvature, etc. leaving allowances for further process of polishing and centering.

This process leaves very fine tool marks and damaged layer of glass on the surface of optics. The process is performed on a curve generator machine or CNC optical grinder. Radius of curvature within 0.5 per cent of the specified value is maintained in this process.

Curve Generation Machine and Diamond Tools

Smoothing

This process is used to remove any tool marks generated on the optics and to remove the sub surface damage caused during the generating process. In this process the optics is rubbed against a matching cast iron tools with aqueous slurry of optical emery.

The particles of emery causes tiny fractures in the glass, which results in material removal as the fractures intersect. The smoothing is done by successively reducing the particle size of the optical emery. An inventory of more than 500 hundred tools is maintained at IRDE for this process.

Grinding/Smoothing Machine and Smoothing of a Block

Polishing

In this step, optical surfaces are polished to provide specular surface accurate to within 0.1 μm to the designed surface. With repeated polishing cycles guided by measurement feedback, surfaces can be attained with 0.005 μm accuracy. For flat and spherical surfaces, conventional pitch polishing is used. The chemo-mechanical nature of pitch polishing reduces the micro roughness of glass and very smooth surface is obtained.

Pitch polishing is a chemo-mechanical process where chemical and mechanical interaction takes place between pitch, polishing compound and optical material. Due to wide difference in the properties of optical materials different polishing compounds are used according to the material. Similarly the composition of pitch is changed to meet the lap compliance.

IRDE has developed polishing recipes for most of the optical glasses, fused silica, quartz, Zerodur, stainless steel and IR materials like silicon, germanium, zinc selenide, zinc sulphide.

Polishing Machine and a Polisher Block

The surface figure and surface finish are the two most challenging specifications to meet in the fabrication process. A number of testing methods have been developed for measurement of these two parameters. At IRDE, the surface figure is maintained at workshop level using Newton interferometer and test plates while final testing is done with laser interferometer. The surface roughness is measured using white light interferometer. Using computer-controlled phase-shifting interferometry, surface figures can be measured upto λ/10 (λ=633 nm) and surface finish upto 0.5 nm.

Centering and Edging

The centering and edging process is used to align the optical axis of the lens with its mechanical axis. The optic is aligned on a spindle and the diameter is edged to the final specification. Both optical and mechanical centring options are available at IRDE. Typical centering accuracies of 30" sec is achieved. With the help of CNC edging machine, circular, rectangular and even freeform geometries can be edged.

Manual and CNC Centering and Edging Machine

Cementing

Cementing is used to form doublet lenses to control chromatic aberration in optical system. Many times prisms need to be cemented to form complex prisms. UV curable cement is mostly used for cementing of lenses.

Using PC controlled cementing station an in-situ measurement of centering error is made after which both the lenses are aligned to meet centering requirement and then cemented with UV curable cement.

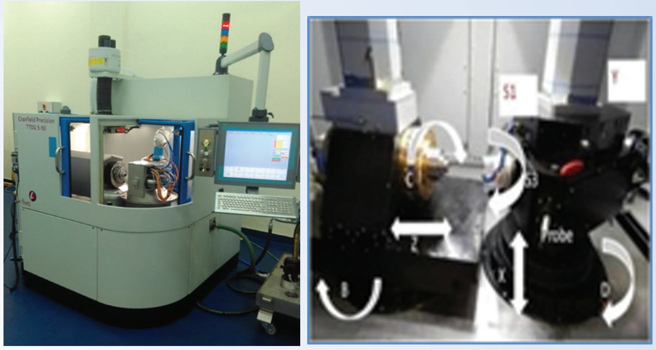
Modern Optics Fabrication

Conventional optics fabrication technique is very useful for fabrication of flat and spherical optics. Using suitable blocking schemes, batches of optical components can be rapidly produced in a cost-effective way. But this fabrication technique is of very little use for aspheric surfaces. Aspheric lenses are being increasingly used to realise high performance optical systems. Aspherical surfaces are used in optical design to control aberrations, to reduce weight, to make optical systems more compact. Fewer elements are needed, making systems smaller, lighter and shorter. With ever increasing constraints on size and weight of optical systems, aspherical surfaces are becoming a common place in optical systems. Manufacturing of precision aspheric surfaces poses significant challenge as limited recourses are available to grind, polish and test aspheric surfaces.

IRDE has been developing robust processes to manufacture and test critical aspheric surfaces. This is being achieved by using industry standard grinding, polishing machines, profilometer, and interferometer and by developing application specific solutions such as stitching interferometery based on Shack Hartman sensors and computer generated holograms.

Aspheric Surface Generation

At IRDE Twin Turret Optical Grinders (TTOG) are being used for aspheric surface generation. These are 5 axes optical grinders based on deterministic micro grinding utilising latest advances in axis positioning. These grinders uses two vertical rotary axes and one in-feed axis to produce relative motion (position and angle) between two points in space over a swept area. Due to reduced thermal and stiffness loops, resulting in a highly stiff, thermally insensitive machine tool very smooth optical surfaces are generated. In-situ measurement probe is used for alignment of optics and to provide measurement feedback for corrective grinding. Aspheric surfaces upto 350 mm diameter can be generated on these machines with form error < 2 µm and surface roughness < 200 nm.

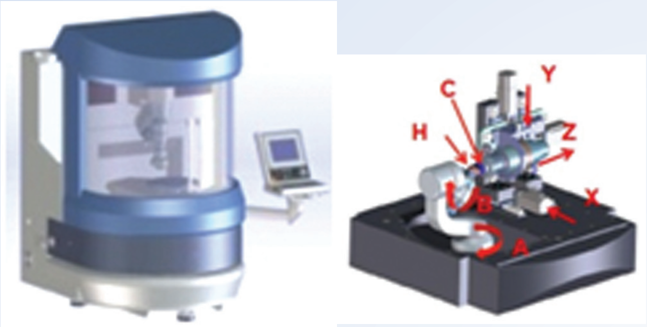


5 Axes Twin Turret Optical Grinder

Aspheric Surface Polishing

In conventional techniques, flat and spherical surfaces are polished mostly by full aperture polishers made of pitch or polyurethane pads. No such approach is possible for aspheric surfaces as polisher needs to conform to the changing local curvature of aspheric surface. For such aspheric and freeform surfaces, sub-aperture polishing is a very attractive option as it forms a small polishing spot over the surface of the optics and the path of this spot in multi-axis configuration is precisely controlled by the computer.

At IRDE, sub-aperture polishing based on Intelligent Robotic Polishing (IRP) machines has been established. IRP 50 and IRP 400 are 7 axes CNC polishing machines in which a flexible membrane tool (Bonnet) is used for polishing. This bonnet forms a sub-aperture tool for polishing process. The footprint of this tool on the optics is known as spot, which can be altered by changing the tool offset. The footprint of the spot in terms of material removed is known as influence function and is used for generating dwell time tool path map based on form error. Measurement feedback obtained from various measuring instruments is used for the corrective polishing. This polishing process follows a deterministic approach and with correct set of parameters accuracies of the order of λ/4 (λ=633 nm) are achieved without much complexity.



Intelligent Robotic Polishing (IRP Machine)

Measurement of Aspheric Surface

Accurate measurement of aspheric surface is crucial to facilitate the fabrication process. Both aspheric grinding and polishing require measurement feedback to correct aspheric form to the desired specification. Contact profilometer (Marsurf LD 260 Aspheric) is used to test grinded as well as polished optics. Aspheric interferometer (Zygo Verifire Asphere) based on axial stitching of aspheric null zones is used to test polished optics.

Aspheric Interferometer

IRDE has also developed aspheric testing methodology based on stitching interferometry on a Shack Hartman wavefront sensor platform. Customised test set-ups based on computer generated hologram are also used for testing of aspheric optics. IRDE has developed the method for designing computer generated holograms.

Fabrication of Infrared Optics

The response of human visual system is restricted to visible region of spectrum only. With continuous development of IR detector technology, the imaging capability is extended to IR region of spectrum. All objects above absolute zero temperature emit IR radiation. In thermal imagers, this radiation is focussed by IR transmitting optical components over a IR detector to form images. After read-out from sensor element and video processing these images are displayed on a display unit. IRDE has developed a number of IR optical systems working in both Long Wave IR (LWIR) between 8-14 μm and Mid Wave Infrared (MWIR) between 3-5 μm region of spectrum.

These IR optical systems require optical components made of IR transmitting materials like silicon, germanium, zinc selenide, zinc sulphide, etc. The grinding and polishing of IR materials is similar to the glass optics, but there are remarkable differences too. These differences arise due to their different mechanical, chemical and thermal properties. IRDE has successfully established methods for fabrication of IR optics.

The methods of grinding IR components and various polishing recipes for different IR materials have been developed over the years. Flat, spherical and aspheric optics in most of the IR transmitting materials are being fabricated using these methods.

Optical Testing

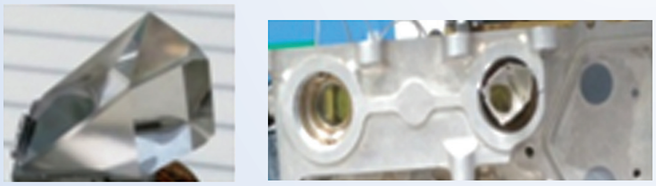
IRDE has extensive test facility to test optics during the various stages of fabrication and final acceptance of optical systems. Optical testing starts with testing of glass blank for its refractive index and Abbe value. Test facilities like focometer for measurement of focal length (EFL, BFL) and eccentricity, computerised goniometer for measurement of angle, through angle, image shift, pyramidal error of prisms and wedge angle of flats are available. Surface accuracy and radius of curvature are measured using phase shift laser interferometer. Linear dimensions of graticule are measured using zoomatic microscope.

Modulation Transfer Function (MTF) test facility for measurement of chromatic-aberration, astigmatism, field curvature, EFL, BFL and MTF are also available. For transmission measurement integrating sphere is used. Assembly of optical systems can be done on PC controlled test station.

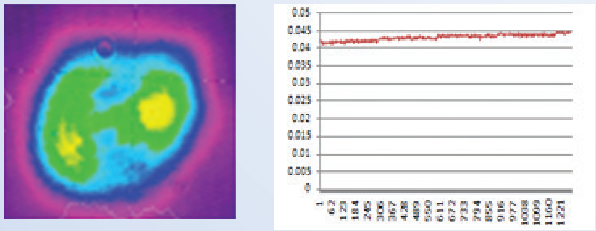
Technology Development in the Field of Optics Fabrication and Testing

Development of Z Phase Prism for High-Power Nd:YAG Laser Cavity

IRDE has designed and developed various types of laser designator for designating targets in the battlefield scenario. Laser transmitters of these designators use simple TIR prism reflectors that present certain problems due to the phase changes on total internal reflection. An innovative fabrication and metrology process was developed to realise a special kind of roof prism called Z-prisms. This prism is used in polarisation based laser resonator cavity to improve performance. It minimises de-polarisation loses, compensates for thermal birefringes, gives stable energy output without compensation current.



Z-prism and Laser Resonator Cavity Lenses



Beam Profile and Performance of Laser Resonator Cavity

Development of Freeform Optics

Freeform surfaces are non-rotationally symmetric surfaces having advantages over rotationally symmetric surfaces in imaging and non-imaging applications. The use of freeform surfaces in the optical system provides more degrees of freedom to the optical designer for better control of aberrations and allows one to develop compact and light-weight systems.

A freeform saddle surface was grinded using TTOG and subsequently polished using sub-aperture polishing.

For metrology, a new method based on sub-aperture stitching for measurement of freeform wave front was developed and experimentally validated using in-house developed stitching software and implemented on scanning Shack Hartman sensor. Using this measurement scheme, corrective polishing is done.

Grinding of Freeform Surface and Measurement

Development of Freeform Optics

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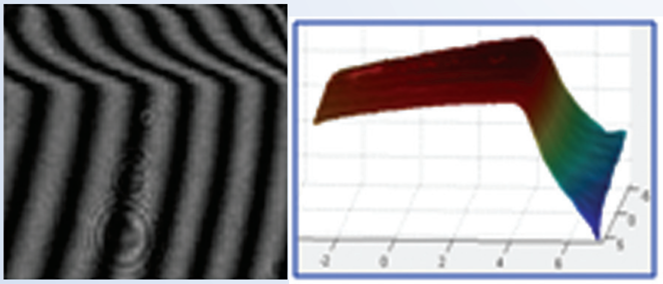
Fabrication of Thin Windows

Optical windows are often required to shield the optical system from harmful effects of environment. The thickness of these windows is kept minimum to make optical system lighter and compact. But higher aspect ratio (diameter:thickness) makes it prone to deteriorate under de-blocking stress during polishing. To avoid this, such windows are now polished using blocking interferometric analysis. In this scheme, pitch buttons are used for blocking. Layout of the pitch button is optimised according to size of the window. Using this technique, aspect ratio upto 20:1 has been polished.

Pitch Button Blocking and a Polished Si Window

Development of Wedge Plate for Evanescent Wave Capturing

A wedge plate is required to combine two counter rotating beams by capturing evanescent waves. The required wedge angle was 42 sec (± 5"). A polishing method was developed to fabricate such a wedge plate. Polishing parameters are optimised to obtain a wedge angle of 42 sec.



Interferogram of Wedge Plate and Surface Profile of Wedge

Development of Annular Obscured Aspheres

Computer controlled sub-aperture polishing is used for the polishing of aspheres from a grinded aspherical surface. A grinded spherical surface generally has a form error less than 1 μm. With such a grinded part aspherical surface can be polished easily in a short duration. It is sometimes desirable to polish aspherical surface from the best fit spherical surface. A sub-aperture polishing process has been developed to polish annular aspheric surfaces and IR aspherics within the accuracy of wavelength order.

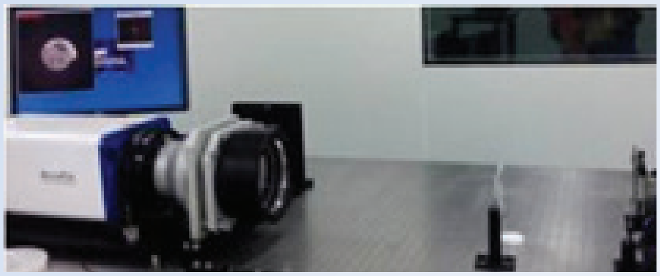
Polished Annualar Obscured Aspheric Mirror

Computer Generated Hologram for Aspheric Testing

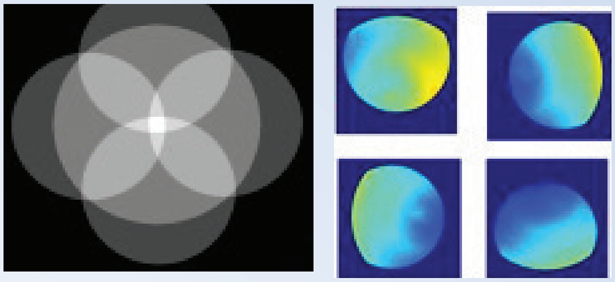
Computer Generated Holograms (CGHs) are used for testing an aspheric surface. IRDE has established the method to test aspheric surfaces using CGH. A software package was developed to design the CGHs. Using this software, a binary CGH is designed for a known aspheric surface. This CGH can be fabricated using in-house fabrication facility. The CGH is then used to test aspheric surface in an interferometric set-up.

Measurement of Large Optics Using Sub-aperture Stitching

The measurement capability of the interferometer is limited by the size of the reference sphere. In most of the cases it is not possible to test optics with diameter greater than 150 mm. For such optics IRDE has developed sub-aperture stitching process for surface profile measurement. The stitching software has been developed and stitching process has been validated. Stitching error has been limited to 0.002 λ.



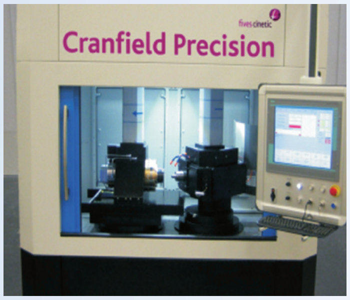
Test Set-up for Aspheric Testing



Sub-aperture Zones and their Measurement

Infrastructure Facilities for Optics Fabrication and Testing

Twin Turret Optical Grinders



Twin Turret Optical Grinders (TTOG 100 and TTOG 400) are capable of generating spherical, aspheric, cylindrical surface in glass as well as IR materials. These are 5 axes CNC optical grinders. With these two grinders various operations such as curve generation, scooping, trepanning can be performed upto 350 mm diameter.

Computer Controlled Polishing Machine

Intelligent robotic polishers (IRP 50 and IRP 400) are 7 axes CNC polishing machines. Plano, spherical, aspheric, cylindrical and freeform surfaces can be polished using these machines. With these two machines a diameter range from 10-350 mm is covered. Form accuracies better than 75 nm and surface roughness less than 5 nm can be easily maintained.

Contact Profilometer

A contact profilometer Marsurf LD 260 aspheric is used to measure surface profile of optics. Both 2D and 3D surface profiles of spherical, aspheric and asphero diffractive surfaces can be measured. This system is mostly used to provide measurement feedback to optical grinder and polisher.

CNC Centering and Edging Machine

6 axes CNC centering and edging machine is used to align optical axis of lens with its mechanical axis and for edging of lens. The machine has provision for automatic centering, manual centering and optical centering. Centering accuracies of less than 30 arc sec are easily achieved and optical component can be edged in circular, rectangular or even freeform shapes.

Contact Profilometer

CNC Centering and Edging Machine

Curve Generator Machine

A manual optical grinder from M/s Adcock & Sheply, UK is used for curve generation process. Plano and spherical surfaces can be produced by this curve generator. Radius of curvature can be generated on glass blanks of diameter 30-300 mm range.

Slicing Machines

A table top slicing machine and an NC slicing machine is used to cut thick glass blank in to desired shape and size.With an NC slicing machine glass upto 2 mm thickness can be sliced.

Curve Generator Machine

Slicing Machine

Loose Abrasive Grinding and Smoothing Machine

These machines are used to remove tool marks created during the curve generation process and for fine grinding. Grinding is done by cast iron tools. Optical emeries of various grades are used as an abrasive.

Conventional Infrared Polishing Machine

These are re-circulating slurry based overarm polishing machines with pneumatic pressure control. Pitch polisher with aqueous slurry of aluminium oxide is used for polishing of infrared materials such as silicon, germanium, zinc sulphide, etc.

Loose Abrasive Grinding and Soothing Machine

Conventional Infrared Materials Polishing Machine

Abbe Refractometer

Abbe Refractometer

This refractometer is used for measurement of refractive index and abbe value of optical glasses. Refractive index from 1.4 to 1.7 can be measured using this refractometer. For high index glasses, IRDE has developed a method for measurement of refractive index.

Focometer

Focometer is used for the measurement of EFL, BFL and eccentricity of lenses. Focal lengths can be measured with an accuracy of ± 0.1 mm. IRDE has also developed method for measurement of focal lengths shorter or longer the above mentioned range.

Zoomatic Microscope

Zoomatic microscope is used for measurement of linear dimensions of reticule patterns with 1 μm accuracy. Objectives of 30X-160X are used in this microscope.

Computerised Goniometer

A computerised goniometer is used for measurement of angles with an accuracy of ±1 arc sec. Individual angles, through angle, image shift and pyramidal error for different types of prisms and wedge plates can be measured using this goniometer.

MTF Measurement System

MTF system is used to evaluate the performance of optical system in visible region of spectrum.

Centeration Measurement and Assembly

PC controlled test station is used for measurement of centering error in reflection mode, decentre investigation of multi-lens systems, alignment of optics inside housing, cementing of doublets, assembly of optics.

Integrating Sphere Based Transmission/ Reflection Measurement System

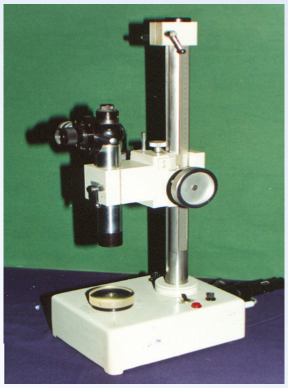
Transmission measurement system is used for measurement of transmission or reflection in visible and SWIR region of spectrum. Transmission or reflection can be measured at wavelengths from 450 nm to 1550 nm.

Phase Shift Laser Interferometer

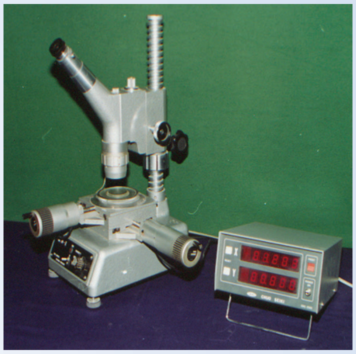
Phase shift laser interferometer in Fizeau configuration is used to measure radius of curvature of lenses with 1 μm accuracy and surface accuracy upto $\lambda/10$. (λ=632.8 nm)

Aspheric Interferometer

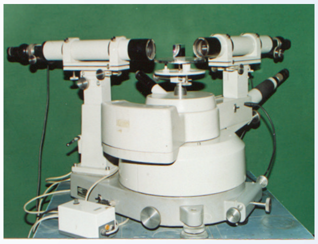
An aspheric interferometer based on axial stitching of annular null zones is used for the surface profile measurement of aspheric surfaces. Aspheric surfaces upto 130 mm diameter can be measured with accuracy $\lambda/10$ (λ=632.8 nm).



Focometer



Zoomatic Microscope



Computerised Goniometer

MTF Measurement System

Centeration Measurement and Assembly

Upcoming Facilities

IRDE has established the facility for fabrication of Optical components upto 300 mm diameter in glass as well as IR materials and fulfilling the critical optics requirement for various projects and R&D activities of its own and other DRDO laboratories.

To fulfill the future requirements of DRDO, IRDE is creating infrastructure for optics upto 1200 mm diameter. This infrastructure facility is expected to be functional by January 2017.

With this facility, mirrors upto 1200 mm diameter can be grinded and polished. The facility consists of a large optics grinder and a large optics polisher with in-situ metrology. The in-situ metrology eliminates the requirement of moving mirror to a separate test station and reduces the cycle time. The in-situ metrology has provision for both surface profile and surface texture measurement. Surface profile can be measured using Swing Arm Profilometer or an interferometer. In swing arm profilometer, a probe scans the profile of mirror along an arc, several such profiles can be stitched to get a 3D surface map of the mirror being polished. This error map is then used for corrective polishing of the mirror. In the final stages of polishing, a non-contact method is preferred. For such methods, provision of an integrated test tower has been made. This test tower is utilised for the interferometric measurement of the mirror surface.

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