Manx Precision Optics

Catalogue.

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About Us

Overview

Established in 2013, Manx Precision Optics Ltd. (MPO) is a family-owned company manufacturing a wide range of precision optics. Our optical components for Ultra-fast and high power lasers are used by many leading companies and research facilities throughout the world.

Manx Precision Optics **employs an** experienced workforce with all senior employees having over 20 years experience in precision optics manufacture.

Since 2013 we have grown significantly and expanded our workforce and workspace year on year. Furthermore our commitment to long-term sustainable growth has seen us invest significantly in equipment, including our brand new Lapmaster pitch polishing machine delivered in November 2019 and a 1.35m IAD-coating chamber in 2018.

Moving forward Manx Precision Optics looks to have a new physics lab installed by the end of 2020, increasing our metrolgy capacity as well as adding further research and development capabilities

Craftsmanship, Quality , Service

Our state of the art production facility is based in an Isle of Man Government owned high-tech industrial park and comprises over 9500ft² in manufacturing space in close proximity to the Isle of Man Airport.

To ensure full traceability and the highest quality standards Manx Precision Optics' manufacturing processes are all ISO 9001:2015 certified.

Within our facility we control all aspects of the manufacturing process from shaping, grinding and polishing to optical coating (e-beam, IAD and sputter) and assembly. This means we can guarantee the quality of the materials craftsmanship throughout the manufacturing process allowing us full traceability of every optic we make.

We work with our customers to identify cost drivers at the very early stages of development and find the best, tailor-made solutions for their applications. Our large stock enables us to manufacture prototypes within a short time-frame.

As a leading manufacturer of optical components for high laser-induced damage threshold and ultra-short pulse laser applications we constantly expand our product range to offer our customers the latest, state-of-the-art components.

Full Manufacturing Capabilities

Our 9500ft^2 + manufacturing facility is fully equipped for all stages of the optical manufacturing process. From raw material through to substrate and final coated optic our control of the entire optical manufacturing process makes us the perfect one stop shop.

Process

Once an order is placed for either one of our catalogue or custom made optics we can manufacture it from scratch.

From initial substrate shaping and grinding, through to polishing and coating, our state of the art facility based on the Isle of Man is capable of manufacturing a significant number of optics.

Why is this important?

Having the ability to manufacture optics from scratch allows us to better control the quality of our products. By having the full ISO9001:2015 certified manufacturing process in house, we can be certain that no unwanted variations to our processes affect the quality of our optics.

Our full manufacturing capabilities mean that we act as a **one stop shop** so our customers can order a fully specified and warranted product from a single source. Should any issues arise during the optical fabriaction process, having one manufacturing source allows issues to be discussed and resolved through a single point of contact.

Furthermore, our manufacturing capabilities allows us greater understanding of the optics we produce. We can see first hand how different raw materials work with different coatings and polishing processes, allowing us to make better recommendations and give more comprehensive advice to our customers. Combine this with our competitive pricing and world leading quality, Manx Precision Optics makes an ideal partner for any optical requirements.

Research And Development

Since our founding in 2013 Manx Precision Optics has fostered a positive attitude towards research and development. With an eager willingness to take on challenges we have been finding innovative solutions for our customers across the world.

As science progresses towards developing more advanced high power laser systems, the need for high performance, high Laser Induced Damage Threshold (LIDT) components becomes increasingly apparent. Recognising this, MPO are constantly pushing the boundaries of optical coating performance and Laser Induced Damage Threshold (LIDT).

As part of our ultrafast component range, we have developed a line of broadband low dispersion mirrors – TTMH, TTW, TTB and TTS to have a suitable solutions for all our customers' applications. Boasting wide bandwidths in S and P polarisations, low (down to ±50fs2 Group Delay Dispersion (GDD) and a high LIDT we have the ideal solution for all your ultrafast optical needs!

Another area in which we strive to improve upon is surface flatness and finish quality. Our methods and experienced team are capable of achieving surface roughness down to around 2 Angstroms or two atomic widths, and we have plans to achieve even lower surface roughness in the future.

Our developments are supplemented and enabled by our investments into new equipment, such as our acquisition of a 1.35m coating chamber with Electron Beam and Ion Assisted Deposition technology in 2018, or our more recent 2019 installation of a brand new 72" Lapmaster pitch polisher capable of polishing optical components up to 500mm in diameter.

We work with a range of international partners whose state-of-the-art metrology allows us to accurately test our developments in LIDT and surface flatness. We deeply value the **valuable** insight working in tandem with our customers and partners alike brings to product development.

Our History

2013

Helmut and Jeanette Kessler found Manx Precision Optics on February 11th with production starting in October 2013.

2014

First major expansion of the work-force in February with MPO's second coating chamber a rriving in April.

2015

Acquisition of third coating chamber to increase capacity.

2017

Floorspace expanded to include additional unit to accommodate increased production levels.

2018

Acquisition of fourth coating chamber - a 1.35m chamber with E-beam and IAD capability.

Installation of new metrology to enable manufacture of spherical optics up to 205mm diameter.

Expansion of range to include l arge spherical optics. An additional mezza-nine floor is installed in unit 12a

2019

Acquisition of fourth coating chamber - a 1.35m chamber with E-beam and IAD capability.

Installation of new metrology to enable manufacture of spherical optics up to 205mm diameter.

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2020

Launch of the new MPO website

Technical Guide

Technical Fundamentals

Light as a Wave

Light is a type of radiation consisting of vibrating electric and magnetic fields moving through space, much like how a sound wave is just a vibration travelling through the air. Electric and magnetic fields oscillate perpendicular to each other and to the direction of motion as depicted in figure 1.

Owing to its wave-like behaviour, light can be characterised by a number known as it's wavelength which is just the physical length of a single cycle of oscillation. The different colours we perceive correspond to different wavelengths of light, however visible light only makes up a small part of what is known as the electromagnetic spectrum which is typically divided into gamma rays, x-rays, UV, visible light, infrared, microwaves and radiowaves. White light is simply all the different wavelengths of visible light travelling together. A light wave consisting of a single wavelength is known as "Monochromatic".

A property of waves critical to optics is the phenomena known as "interference". When two or more waves exist in the same area of space, they will combine with each other and produce a wave with modified properties. A simple example is two waves of the same wavelength and amplitude interfering constructively and destructively. When the waves are in phase, their peaks and troughs match each other and produce a wave with twice the amplitude. This is known as constructive interference. If the waves are 180deg out of phase (half a wavelength) then the peaks and troughs cancel. This is destructive interference.

For a number of waves of different wavelengths, amplitudes and phases the interference becomes very complicated and the resultant wave may look quite messy. Virtually all precision optics from AR coated lens to Etalons to ultrafast mirrors exploit interference phenomena to achieve the desired functionality. Interference also plays an extremely important in the aptly named field

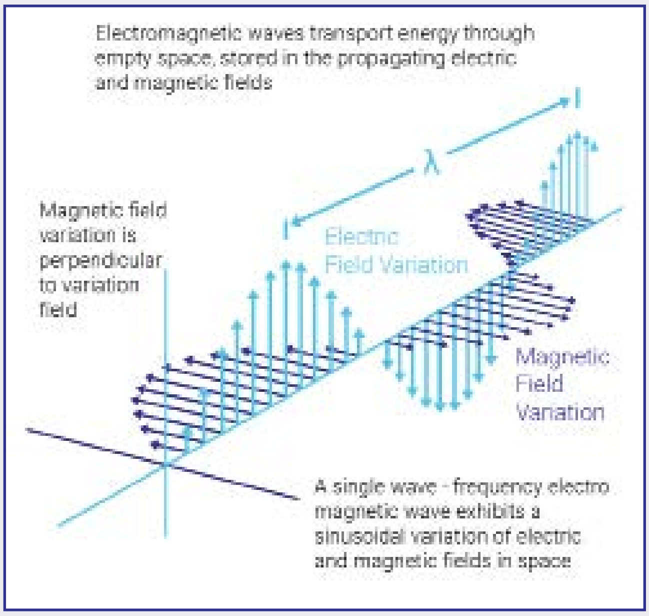

Figure 1: A propagating electromagnetic wave. The magnetic and electric fields oscillate at right angles to each other and the direction of propagation.

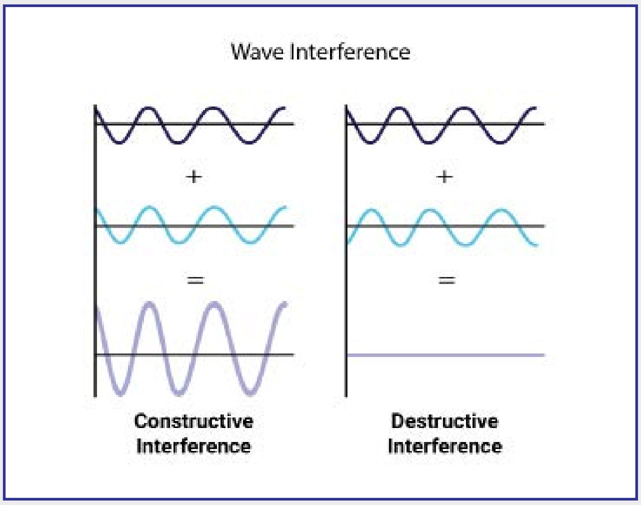

Figure 2: Constructive and destructive interference. The in phase waves reinforce each other whereas the out of phase waves cancel out.

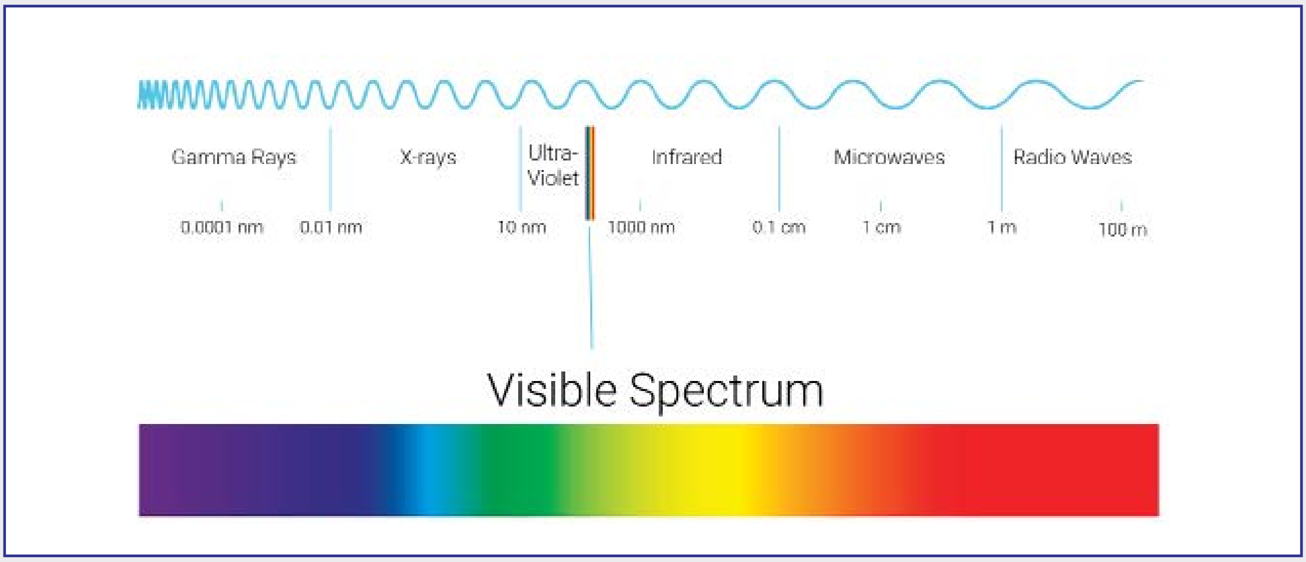

Figure 3 The electromagnetic spectrum

of "interferometry" where interference effects are utilised to measure the flatness or shape of optics to an extreme level of precision.

Another important trait of waves is the phenomena referred to as diffraction. Diffraction broadly refers to the behaviour of light incident upon slits or obstructions. A helpful idea is Huygen's principle which asserts that every point of a wave-front can be considered a source of secondary "wavelet's" whose interference gives the resultant wave. When light passes through an aperture the interference of the wavelets causes diffraction. This is illustrated in figure 4.

Diffraction through a circular aperture causes the appearance of what is known as an "Airy Disk", a bright spot surrounded by faint rings. The size of an airy disk for a given aperture is an important consideration in optical systems as it determines the smallest point to which light can be focused. A famous example illustrating both diffraction and interference principles is the double slit experiment depicted in figure 5.

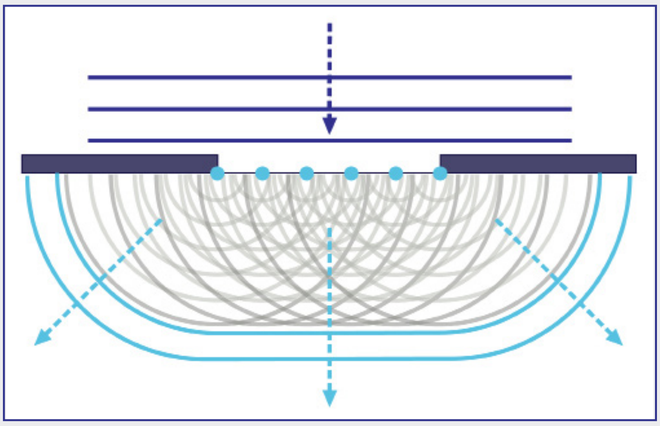

Figure 4: Huygen's principle in action. Wavelets on the wave-front passing through the aperture interfere to produce a more circular wave-front, the wave is thus diffracted as it passes through the slit.

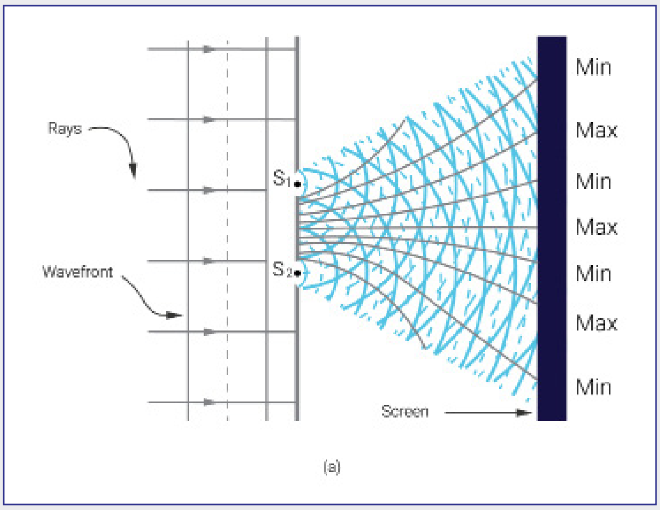

Figure 5: The double slit experiment. A wave-front arrives at two slits and diffracts through. The diffraction causes two circular wave fronts to emit from the slits, these interfere to produce the famous interference pattern.

Refractive Index

The index of refraction or refractive index is an extremely important parameter in optics as it characterises the optical behaviour of materials. It is simply defined as the ratio of the speed of light in a vacuum c= 299792458 m/s, generally approximated to 3x10^8m/s, and the speed at which light propagates through the material, i.e. the index of refraction n is given by:

$$n = \frac{c}{v}$$

For example, crown glass has an index of refraction n=1.52 meaning that light travels only about 66% of the speed of light in a vacuum whilst travelling through that material. Much of optics comes down to the study of light travelling through media of different refractive indices.

When light is incident upon a dielectric material such as glass, some of the light is reflected at an angle equal to the angle of incidence, and some light is transmitted or "refracted" through at an angle defined by Snell's law

$$n_0 \sin\theta_r = n_1 \sin\theta_t$$

Where n_0 is the index of refraction of the incident medium, n_1 is the index of the refracting medium, θ_r is the angle of incidence/reflection and θ_t is the angle at which the light is refracted.

The amount of light that is reflected and transmitted is determined by the so called "Fresnel" equations which will be covered by a future technical note. Additionally, the "phase" of the light is shifted by 180 deg ($\pi/2$) when light is reflected of a (dielectric) surface of higher index of refraction, though the refracted light retains the same phase.

Dispersion

The refractive index of a material varies with the wavelength of the light passing through, this is an effect known as dispersion. A well-known, illustrative example of this is white light incident upon a prism.

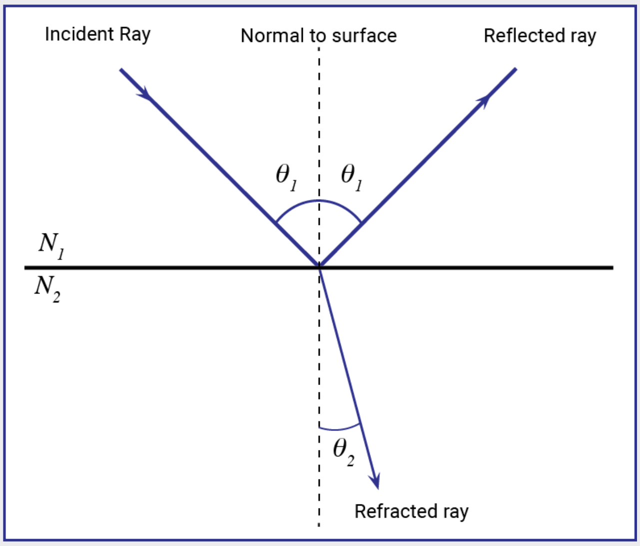

Figure 1: A ray of light incident obliquely upon a medium of differing refractive index is reflected at the angle of incidence, and refracted at an angle determined by Snell's law.

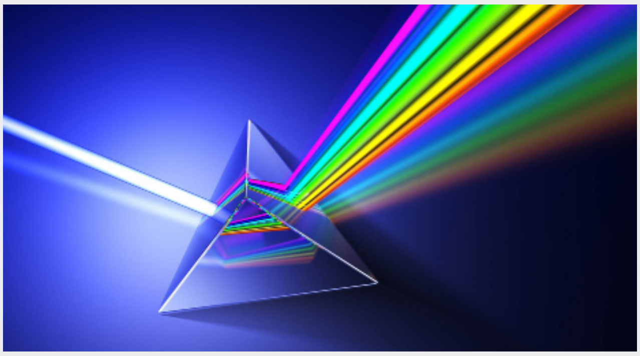

Figure 2: Refraction of light through glass

White light is made up of lots of different colours which experience different refractive indices when they enter the prism. Thanks to Snell's law they will transmit through the prism at different angles and so the white light is split apart.

Accounting for dispersion is very important in the design of optical systems, especially those that operate across multiple wavelengths or large bandwidths. In optical coatings the refractive index can also depend on the production process and the exact nature of the coating microstructure. In bulk substrates the dispersion depends on the glass type though it is often low for standard materials like Fused Silica and BK7. In substrate material specifications the dispersion is characterised by a quantity known as the "Abbe number" commonly denoted as V_d. The Abbe number is defined by

$$v_d = \frac{n_d - 1}{n_f - n_c}$$

Where $n_{d,f,c}$ is the refractive index value at 587.56nm, 486.13nm and 656.27nm respectively. Glasses characterised by a low index and low dispersion tend to have a high Abbe number, whereas the number is low for high index, high dispersion glasses. The Abbe number along with the principal dispersion $n_f - n_c$ are of course loose estimates for the characterisation of dispersion. For more details refer to partial dispersions provided by glass manufacturers and the Sellmeier dispersion formula.

Absorption Coefficient

A closely related number to the refractive index is the extinction coefficient commonly denoted by k. The extinction coefficient determines how much the intensity of light is reduced as it penetrates a material, i.e. the absorption of the material. Together with the index of refraction it constitutes the imaginary part of the "complex refractive index" N=n+ik where i is the imaginary unit. In optics the distinction between dielectrics and metals is that metals have a non-zero extinction coefficient and are hence absorbing whereas dielectrics do not and absorb no light. Like the refractive index, the extinction coefficient can also be dispersive. For example whilst fused silica is an excellent dielectric material across the visible spectrum, it can suddenly become absorbing in the UV.

Realistically many dielectric materials, both substrates and coating materials in fact have small extinction coefficients and so are slightly absorbing. Appropriate choice of material is incredibly important when designing and producing high LIDT parts as even a tiny degree of absorption can have catastrophic results!

Glass Type	Refractive Index	Abbe Number Vd	Transmission @546nm
Schott Fused Silica	1.45843	67.87	3.4971%
Schott N-BK7	1.5168	64.17	4.2414%
N-BAK1	1.57250	57.55	4.9846%
N-LAK10	1.72003	50.62	7.0558%
N-SF2	1.64769	33.82	6.0474%
N-FKS	1.48749	70.41	3.8616%
N-KZFS2	1.55836	54.01	4.7096%
SF6HT	1.80518	25.43	8.3479%

Table 1: Refractive indices and dispersions of various glass types. Optical constants provided by Schott Glass.

Glass Type	Refractive Index @633nm	Extinction Coefficient @ 633nm
Fused Silica	1.4570	0
Zirconium dioxide	2.1517	0
Germanium	5.4699	0.81446
Silver	0.056206	4.2776
Hafnium	2.1056	0
Aluminium	1.37289	7.617691

Table 2: The refractive indices and extinction coefficients for various materials.

Introduction to Geometric Optics: Mirrors

Geometric optics refers to an approximate but useful framework in which the optical behaviour of mirrors, lenses and other components can be studied. Doing away with the wave-like nature and interference properties of classical light, geometric optics operates with the simple description of light as rays that reflect and refract when incident upon a medium of differing refractive index. In this picture the optical engineer or component designer may construct ray diagrams that allow for the calculation of key parameters of an optical system via the laws of reflection and refraction, or aid in visualising optical behaviour. In this technical note mirrors are the focus of study and are used to introduce basic concepts such as ray-tracing, image formation and focal points. Lenses are discussed in the following section..

A light ray is defined as a physical line in the direction of energy flow or propagation of a wave, perpendicular to successive wave-fronts.

Light reflecting off an optical surface can be visualised as light rays that are redirected from a tangent at the point of incidence according to the law of reflection i.e. the angle of incidence is equal to the angle of reflection and lies in the same plane. This is well illustrated by figures 1.a. and 1.b. which depict reflection due to a point source and the image of an extensive object in a mirror. In 1.a. the light rays diverge from real source S and reflect towards an observer, appearing to diverge from a source S' that lies at the same distance from the mirror surface (image distance) as the real source distance.

Many source points forming an extensive object as in figure 1.b. results in an image of the same size (magnification is unity) and apparent distance as the real object, though it will appear horizontally flipped as expected. In a ray diagram if light rays appear to diverge from points from which they are not actually physically diverging then the image is said to be "virtual", otherwise an image is called "real".

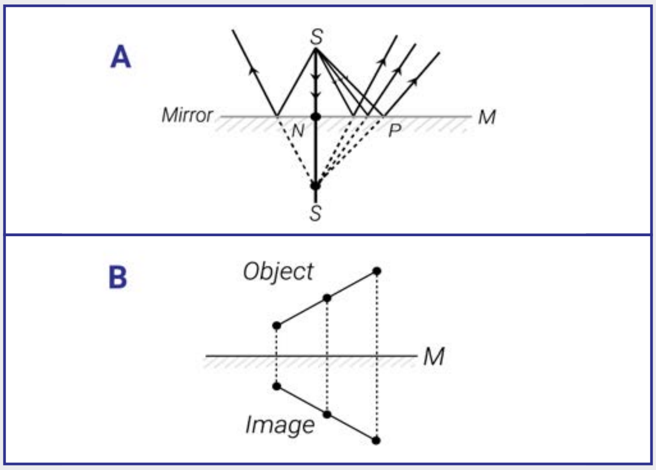

Figure 1: a. Light from point S reflects off flat surface. The rays appear to diverge from a virtual source at S'. b. An extensive object with an image of equal magnitude and distance away from the mirror surface.

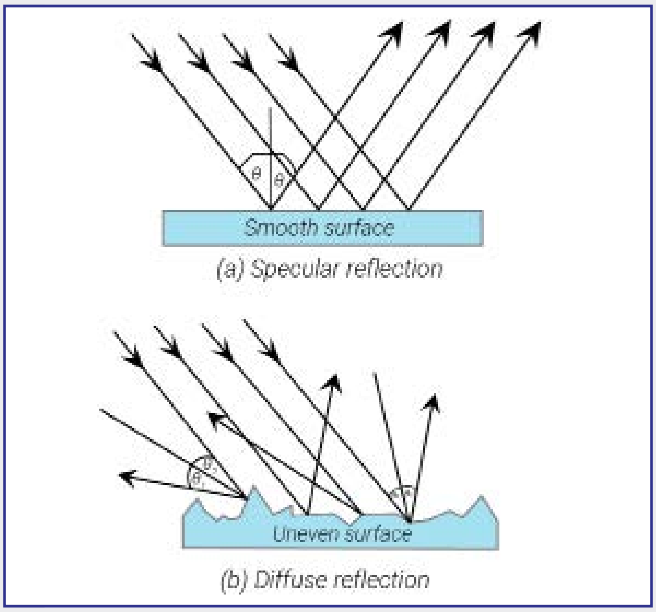

Figure 2. depict reflection from two "flat" mirrors where one mirror has an uneven surface. In both cases the light rays always obey the law of reflection, however in the first case (specular reflection) the mirror is sufficiently flat for the light rays to remain parallel meaning they will accurately produce the image of the light ray source. For the uneven surface the light rays are incident to many different planes and thus scatter at random angles in different directions (diffuse reflection). This is what gives an unpolished glass substrate its rough and seemingly opaque appearance.

Ray Tracing with Spherical Mirrors

When it comes to the design of lenses, spherical mirrors and other optical components the graphical ray trace method is utilised where the behaviour of the light rays is traced through the optical system. Curved optical surfaces generate particular points along the optical axis known as “focal points” which are of especially great importance in ray tracing and optics as a whole. The length from the focal point to the vertex of the surface generating it is referred to as the “focal length”. The focal points of spherical mirrors are defined by how incident collimated light behaves. For a concave mirror the parallel light rays will all converge to the focal point whereas for convex mirrors they will diverge as if travelling from a virtual source at the focal point.

For spherical mirrors, ray tracing only requires two or three “principal” rays to be drawn. These being a ray from an object P parallel to the optical axis which passes through or appears to arise from the focal point F, a ray passing towards focal point F and reflecting parallel to the optical axis and a ray towards the centre of curvature, reflecting back to where it came from. The intersection of two/all three of these lines (real or virtual) gives the location and length of the image. All rays still obey the law of reflection, they reflect off tangents at the point of incident upon the mirror surface.

A full calculation giving the location and length of the image requires computer software and so the small angle, paraxial approximation is generally utilised for calculations by hand. This results in aberrations not predicted by the first order theory (these aberrations are discussed further in another technical note). However, the end result is easy to use equations that are accurate within 1% for incident ray angles (with respect to the optical axis) of 10° or less. The object distance S, image distance S’ and focal length f are related by:

$$\frac{1}{S} + \frac{1}{S'} = \frac{1}{f}$$

Where focal length is related to the radius of curvature R by

$$f = -\frac{R}{2}$$

The magnification m, i.e. how a mirror changes the apparent size of an object is given by

$$m = \frac{h_i}{h_o} = \frac{S'}{S}$$

Where $h_{o,i}$ are the object and image lengths respectively. If m is positive the image is erect, otherwise if it is negative it is known as inverted. The signs of quantities in the above equations are given by various sign conventions, an example of a compatible convention is given below.

- Object and image distances are both positive when located outside the mirror (concave mirror), the image distance is negative when on the same side as the mirror (convex mirror)

- Radius of curvature is positive when the centre of curvature is outside the mirror (concave), otherwise it is negative when on the same side of the mirror (convex)

- Vertical dimensions are positive above the optical axis and negative below. (the ratio for m acquires a minus sign)

It does not matter which sign convention is chosen as long as the convention is stuck to throughout calculations.

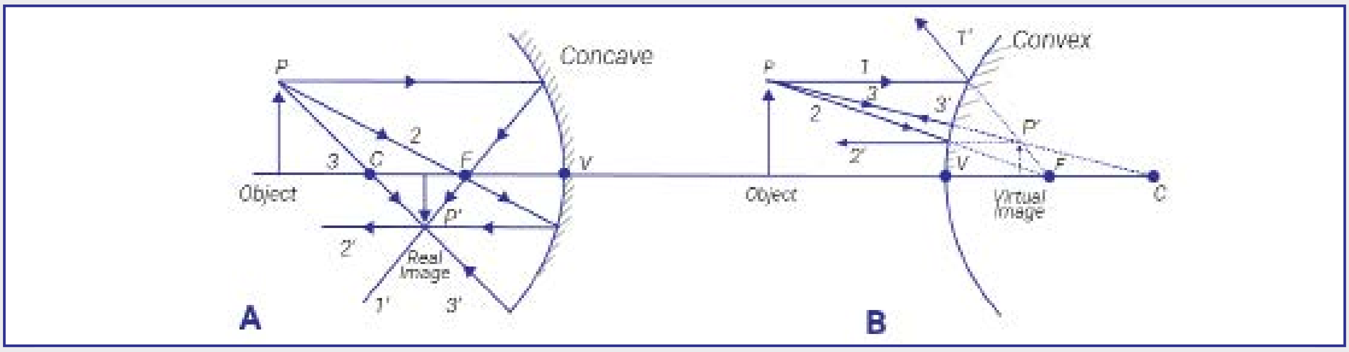

Figure 3: Graphical ray tracing for a. concave and b. convex mirrors. Note how concave mirrors result in an inverted “real” image whereas the convex mirror produces an image that is upright but “virtual”.

Introduction to Geometric Optics: Lenses

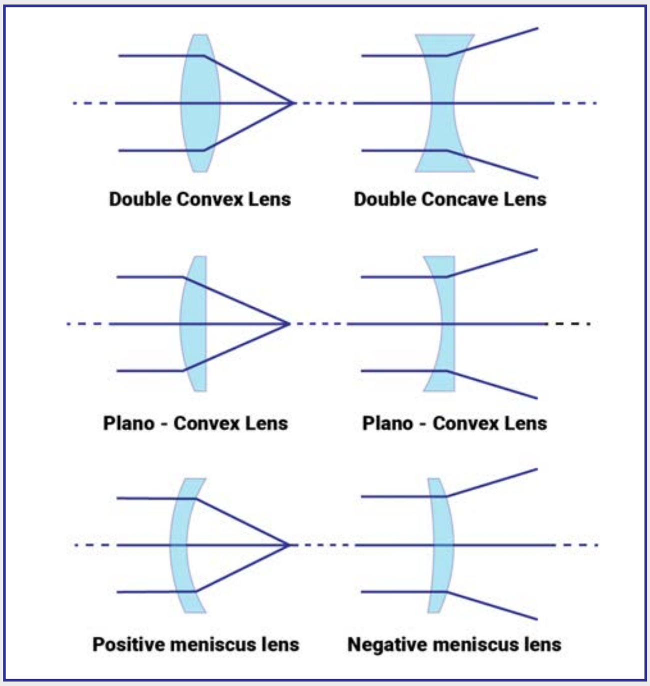

Figure 1: The six forms of the spherical lens and the behaviour of incident, collimated light rays passing through. On the left are converging, positive lenses and on the right are diverging, negative lenses.

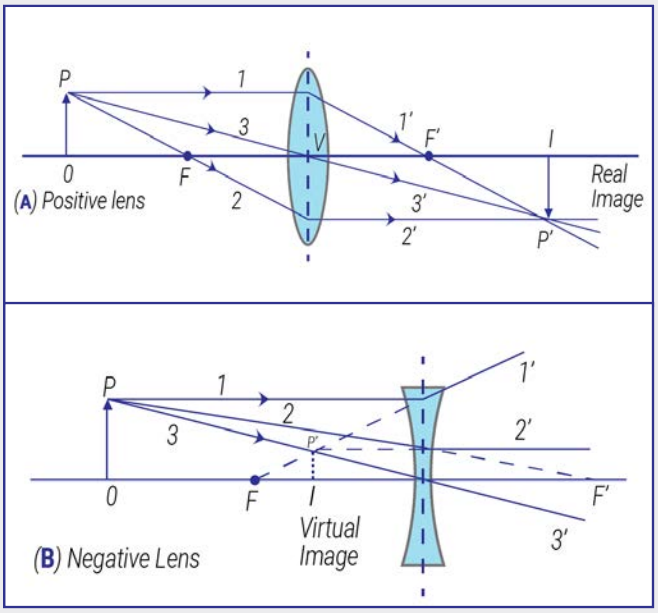

Figure 2: Paraxial ray tracing for a. bi-convex and b. bi-concave lenses. Note how in this case the positive lens produces a real but inverted image whilst the negative one produces one that is virtual and upright.

The geometric optics of lenses is treated similarly to that of a mirror, but involves refraction rather than reflection and utilises two focal points for both surfaces of the lens. A light ray is defined as a physical line in the direction of energy flow or propagation of a wave, perpendicular to successive wave-fronts. Light refracting through an interface can be visualised as light rays that are redirected from the point of incidence at an angle determined by Snell's law. The distinct spherical surfaces of a lens take advantage of refraction to redirect light in a useful fashion, such as to form an image, focus light to a focus or collimate rays.

Lenses can come in all shapes and sizes though there exist commonalities in their optical behaviour. There are six distinct types of spherical lens consisting of either two spherical surfaces or one spherical and one planar surface. These different lens types are depicted in figure 1.

We can identify two main types of lens defined by the behaviour of collimated light rays or rays from an infinitely distant source. If the rays converge onto a focal point then the lens is converging (positive), otherwise if they diverge away from a focal point the lens is diverging (negative). Initially parallel wave-fronts take on a characteristic spherical shape due to the difference in OPD between different points along the front as a result of varying glass thickness. All bi-convex and plano-convex lenses are positive lenses whilst bi-concave and plano-concave lenses are negative. There also exists meniscus lenses consisting of concave and convex surfaces which can be either positive (thicker at the edges i.e. if the convex surface has a larger radius of curvature) or negative (thicker at the centre i.e. if the concave surface has a larger radius of curvature).

Ray Tracing with lenses

Like with spherical mirrors we can use ray tracing to study the optical behaviour of lenses. The simplest case is that of a thin lens, i.e. when the radii of curvature are much larger than the lens thickness such that displacement of rays due to refraction can be ignored At least two principal rays are drawn to determine the size and location of the image, which consist of a perpendicular ray from the object which is re-directed such that it appears to propagate from the focus of the first surface, a ray directed towards the focus of the second surface and a ray that passes through the centre of the lens (the path does not deviate in the thin lens approximation). Examples for positive and negative lenses are given by figures 2a and 2b (left).

Like with mirrors, a full calculation relating object heights and distances to that of the image is left to computers, a first order, paraxial solution is often sufficient. Assuming the lens width is small in comparison to radii of curvature, the thin lens equation is obtained:

$$\frac{1}{S} + \frac{1}{S'} = \frac{1}{f}$$

Where S is the distance of the object to the vertex and S' is the distance of the image to the vertex. Focal length f is given by the famous "lensmaker's equation":

$$\frac{1}{f} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2}\right]$$

Where n is the refractive index of the lens, R_1 R_2 are the incoming and outgoing radii of curvature respectively. Outside of the thin lens approximation, where the lens thickness d is comparable to the radii of curvature the lensmaker's equation becomes:

$$\frac{1}{f} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n-1)d}{nR_1R_2}\right]$$

Given image and object heights H_I and H_0 respectively the magnification m of a thin lens is given by:

$$m = \frac{h_i}{h_o} = \frac{S'}{S}$$

These equations must also follow a sign convention, an example of one such convention is:

• Object distance is positive for objects on the left side of lens (assuming rays move from left to right)

• Image distance is positive for real images and negative for virtual ones.

• Focal length is positive for a converging lens and negative for diverging lens

• Radius of curvature is positive for a convex surface and negative for a concave one

• Vertical distances are positive above the optical axis and negative below

A higher order analysis of a spherical lenses system reveals a number aberrations which cause the optical behaviour to deviate from the ideal, first order paraxial case. This leads to another type of lenses known as the "aspheric" lens. The surface profile of an aspheric lens tends to be rotationally symmetric but deviates from a spherical one in such a way as to reduce aberrations.

To summarise, ray tracing and geometric optics are fundamental and important techniques in the repertoire of the optical designer. Though ray tracing can be carried out by a computer it is a practise that does well to illustrate optical functions and image formation. The equations derived under the paraxial equation are still accurate for many optical systems and offer a means to easily calculate optical specifications without resorting to computer software. On the downside, the paraxial approach does not take into account aberrations, and aspheric lenses may be required.

Polarisation Optics

Polarisers are optical instruments that are used to polarise light and are utilised in a variety of ways such as in photography to reduce reflection from reflective surfaces. There are numerous methods for achieving polarisation, some polarisers will absorb light of unwanted polarisation, only letting through components oscillating in a particular direction. Others act as beam splitters, splitting incident light into separate beams of differing linear polarisation via thin film interference or birefringence.

In an ideal case, given an incident, randomly polarised beam the polariser lets the component of the light oriented with the polariser through. Give an incident polarised beam (achievable with an additional polariser) the resultant linearly polarised beam will possess an intensity prescribed by Malus' law (1)

$$I = I_0 \cos^2\theta$$

Where I_0 is the intensity of the incident, linearly polarised beam and θ is the angle between the polarisation of the incident beam and that of the polariser.

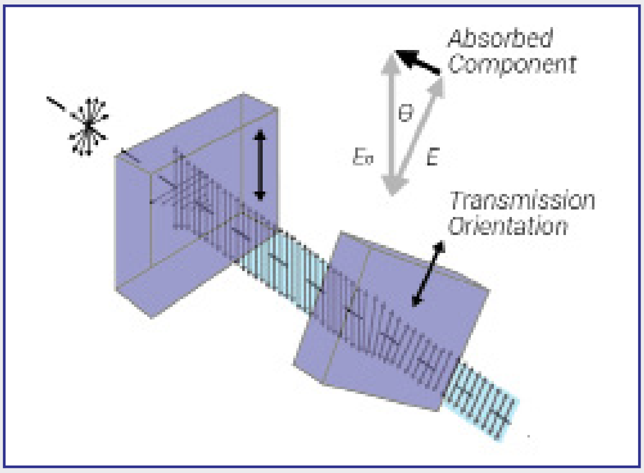

Figure 1: Unpolarised beam incident upon two crossed absorbing polarisers. The first filter linearly polarises the light into a particular direction and absorbs other components. The second filter polarises the light to a different orientation reducing the intensity further.

At 90° this intensity is reduced to zero as all the light is absorbed or reflected for this orientation, and conversely at 0° all the light is let through however in reality the transmission is reduced as some light is absorbed by the polariser and unwanted polarisations may also be let through. A more realistic characterisation of polariser performance is then given by equations (2) and (3).

$$T = \left(T_{max} - T_{min}\right)\cos^2\theta + T_{min}$$

$$P = \frac{T_{max} - T_{min}}{T_{max} + T_{min}}$$

Where T_{Max} and T_{Min} are the maximum and minimum transmittances. The value is known as the polarisation efficiency, for an ideal polarise $P = 1$. Another value commonly used to describe polariser performance is the extinction ratio T_{Max} / T_{Min} or sometimes T_p/T_s for S and P polarisers.

A polariser which absorbs unwanted polarisation states is known as a dichroic polariser. Perhaps the best-known example of such a polariser is the polaroid filter which is commonly used in LCD displays and sunglasses. Such a polariser is unsuitable for use in the presence of highly intense lasers due to their absorptance. It is however possible to construct dielectric polarisers with high LIDT based on Fresnel reflectivity.

At non-normal incidence upon a dielectric the S and P polarised components of the incident light will experience differing reflectivity and transmission according to the Fresnel equations. When the light is incident at an angle known as Brewster's angle defined by $\theta_B = tan^{-1}\ (n_1/n_0)$ (where n_0 is the refractive index of the surrounding medium and n_1 is the refractive index of the incident medium) the transmission of P-polarised light becomes 100% and S-polarised light is partially reflected. With a succession of such filters, separate S and P polarised beams are produced though this method is impractical for achieving polarisation.

The use of thin film dielectric coatings is however more efficient, enabling high performance and high LIDT whilst taking up less space. Two such types of polariser produced at MPO are plate and cube polarisers which are generally constructed with fused silica substrates.

Plate polarisers consist of a substrate coated with a high reflectance coating. The width of the reflectance zone of a HL coating depends on the ratio of the indices of refraction/optical admittances which are different for s and p polarised light at non normal incidence. It can be shown that for such a coating the width of the high reflectance zone for p-polarised light is always less than for s-polarised light. The wavelength region where the reflectance drops for p-polarisation may therefore lie inside the region where s-polarised light is still reflected leaving a small region where the p-polarised light is fully transmitted and s-polarised light is fully reflected. This makes such a filter ideal for single wavelength operations such as a laser line. Plate polarisers can also be designed with any coating possessing a sharp edge between transmission and reflection.

A beam splitter cube consists of a pair of optically contacted prisms with a dielectric multilayer stuck between them and the outside coated with an AR coating. A coating immersed in prism material has a reduced Brewster's angle, enhanced polarisation splitting and a broader polarising region than with air as the incident medium, and is capable of separating unpolarised light into very highly polarised out-put beams at an almost angle. MPO produces high quality fused silica cube polarisers capable of achieving >99.5%R in s-POL and >95%T in p-POL at operational wavelengths with outside faces coated in a <0.25%R coating.

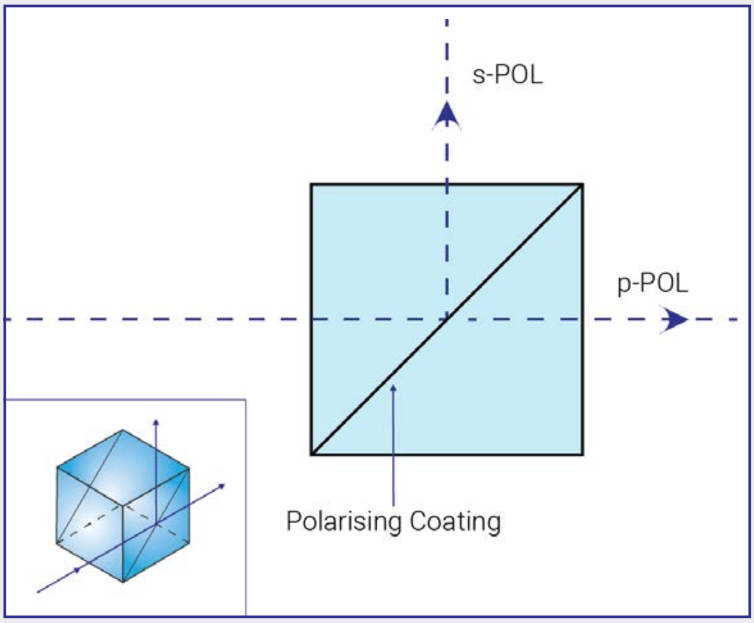

Figure 2: Light incident upon a plate polariser. The coating reflects the s-polarised component at the operational wavelength whilst letting through p-polarised light.

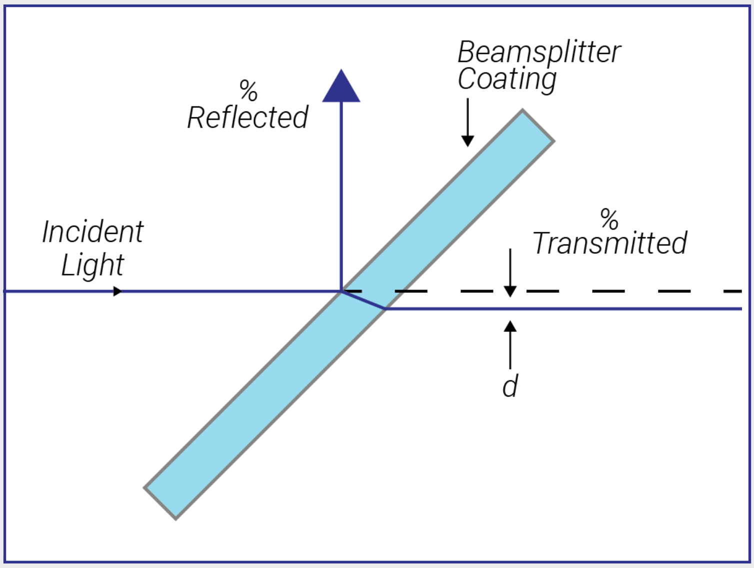

Figure 3: A beam-splitter cube consisting of two prisms optically contacted or cemented together with a dielectric coating. The incident beam at 45° to the coated surface is split into reflected s-polarised and transmitted p-polarised beams which are perpendicular to each other.

Aberrations

In optical systems, minimal distortion and blur in the final image is generally desirable. One of the main challenges of fabricating precision optical components satisfying this requirement is the correction of aberrations, aberrations being the distortions in the image produced by a lens due to the curved surface of the component.

In standard lens design utilising geometric optics, wave effects such as diffraction and interference are not taken into account. Diffraction from an aperture produces blur, limiting the resolution of an image. An ideal but realistic lens with minimal diffraction blur is said to be "diffraction limited". Because the approximate, first order paraxial ray tracing is utilised in geometric optics, noticeable errors arise if the optical system has a finite aperture and large fields of view, as rays far from the optical axis may end up outside the diffraction blur. A lens that has been well corrected for aberrations may therefore be defined by the requirement that errors in focus lie within the diffraction blur.

Aberrations can be subdivided into two classes, chromatic and achromatic aberrations. Chromatic aberrations occur due to the dispersive properties of the glass, whereas achromatic aberrations are wavelength independent and arise as a result of the spherical shape of the lens as well as due to surface deviations.

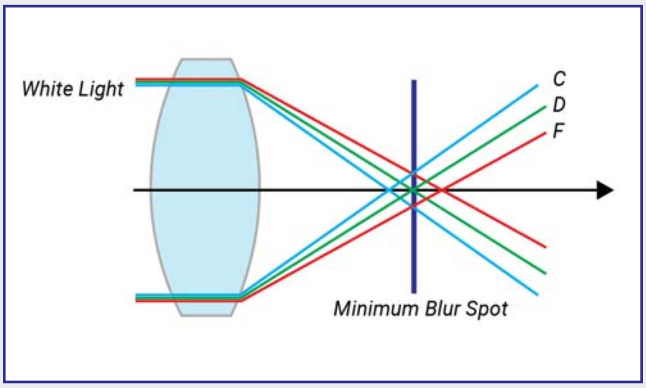

Figure 1: Longitudinal chromatic aberration

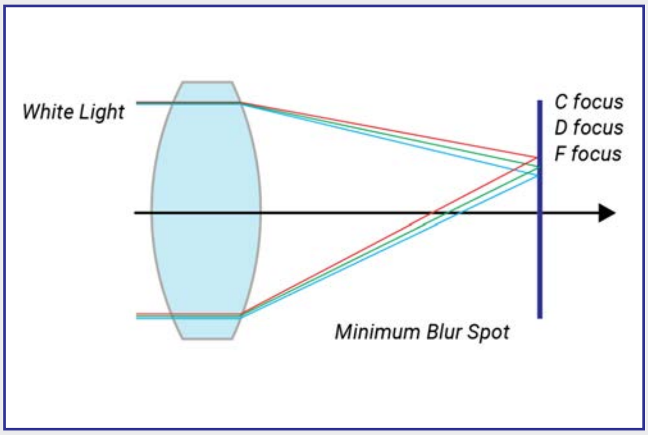

Figure 2: Transverse Chromatic aberration

Chromatic Aberrations

Because the refractive index of the glass varies with wavelength, light of different wavelengths will be refracted at different angles causing chromatic aberrations as depicted in figures 1 and 2.

Figures 1 and 2 depict two distinct forms of chromatic aberration, longitudinal aberration along the optical axis and transverse aberration in the image plane. Longitudinal aberrations are caused by different wavelengths experiencing different focal lengths due to dispersion, and as a result they are focused onto multiple focal points along the optical axis. For example, light corresponding to the F (656.3nm), d (587.6nm) and C (486.1nm) spectral lines are focused at different points, longer and shorter wavelengths experiencing longer and shorter focal lengths respectively. Transverse aberration is when light of different wavelengths is focused to different points in the image plane, for example when white light passes through the lens at an angle.

The blurring introduced via longitudinal chromatic aberration can be reduced by cementing two lenses together to form an achromatic doublet lens. A lens made from a low dispersion (crown) glass of positive optical power can be cemented with a high dispersion (flint) glass lens of negative optical power to correct the focal length for two wavelengths. For example, we can correct the foci for C and F wavelengths in figure 1 such that both wavelengths are focused to the same point, though residual aberration will shift the focus at the d wavelength. We can remedy this further by cementing three lenses of appropriate dispersion and optical power to form an apochromatic, or 4 lenses for a superachromat and so on, each lens correcting the focal shift at a specific wavelength.

In lenses designed for operation at a single wavelength or over a small bandwidth chromatic aberration can be ignored, though if you have any concerns or questions regarding chromatic aberrations then do not hesitate to contact us.

Monochromatic Aberrations

Monochromatic aberrations are wavelength independent aberrations generally caused by the geometry of the lens itself. As the field of interferometry is concerned with measuring optical surfaces, monochromatic aberrations are often the subject of study in interferograms. Aberrations can be represented by the coefficients of an expansion of the wave-front in terms of Zernike Polynomials.

$$W(\rho,\theta) = \sum_{n=0}^{\infty} \sum_{m=0}^{n} c_{nm} Z_n^m(\rho,\theta)$$

Where W is the wave-front, C_{nm} are the coefficients and $Z^m{}_n$ are Zernike polynomials.

The most important aberrations are given by the 1st and 3rd order coefficients (order is given by $n + m - 1$). The first order aberrations are given the names:

- Piston
- Tilt
- Defocus

These aberrations are mostly trivial, piston merely being the mean value of the wave-front in the absence of aberrations and tilt arising due to the tilt in the component. They are easy to subtract from interferograms. Defocus, as the name suggests arises when the object being imaged is out of focus. The real meat in aberrations analysis comes from the third order aberrations which are certainly not trivial. These aberrations, sometimes known collectively as "Siedel Aberrations" are called:

- Spherical Aberration
- Coma
- Astigmatism
- Curvature of Field
- Distortion

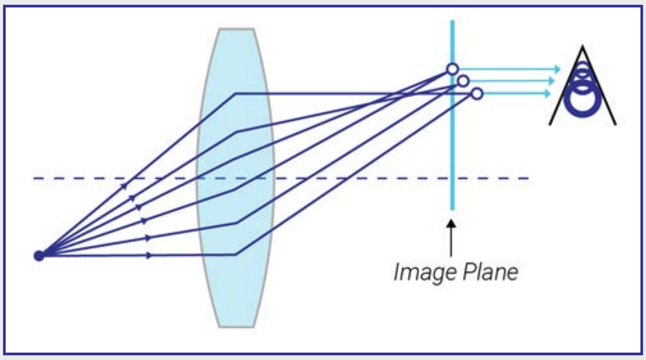

Figure 3: Spherical aberration is an aberration that is circularly symmetric about the optical axis. It arises from the different directions light is refracted through due to their height relative to the optical axis, causing a smearing of the focal point.

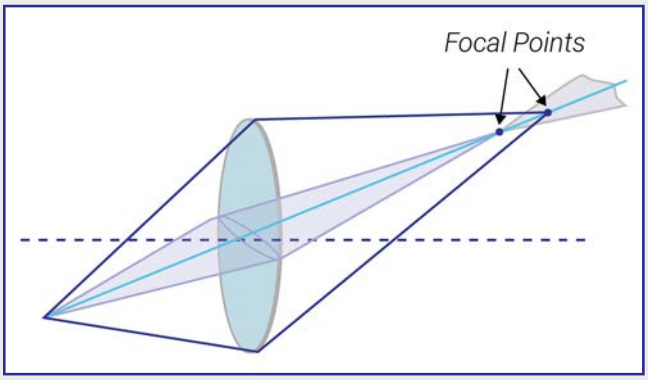

Figure 4: Coma is an aberration that occurs when a wave-front is tilted with respect the optical axis. It causes the result to image to appear smeared at the edges, with a comet-like tail pointing towards the optical axis.

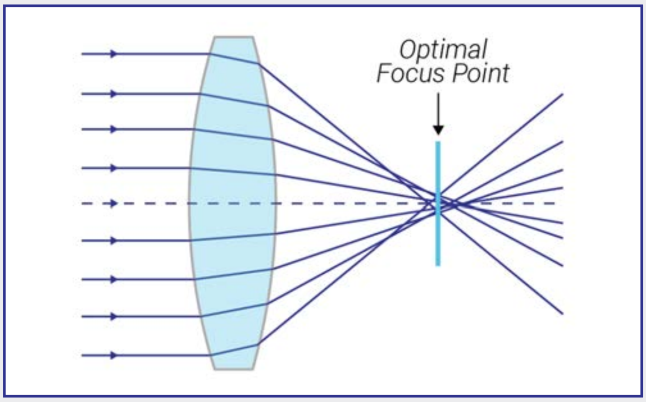

Figure 5: Astigmatism occurs when rays propagate in two perpendicular planes and are focused at two separate points. As the field of view increases astigmatism grows as the separation between the two focal points is proportional to the square of the field angle.

These aberrations are depicted in figures 3 through 7.

There are many means available for correcting third order aberrations. Some methods involve re-shaping a lens, for example spherical aberrations can be corrected via aspherical surfaces (e.g. a hyperboloid, convex lens). Astigmatism is corrected by shaping the lens such that the tangential and sagittal focal lengths are equal and coma can be corrected through bending. Spherical aberrations, along with coma, and distortion can be reduced via appropriate aperture stops. Monochromatic aberrations can also be corrected via optical assemblies or with extra lenses similar to how chromatic aberrations are corrected. Distortion can, for example be corrected via orthoscopic doublets and the curvature of field is eliminated via the combination of two lenses of equal but opposite optical powers, such that the curvature of field for each lens cancels leaving a flat field across the image plane.

As a wave-front expanded as a series of Zernike Polynomials has infinite terms, we can of course correct for 5th, 7th and higher order aberrations, though accounting for third order aberrations tends to be sufficient, especially since many higher order terms tend to simply be more developed versions of previous aberrations.

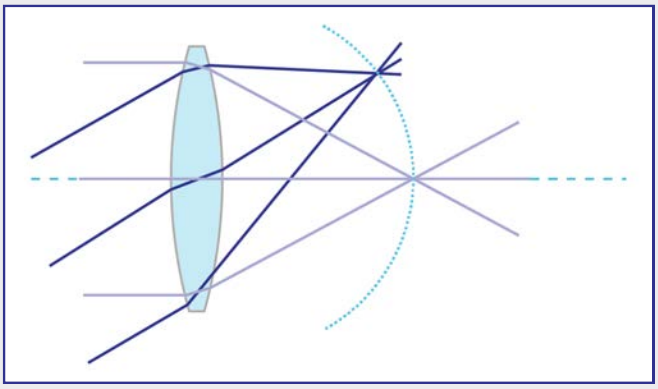

Figure 6: Curvature of field is an aberration that arises due to the way in which off axis rays are focused over a spherical surface meaning it is present even in a "perfect" lens. As a result, given a flat sensor the light will be well focused at the centre but increasingly blurred away from the optical axis.

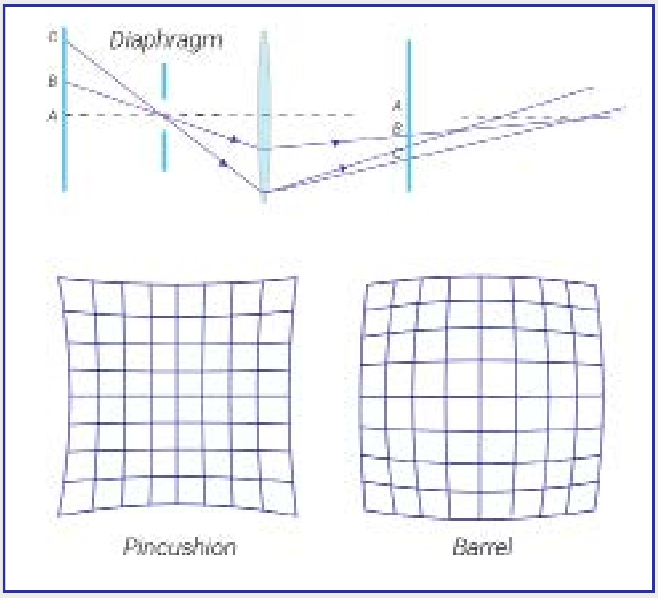

Figure 7: Distortion is caused by variation in the magnification over the field angle of the lens. It comes in two types, pincushion and barrel distortion where magnification increases and decreases with radial distance in the former and latter respectively.even in a "perfect" lens. As a result, given a flat sensor the light will be well focused at the centre but increasingly blurred away from the optical axis.

The Cleaning of Optics & The Cleanroom Environment

A brief overview

Throughout manufacturing an optic must be frequently cleaned to ensure it is free of dust and other contaminants throughout the process. Dust contamination can affect all stages of optical fabrication process for example dust within the polishing process can cause scratching on the optics. Dust contamination during the coating process (which primarily occurs whilst the optics are being prepared for coating) can lead to inclusions in the optical coating, thereby rendering an expensive optical component worthless. Cleaning takes place at multiple points during fabrication, often before and after key processes.

It is important to keep in mind that once a product reaches a customer it should be handled with great care and kept clean to ensure optimal functionality. This is even more critical in the case of high LIDT components as even a small amount of dust can scatter laser light and drastically reduce LIDT, risking irreversible damage to the part.

MPO's coatings come in two classifications with regards to handling and cleaning: durable and ultra-hard. Generally, durable coatings correspond to some protected metal or fluoride-based coatings, and ultrahard coatings tend to be fully dielectric, but also include specific metal and metal-hybrid coatings. For a durable coating, dust should be removed from the surface by gently blowing it off with Nitrogen or other inert gas. Wiping it may damage the coated surface. An ultrahard coated surface may be wiped clean with lint free tissue, dampened with pure methanol or Isopropanol. Care should be taken, although moderate pressure may be applied when cleaning this coating.

Cleanrooms

Any reader who has ever visited a semiconductor manufacturing plant cannot fail to be impressed by the extensive cleanroom facilities that such factories have. In general, a cleanroom can be described as an environment with a low level of pollutants, in the case of optical coating manufacture dust particles.

Outside, under the open sky, a typical cubic metre of air contains between 30 and 40 million dust particles of 0.5mm diameter or larger. It becomes immediately apparent that such an environment is unacceptable for the manufacture of precision optics. Hence, an environment needs to be created that reduces dust contamination to a suitable level.

ISO Class Number	Maximum allowable concentrations (particles/m³)						FED STD 209E Equivalent
	0.1µm	0.2µm	0.3µm	0.5µm	1µm	5µm	
1	10						
2	100	24	10				
3	1000	237	102	35			Class 1
4	10,000	2370	1020	352	83		Class 10
5	100'000	23,700	10,200	3'520	832		Class 10
6	1'000'000	237'000	102,000	35,200	8320	293	Class 1000
7				352,000	83,200	2930	Class 10000
8				3,520,000	832,000	29,300	Class 100000
9				35,200,000	8,320,000	293,000	Room Air

Table 1: Cleanroom classifications as per ISO 14644-1:2015 In empty spaces no particle concentration is specified due to sampling and statistical limitations due to very high or low concentrations.

ISO 14644-1:2015 is an international standard that defines nine classes of cleanrooms, with class 1 being the highest and class 9 the lowest standard. The standard defines the number of particles per size allowed within one cubic metre of air. While many newer specifications refer to ISO 14644-1:2015 when specifying a manufacturing or packaging requirement, older drawings often refer to an old US standard (US FED STD 209E) which was cancelled in 2001. To allow cross-referencing, table 1 below lists the equivalent of the old US standard in relation to the ISO standard.

Most coating chambers are single door chambers, which means that they get loaded and unloaded through the same door. This also requires the cleaning to be done from the room where the coating chamber is situated and loaded/unloaded.

The protective shields inside a coating chamber get coated during the normal production process and therefore require regular removal and cleaning. During the removal it is unavoidable for coating particles to flake off the shield surfaces and increase the dust contamination inside the coating department. Hence, care must be taken to avoid contamination of other parts of the department.

For this purpose, optics are cleaned and stored within the department in laminar flow cabinets. These are enclosed benches, where air is drawn in through a particle filter (generally situated above the bench or behind it) and blown towards the user in a smooth, laminar flow (vertical or horizontal, depending on type of cabinet).

Typically, laminar flow cabinets are available in cleanroom classes of ISO 4 or ISO 5. When operating laminar flow cabinets, it is important to follow the manufacturer's requirements on maintenance. These usually ensure that the filter and air intake seals are regularly checked and that the filters are cleaned/changed at regular intervals to maintain the required cleanliness standard.

In practice, a critical interface is the process of loading the optics into the coating chamber prior to coating. During this process, the optics are being removed from the laminar flow cabinet and positioned into their respective positions in the calotte within the coating chamber. To minimize the risk of dust settling on the optics surface and then getting embedded in the coating during the coating process, it is important that particular care is being taken during this step. The optics need to be transported in an enclosed box and the surfaces protected by caps, which are only removed immediately prior to closing the coating chamber door and putting the chamber under vacuum.

It is vital that the correct materials such as lint free cleaning tissue and chemically pure cleaning solvents are being used. A thorough inspection of a cleaned optic, usually under a bright halogen light against a black background, is also vital.

Introduction to Optical Coatings

Thin film coatings take advantage of interference effects in order to produce optics with various properties. The properties of such coatings, though limited by the finite number of suitable materials, is extremely diverse. Everything from antireflection coatings (AR) to high reflection coatings (HR) to optical filters across a huge range of wavelengths is possible. To understand how a mere thin sliver of material can drastically modify the optical behaviour of a piece of glass it is best to begin with the example of a single thin film sitting atop a substrate.

Consider light travelling through air with index of refraction $n_0 = 1$ incident upon a thin film of material with index of refraction --- which itself sits atop a substrate with index of refraction n_2. Let's also say that $n_0 < n_1 < n_2$ (this way we do not need to worry about phase shift upon reflection). When the light hits the film, it reflects off but some light is transmitted through the film, reflects off the substrate at the bottom and comes back out the top. Because this second beam had to travel through twice the thickness of the material, it is out of phase compared with the reflected wave by

$$\varphi = \frac{2\pi n_1 d}{\lambda}$$

If the thickness d is a half wavelength times $1/n_1$ the phase difference is 2π and the interference is constructive. However, if the thickness is a quarter wavelength times $1/n_1$ the phase difference is ----- and the interference is destructive, reducing the intensity of the reflected wave.

For example, consider the quarter wave stack of high and low index materials in figure 2. Whilst the underlying symmetries of this particular multilayer make a theoretical

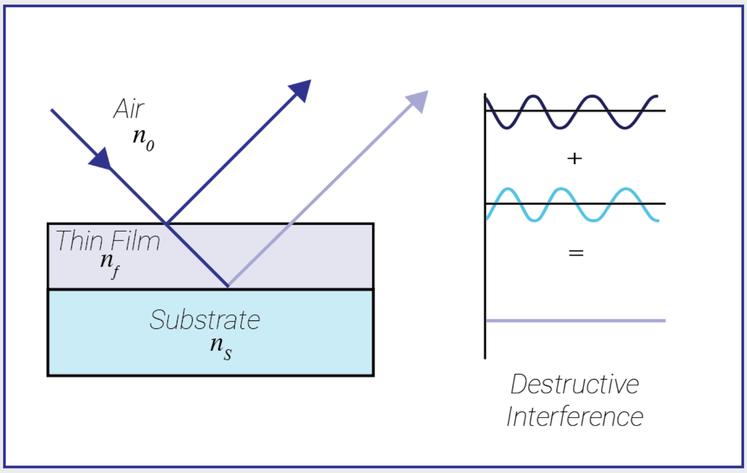

Figure 1: Reflected light from a thin film interfering with itself. In this case the interference is completely destructive and there is no resultant reflection

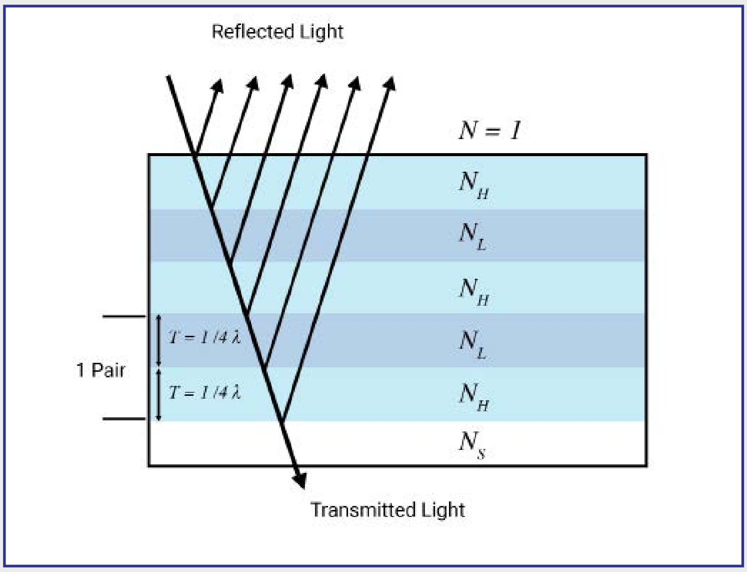

Figure 2: A quarter stack dielectric multilayer. This is a very frequent and robust type of coating

treatment more manageable than one might expect, in the general case to determine the reflectivity and transmission of this system one must consider every reflection at every interface, the phases of many reflecting beams of light and determine how they interfere.

Most coatings are structurally similar to the one depicted above, consisting of alternating “low” refractive index layers denoted by L and “High” refractive index layers denoted by H, though some coatings may consist of more than two materials.

Metals generally show a higher absorption than dielectric coatings but are nevertheless also used for mirror coatings. They are generally simpler in design and therefore less expensive to produce than mirrors composed of dielectric materials and possess high reflectance over a high bandwidth. On the downside the metal may oxidise, corrode or scratch easily and suffer a drop in reflectance. As optical components such as mirrors require regular cleaning this is a serious problem as simply wiping the bare layers can render the mirror unusable. As an example, consider gold. Gold is extremely useful for reflecting infrared light though the reflectance rapidly drops off past 700nm. It is also well known as a very soft metal that scratches easily.

Metal mirrors are typically overcoated with a thin dielectric film to mitigate these disadvantages, serving as a protective layer against environmental attacks with minimal modification to the reflective properties of the mirror.

Thin films are deposited on substrates by various deposition methods, typically in low pressure or vacuum environments. The class of methods known as Physical Vapour Deposition are the most preferred in the manufacture of precision optics. In physical vapour deposition substrates are installed into a rotating planetary holder within a coating chamber. The coating materials, located in crucibles at the base of the chamber are evaporated and the molecules then rise and settle upon the substrates, forming a thin crystalline film. This process is performed either under vacuum, sometimes with a reactive gas bled into the coating chamber to induce intentional chemical reactions.

PVD methods can be subdivided into evaporation

and sputtering depending on how the material is converted into vapour. The classic method is to heat up the material until it evaporates which is achieved by simply heating the crucible or bombarding the film with electrons (electron beam deposition). Evaporation methods are further improved when coupled with Ion and Plasma Assisted deposition techniques. In Ion Assisted Deposition the substrate is bombarded with ions (typically Argon), adding energy to the film process and improve stoichiometry.

In sputtering, the coating material is bombarded with ions to induce the ejection of atoms which settle upon the substrate. A common method is Ion Beam Sputtering (IBS), where the material is bombarded directly with an ion gun. Magnetron sputtering is another popular method whereby ions are extracted from a gas and trapped by magnetic fields about the coating material.

It is thanks to 20th century pioneers in the field of thin film optics, pioneers such as A. Thelen and S. D. Smith who devised ingenuous and informed methods of calculation and design, as well as the advent of modern computing that we are able to utilise such complex physics for the purposes of optical coatings. MPO specialises in bespoke, multilayer optical interference coating.

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Technical Guide

Optical Substrates

Material Specifications, Homogeneity, Straie and Thermal Coefficients

The refractive index is perhaps the most important parameter in an optical component and variations (at the design wavelength) are ideally kept to a minimum as otherwise a manufacturer runs the risk of introducing unwanted aberrations in the transmitted wave-fronts and the overall performance of the compenent. This is especially important in components such as Etalons where even tiny variations in optical path difference (OPD) can destroy performance or lenses as far as their focal length is concerned.

A variation in the refractive index is called an inhomogeneity and represents the difference between the highest and lowest refractive index found in the material sample. The application usually dictates the homogeneity requirement of the optical material, but great care must be taken when specifying the homogeneity as it also has an influence on the cost – the more homogenous the refractive index has to be and the larger the substrate, the more expensive the raw material becomes. If a material is not used in transmission, but, for example, as a mirror, the homogeneity is of little importance.

ISO 10110 Part 4 specifies six different inhomogeneity classes as listed in table 1 below:

Inhomogeneity Class	Max. variation of refractive index • 10^{-6}
0	±50
1	±20
2	±5
3	±2
4	±1
5	±0.5

Table 1: Inhomogeneity classes in optical materials as per ISO 10110 Part 4

Extreme examples of inhomogeneity in a material can be found in Georgian and Victorian window panes which are made of sheet glass. The variations in the window panes are generally visible by the naked eye, causing objects viewed through the window to appear clearly distorted.

Inhomogeneities can arise from multiple sources during the glass production process.

They can arise from gradients in the chemical composition of the molten glass due to evaporation or reactions with the walls at the surface. Density variations (and therefore refractive index variations) can emerge as the glass approaches equilibrium densities at high temperatures faster than for low temperatures. This density is itself different for different temperatures around the temperature at which the glass-liquid transition takes place. Additional inhomogeneity may arise from stress developed during the cooling process.

A manufacturer can refine the production process however by carefully controlling the cooling process and measuring the refractive index in situ at different regions. A large ingot of material is manufactured and then cut up according to areas of lower and higher homogeneity. A key take-away is the understanding that inhomogeneity is mainly a result of the production process as opposed to being an intrinsic property of the material though the glass type plays a role, as does the size of the component.

A very predominant glass type for our products is Corning 7980 Fused Silica and equivalent materials from other manufacturers. This type of Fused Silica has over the years proved itself as a staple of the precision optics industry due to its low refractive index (n_d = 1.4585), low dispersion (v_d = 67.8), low coefficient of thermal expansion and exceptionally high transmittance from the deep UV through the visible and infrared. Additionally, Fused Silica substrates are non-crystalline, exhibit extraordinarily low refractive index variations, low birefringence and are highly laser resistant. As a result, Fused Silica is a suitable material for most precision optic purposes including systems requiring extremely high LIDT and for very large components.

Inhomogeneity Grade						
Thickness (mm)	0	1	2	3	4	5
6.35	635nm	254nm	63.5nm	25.4nm	12.7nm	6.35nm
9.52	952nm	381nm	95.2nm	38.1nm	19.0nm	9.52nm
12.7	1270nm	508nm	127nm	50.8nm	25.4nm	12.7nm
25.4	2540nm	1016nm	254nm	102nm	50.8nm	25.4nm

Table 2: Wave-front deviations for substrates of various thicknesses and homogeneity grades.

Inhomogeneity can have an undesirable and sometimes catastrophic impact on the quality of a transmitted wave-front. We can estimate this impact by considering an inhomogeneity in an optic of thickness d. The resultant deformation of the wave front is given by

$$\Delta W = \Delta n \bullet d$$

Where ΔW is the transmitted wavefront and Δn is the peak-to-valley refractive index variation. Table 2 below illustrates the magnitude of this deformation for various optic thicknesses.

To highlight the importance of inhomogeneity, consider the wave-front deviation in a 12.7mm thick optic of inhomogeneity grade 3 and that this product requires a surface finish of flatness no more than $\lambda/20$ where λ = 633nm. Polishing the optic to more than a $\lambda/10$ is pointless as the wave-front deviations introduced by inhomogeneity are greater than deviations caused by surface flatness $\lambda/20$. Material of grade 4 or higher would be more suitable. Additionally, in highly sensitive and thick optics like etalons too much inhomogeneity can have a catastrophic impact on performance and finesse.

When investigating the material, one also commonly finds bands up to a size of a few mm running through the material where the refractive index varies. These are called striae and are also classified in ISO 10110 Part 4. The definition of striae refers to the finished optical component and there are four different classes (see Table 2014-02b), with only striae causing an optical path difference ('OPD') of at least 30nm being considered in most cases.

Striae Class	Density of Striae causing an OPD of at least 30nm in %
1	≤ 10
2	≤ 5
3	≤ 2
4	≤ 1
5	Striae free, 30nm OPD rule does not apply

Table 3: Striae classes in optical materials as per ISO 10110 Part 4

Corning Fused Silica is notable in that all types are grade 5 in striae aside from industrial grade FS i.e. free of striae. This means that all a customer generally needn't worry about striae introducing additional unwanted aberrations when purchasing an optical component made of Fused Silica from us.

In ISO-compliant drawings, inhomogeneity and striae are referred to by code number 2 followed by a forward slash and the homogeneity and striae classes, for example:

Glass	n_e	• 10^{-6} K 20 - 40°C e-line	expansion cf. a • 10^{-6} K	G • 10^{-6} K
Corning FS	1.46008	10.2	0.52	10.4
N-BK7	1.51872	3.00	7.1	6.68
N-PK51	1.53019	-6.70	12.35	-0.15
N-FKS	1.48914	-1.00	9.2	3.50
N-LAF2	1.74791	1.00	8.06	7.03
F2	1.62408	4.40	8.2	9.52
SF57	1.85504	12.50	8.3	19.6

Table 4 (Above): A sample of glass properties from the Schott glass catalogue with Corning Fused Silica for comparison. (e-line corresponds to 546.2nm)

2/A;B with A being the Inhomogeneity class and B the Striae class

Some manufacturers may also specify the temperature coefficient of the refractive index which prescribes how the refractive index varies with the temperature. This is an additional important consideration for an optical component designed for use in environments of much higher or lower temperatures than room temperature. As before, these variations are rarely appreciable for reflective optics but for transmissive components the quality of a transmitted wave-front may degrade in extreme temperature environments. The variation with temperature also modifies the focal length of a lens. Some temperature coefficients and other specifications for certain Schott glasses are given in table 4 overleaf.

As given in table 4: we see that some glasses are composed of a material with a negative temperature coefficient, meaning that at higher or lower temperatures (within the range of applicability) thermal expansion/contraction can compensate for the variations in optical path length. The effectiveness of this compensation is parametrised by the following equation.

$$G = a(n_{rel}(\lambda, T) - 1) + \frac{dn_{rel}}{dT}$$

Where **n** is the thermal expansion coefficient, **T** is the temperature of the optic and n_{rel} is the refractive index. Components with a value of G close to 0 are said to be "athermal". In powerful laser systems that have a tendency to heat up the optics considerably it may be wise to consider purchasing components constructed from athermal materials.

Especially when specifying larger pieces of material with high homogeneity and low striae (2/5;5, for example) it is advisable to contact potential material suppliers beforehand to ensure the manufacturability of the material and get an indication of potential delivery times. Where budget constraints are present, a cost indication will also be helpful as costs of high grade materials can rise exponentially with the required size of the raw material.

Fabrication of Optical Glass

The fabrication of precision optics is an involved process requiring extensive shaping, grinding and polishing. If required, finishes with Angstrom scale (m) surface roughness (RMS) are achievable. The techniques, science and machinery of glass fabrication is a complex subject and so the purpose of this technical note is to provide a general overview of the process. The specifics and subtleties of optical glass fabrication will be covered in future technical notes.

Chapter 40 of the Optical Society of America's Handbook of Optics Vol. 1 (1995) lays out the five steps of optical fabrication as:

• **Rough Shaping** – Shaping of raw glass into a blank approximately 1mm larger than the finished part

• **Milling**– Further shaping of optical surfaces to better than 0.1mm and preparation for polishing

• **Loose Abrasive Lapping, Grinding** – Grinding or "Lapping" of the optic to remove damage from the previous step and shape the optic to within a few micrometres of the desired curvature

• **Polishing** – Polishing of the ground surface to the desired finish quality

• **Edging** – Realignment of the optical axis joining the two optical surfaces and the mechanical axis of the optic

These steps mainly apply to the fabrication of curved components however many are also applicable to plano-optical surfaces.

Rough Shaping

An optical component will generally begin life as a slab of glass produced by a manufacturer such as Schott, Corning, Nikon, Heraeus or others. Pieces with uniform properties or quality will be cut from the slab and ground into a desired shape, but only very roughly and generally larger than the final piece. Optics can be rounded either manually or via machine rounding, the latter being more economical in most cases. Rounding accuracies of ±0.050 mm are common in the industry. These roughly shaped pieces come in a variety of shapes, sizes and compositions, with properties such as refractive index, Abbe number (dispersion) and dimensions specified by the manufacturer.

Grinding

Blanks straight from a manufacturer are very rough and should be larger than the design of the optical component. To prepare them for grinding and polishing they must undergo a grinding process where they are ground down and shaped to bring them close to the dimensions and curvature of the final optic. Grinding is a collective term for "curve generating", "plano milling" (grinding on a surface grinder) also called "fine grinding". If the final piece is a lens or other curved optic then curve generators are required. These devices consist of two spindles, one to hold the workpiece and the other to hold the diamond cup-shaped grinding wheel which generates the curve. Generation proceeds by either rotating the workpiece at a high rate and allowing the cup-wheel to grind against it at a lower rate or by allowing the diamond tool to cut into the glass and generate a curve at the depth of the cut. In both methods the radius of curvature is determined by the angle at which the wheel is positioned relative to the mechanical axis of the blank.

Plane surfaces are ground according to a method based on surface grinder in machining. The setup consists of a rotating workpiece table and a diamond face wheel. Once loaded, the workpiece table is adjusted and moved underneath the diamond wheel. The wheel is then adjusted and lowered until it makes contact with the rotating table at which point it rotates and the grinding proceeds until the desired amount of material is removed. A typical surface grinder consists of an 11inch diameter diamond wheel which rotates at 1200rpm and a 20in diameter workpiece table which rotates at adjustable speeds such as 15, 24, 41 or 64rpm. Grinding machines tend to be very large and rigid hence they are capable of grinding many workpieces simultaneously to a high and repeatable standard of accuracy. Prism grinding requires diamond tools mounted on machines with adjustable spindle angle and height due to the specific angles involved in the design of a prism.

The methods outlined above can be described as “coarse grinding” operations contrasted with so-called “fine grinding”. Fine grinding involves spherical laps that are studded with diamond pellets and comes after the initial shaping via coarse grinding. Workpieces are mounted onto a convex or concave arm which grinds against the diamond riddled surface. Finely ground surfaces tend to have pores only 2-3 µm deep and polish out faster than surfaces ground with loose abrasives however it is a much more expensive process.

All grinding processes require a liberal supply of liquid coolant to be applied to the workpiece and diamond tool otherwise they will heat due to friction, causing potential damage to both the machine and the workpiece. Coolants should possess highly lubricating properties to reduce wear on the diamond tool and should have a low viscosity, enabling it to carry away eroded material.

Being no more than a piece of glass fresh from a factory, a blank is understandably very rough and will not be in the desired shape of the final optic, so shaping the blank is traditionally achieved via “generating” where cup-shaped grinding wheels generate the concave or convex shape of a lens, the radius of curvature being determined by the angle at which the wheel is positioned relative to the mechanical axis of the blank. A surface mill often consisting of a diamond or abrasive face wheel is a staple of optical workshops as it is generally used to prepare plano-surfaces. The work piece can be either a single part or a (large) number of small parts fixed to a rotating table beneath the wheel. With the table spinning the wheel is lowered until it touches the optics and the milling process begins. Numerous machines with adjustable angles exist for the shaping of plano-prism surfaces.

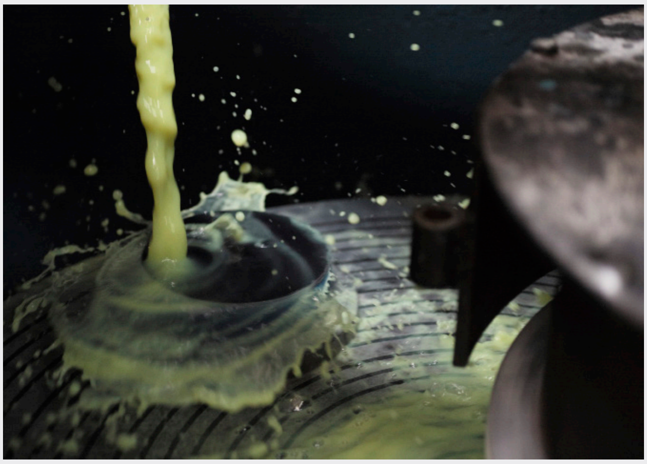

Figure 1: A Blank undergoing shaping/rough grinding

Loose abrasive lapping

With the glass now in roughly the right shape it undergoes Loose Abrasive Lapping (sometimes known as Loose Abrasive Grinding) to remove fractures caused by shaping and to improve the overall sphericity. Before this is done, the edges of the optic are bevelled to avoid small pieces of material chipping off and scratching the surface. The lapping process removes stock via the friction between the glass and the lapping plate in conjunction with a combination of water and grit. The grains in the resultant slurry move back and forth, the sharp edges penetrating the surface of the work-piece. This introduces tiny, local fractures into the surface of the glass, leading to splintering and the removal of material as well as introducing pits into the surface. The size of the individual grains in the slurry can vary from around 3µm up to around 300µm, with a larger grit size leading to a faster removal rate at the cost of a rougher finish. As a result, lapping often begins with rougher solutions in a process known as roughing with grain sizes of at least 120µm followed by a pre-grind (45-80µm) where surface roughness and shape are improved, and centre thickness’ brought to exact dimensions. The work-piece then proceeds to the pre-fine (15-35µm) stage followed by fine grinding with grit size 3-12µm. As small grains produce pits that are about half their diameter the surface is refined to a micrometre scale surface roughness by the end of the process.

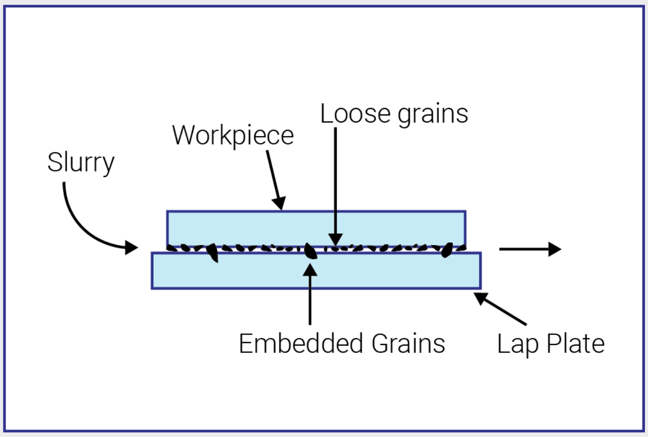

Figure 2: The workpiece is ground against a table or plate whilst a gritty slurry is continuously applied.

Tool Type	Abrasive Grain Size µm
Roughing	115-230
Pre-Grinding	45-75
Pre-Fine	17-29
Fine-Grinding	3-13

Table 1: A typical set of grinding tools

Grinding tools can be either spherical or plano and are generally made of cast iron. They are designed for use with specific grain sizes, for example a typical set of grinding tools for use with specific grain size is given by table 1.

For spherical tools the curvature of the tools must be adjusted such that the next, finer abrasive grinding tool grinds from the edge i.e. the radius of curvature of concave tools becomes shorter and shorter whilst becoming longer and longer for convex tools. This division is necessary to grind off a layer of uniform thickness to remove pits from the preceding stage of the process. There is no such equivalent requirement for plano-tools.

Polishing

The next stage of the optical fabrication process is known as "polishing". It is at this stage that optical components will reach their final shape and acquire a transparent, optical quality finish. The best possible surface finishes are possible through a polishing method known as "Pitch Polishing". In pitch polishing the glass is finely polished in a process similar to lapping only with a lap composed of pitch and a watery slurry containing oxide-based polishing compounds. The pitch covers a circular ring or platform and rotates around with the workpieces affixed to a moving overarm or resting in a jig held by the overarm. Grooves are cut into the pitch to encourage a steady flow of slurry between the lap and the optic. These grooves should be inspected and re-cut frequently as the pitch is worn and down and warps over time. Weight has a significant influence on the rate and quality of the polishing process and so optics should be catered to depending on weight by, for example, placing weights atop a workpiece or overarm.

Pitch is a unique, viscoelastic compound which occurs naturally but can also be produced synthetically, the basic types being wood pitch (deciduous and coniferous), rosin based (green and yellow), petroleum based, and asphalt tar pitch (coal based). Over time the pitch will conform to the shape of the optic, smoothing it without causing deviation in the radius of curvature/ sagitta. Pitch can have a variety of hardness', where hard pitch is more effective for high speed polishing, smaller workpieces, convex surfaces and standard quality optics whereas soft pitch is more effective for the low speed polishing of large workpieces, high precision optics and concave surfaces. The microscopic mechanism behind polishing is thought to be down to the chemical and mechanical reactions between the slurry and glass. Through the energy provided by friction the oxide slurry is thought to chemically soften the surface of the optic down to a depth of a few nm such that it is dissolved into the water or worn away mechanically by the action of the slurry on the glass. It is through these mechanisms that surface roughness is improved from the micrometre scale to 1nm rms or even less

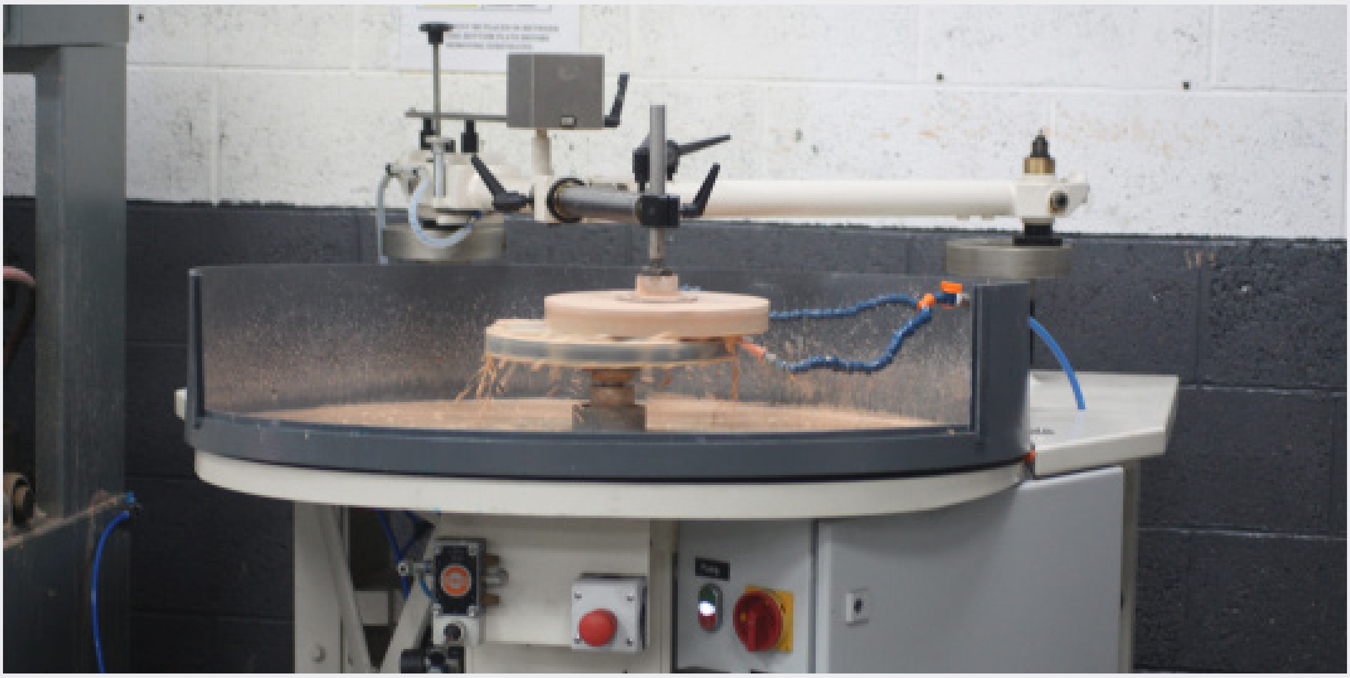

Figure 3: A pitch polisher consisting of a pitch lap and a motorised overarm for the workpiece.

Centering

The last step in the fabrication of precision optics is lens centering and edging. Even though by this point the surface finish and curvature of the optic are extremely high quality the process outlined above may introduce a slight wedge of a few minutes of an arc. This means that the optical axis between the centres of curvature of a lens does not coincide with the actual mechanical axis and must be corrected.

One method for re-aligning the axes is the Transfer Spindle method where the lens is mounted on a mandrel fastened to a spindle such that either the mechanical or optical axis is aligned with the axis of the mandrel. The spindle, mandrel and lens are then mounted to a centering machine which grinds the diameter of the lens concentric to the axis of rotation. This method can be carried out either optically or mechanically. Another method, known as "Bell Chucking" consists of clamping the lens between two precision aligned brass mandrels or bell chucks. As the chucks rotate and grind the edge of the lens it will naturally position itself such that the edges are ground to a point of equal thickness, thus making the optical and mechanical axes co-linear. Bell Chucking is depicted in figure 4.

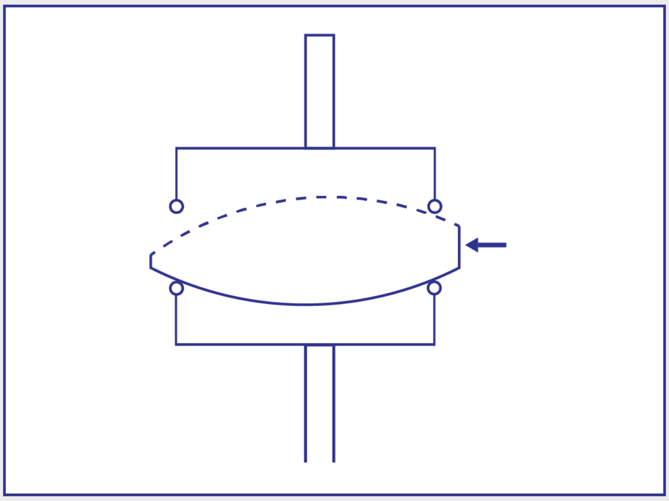

Figure 4: A convex lens having its mechanical axis aligned with its optical axis via the Bell Chucking method.

Surface Cosmetics

The surface of optical components plays an integral part in their overall performance as imperfections on an optical surface can increase scatter loss and reduce coating adhesion, as well as laser induced damage threshold (LIDT).

Therefore, especially when optical components are required to withstand high laser power, a cosmetically suitable substrate surface is essential. The surface standards (MIL and ISO) dealing with surface cosmetics date back to times before the development of powerful lasers and still contain a 'human element', relating to the 'visual appearance' of a surface defect. By comparison, interferometric measurements to determine the surface flatness do no longer rely on the manual evaluation of interference fringes.

The surface cosmetics of optical components is defined in ISO 10110-7 and MIL-PRF-13830B. For catalogue optics the MIL specification is most commonly used, though Manx Precision Optics works according to both ISO and MIL specifications, depending on the customer requirement. Below is a discussion of both the ISO and MIL specification methods.

ISO 10110-7

The ISO standard at the time of writing (ISO 10110:7 2017) defines a surface imperfection as an "artefact of limited extent within a test region on an optical surface, optical element or optical assembly produced by improper treatment during or after fabrication or in use, or by a material imperfection located at the surface". These imperfections are sub-divided and classified as "long scratches" which are imperfections that are at least 2mm in length, "edge chips" i.e. material that has been removed from the periphery and "digs", imperfections which are not long scratches or edge chips. Digs themselves come in a variety of shapes and sizes, they may take the form of scuffs, pits, coating blemishes and adhering particles among other defects.

There exists two methods for specifying tolerances on an optical drawing, represented by a particular code. These two methods are known as the "dimensional" and "visibility" specification methods respectively, though the latter will be discussed in conjunction with MIL as they are very similar. One or more test regions on the optical surface may be specified otherwise the effective aperture of the surface is the test region.

Dimensional Specification

On optical drawings ISO defines a code number and numerical term specifying permissible surface and localised imperfections. The code number for surface imperfections on a particular surface or element is designated with 5/ whilst for localised surface imperfections within an assembly it is 15/. In the dimensional specification method, the maximum permissible surface imperfections are given by:

$$5/ \text{ or } 15/\, N_G \times A_g\, ;\, WA_w$$

or

$$5/ \text{ or } 15/\, N_G \times A_g\, ;\, WA_w$$

Where N_G is the number of allowed imperfections and A_g is the grade number, equal to the square root of the area of maximum allowed imperfection. It should be expressed in millimetres. ISO recommends grade numbers selected according to the Renard R5 series: 4; 2.5; 1.6; 1.0; 0.63; 0.4; 0.25; 0.16; 0.1; 0.063; 0.04; 0.025; 0.016 and 0.01. Values greater than 4 or less than 0.01 are allowed but the standard does not recommend them.

If it is necessary to limit width imperfection then an additional term, WA_w can be specified with A_w being the maximum permissible width of any imperfection in millimetres. For example, the specification 5/1

×1.6; W0.4 means that the maximum allowed area of an imperfection is 1mm^2 and the maximum width is 0.4mm which implies that the maximum length of an imperfection is 2.5mm.

A specification for long (>2mm) scratches is given by the code:

$LN_l \times A_l$

Where L is the indication for long scratches, is the allowed number of long scratches and A_l specifies the maximum allowed width, again expressed in millimetres and a value from the Renard R5 series.

There also exists an ISO code for coating imperfection tolerances indicated by:

$CN_C \times A_C$

Where C is the designation for coating imperfections, N_C is the number of allowed blemishes of maximum permissible size and A_C relates to the area of the coating imperfection the same way A_g does for a surface imperfection. Edge chips are designated by:

EA_e

Where E is the indication for edge chips and A_e is the maximum permissible extent of such a chip in millimetres, measured to the centre of the optical surface. ISO 10110 states that any number of chips are permissible as long as their extent is not greater than A_e, or if the tolerance is not specified then the edge chips should not impinge upon the effective optical area. With all these indication codes a complete imperfection indication is written in the form

$5/ \text{ or } 15/ Ng \times Ag \,;\, CN_c \times A_c ;\, LN_l \times A_l \,;\, EA_e$

or

$5/ \text{ or } 15/ N_g \times A_g \,;\, WA_w \,;\, CN_c \times A_c \,;\, EA_e$

ISO deals with surface imperfections with a smaller grade by permitting them as long as the sum of the areas they cover does not exceed the maximum total area allowed by the tolerance, given by $N_g \times A_g^2$ with a similar calculation for coating imperfections. For example, the designation 5/1 × 1.6 is equivalent to 5/ 16 × 0.4. In this calculation, imperfections of grade 0.16A are not counted, and neither are scratches with a width 0.25A_l.

MIL

The U.S. Military MIL standard is a common specification and convention for specifying optical surface quality. The MIL specification defines the surface cleanliness as 'scratch-dig', two dimensionless numbers relating to the visual appearance of the size of scratches and digs when compared to a reference sample. Scratches are defined as any marking or tearing of the surface whilst digs are defined as imperfections with the appearance

Scratch Grade	Max Width mm	Max. Width in.	Dig Grade	Max Width mm	Max. Width in.
80	0.08	0.0031	50	0.50	0.020
60	0.06	0.0024	40	0.40	0.016
40	0.04	0.0016	30	0.30	0.012
20	0.02	-1.00	9.2	3.50	0.008
10	1.74791	1.00	8.06	7.03	0.004
5	1.62408	4.40	8.2	9.52	0.002

Table 1: Typical scratch and dig grades within both the ISO and MIL standards. Scratch grades are determined using some standard of calibrated visual inspection and are not exact.

of small rough spots. Typical grades for scratches are 80, 60, 40, 20 or 10 whilst for digs typical grade numbers would be 50, 40, 20, 10 or 5. There also exists the requirement that the total length of all maximum grade scratches should never exceed 1/4 of the optic's diameter. The scratch grade is assigned based on a visual inspection using some form of comparison standard, whereas the dig grade is 1/10 times the apparent size of the dig in micrometres, or 100 times the dig width in mm. For example, 10-5 means that the maximum allowable width of a scratch corresponds to grade 10 and the maximum allowable dig diameter is the width corresponding to grade 5. The table below illustrates the possible scratch and dig denominations in more detail.

MIL specifies that when a maximum size scratch is present, the sum of the products of scratch numbers S_i weighted by the ratio of their lengths l_i to the diameter of the optic D or test region shall not exceed half the maximum scratch number S, or:

$$S > \frac{1}{2}\sum_i S_i \frac{l_i}{D}$$

Or if no such maximum grade scratch is present then the same sum takes place with the 1/2 omitted. For digs, MIL specifies that there should be only one maximum size dig per 20mm of diameter of an optical surface, and the sum of all estimated dig diameters should not exceed twice the diameter of the maximum size per 20mm, with >2.5µm diameter digs ignored.

The ISO visibility specification method is another way of specifying cosmetic tolerances that is similar to MIL. On an optical drawing it is indicated with 5/ for a test region on an optical surface or 15/ for a localised surface imperfection within an assembly, and written as:

5/ or 15/ (S-D)

Like MIL the maximum sum of scratch lengths should not exceed 1/4 of the surface diameter, and the scratch and dig grades are the same as those in table 1. At the same time however, it is worth keeping in mind that MIL and ISO define digs and scratched differently. Typically, the designation 40-20 or 5/40-20 is a standard quality for many optical components, with 20-10 a standard tolerance in precision optics and 10-5 necessary for high-power laser systems. If no scratch-dig is designated then the tolerance is assumed to be 80-50.

The relevant inspection methods require an inspection using either a 40W incandescent light source to illuminate the component from behind or a 15W cool white fluorescent light approx. 3" from the component. The component is inspected against a black background. While this is a useful method, it can be improved where a very high surface cleanliness is required and the 40W standard light source does not show up smaller defects sufficiently. This is, for example, important when manufacturing optical components for fibre lasers.

As the table above shows, a size 5 dig is permissible to have a diameter of 50µm. If a powerful laser beam with less than 1mm beam diameter was to hit such a dig, the optical coating would most likely be damaged. Hence, it is important to improve the surface cleanliness even further.

For this reason, all optics at MPO are inspected against a black background, illuminating the optics from the back, but instead of using a 40W incandescent light source MPO uses a 50W halogen light source. This makes a huge difference as many optics passing the 'standard' 10-5 scratch-dig requirement would easily fail this much more rigorous inspection. MPO refers to this much more stringent inspection method as '10-5 scratch dig laser grade'.

Interferometry & Interfermatic testing of Optics

As the name would imply, in the precision optics industry components must be manufactured to an extremely high level of quality in terms of surface finish and shape with minimal aberrations. Therefore, the importance of accurate measurements of these properties is absolutely paramount. Interferometry is a field of measurement techniques exploiting interference for that purpose among many other uses.

There are a multitude of interferometer designs with various advantages and disadvantages. Two beloved examples are the Newton and Fizeau interferometers, though the latter sees far more use than the former nowadays. Newton interferometers are named after Sir Isaac Newton for his observation of the interference fringes that occur when two pieces of glass are separated by a small, air-filled wedge though it was Joseph Fraunhofer who was the first to use this phenomenon to measure optical surface flatness, well over a hundred years after Newton's death. A typical Newton interferometer consists of a monochromatic light source, beam splitters, collimators, an imaging system (a human eye, for example), a test optic and a reference flat. A possible set-up is given by figure 1.

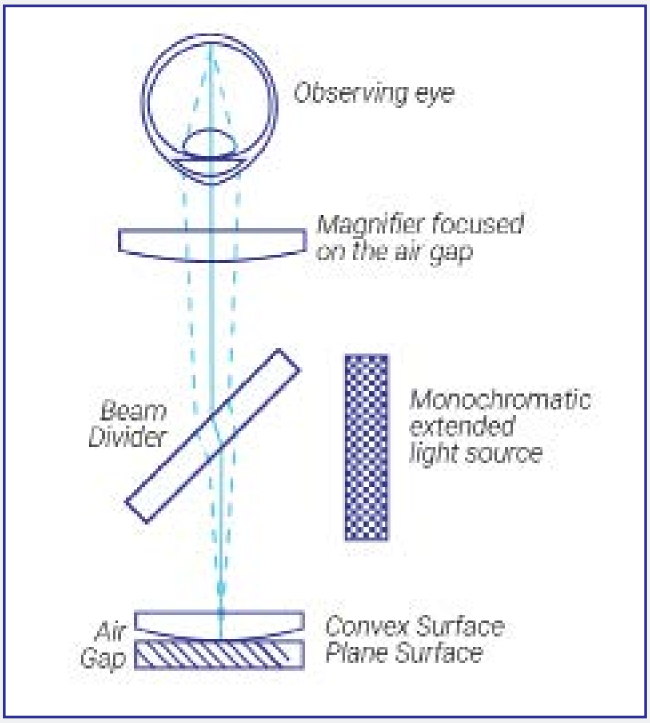

Figure 1: A Newton interferometer. The two contacted pieces of glass are illuminated by monochromatic light directed by beam-splitters and collimators.

In a Newton interferometer two pieces of glass are put into contact and a small wedge is introduced between the pieces. Monochromatic light incident upon the glasses undergoes various reflections off different surfaces. The light reflecting off the bottom of the first piece undergoes a 180deg phase shift whereas the light reflecting off the top of the second piece does not and transmits back through the first optic. These two reflected beams will interfere, the fringe pattern depending on the optical path difference (OPD) arising due to the wedge. At points where the wedge size is an integer number of wavelengths, we see a dark fringe, and at points where it is a half integer we see a bright fringe. If the first surface is curved, we see the famous Newton's rings. In interferometry for optical surface measurements, the first glass piece is the test piece being measured and the second is a reference surface or test flat. The reference flat is a component of many (but not all) interferometric systems, it is often a slightly bevelled piece of glass with a very high-quality surface finish and as the name implies is the standard that the test optic is being compared to. The surface quality of such an optic determines an absolute upper bound on the resolution of the interferogram for determining surface flatness. To understand how an interferogram is analysed, please see our technical note on fringe interpretation.

The Newton interferometer along with other interferometers has the drawback that it requires two optical surfaces to be brought into contact, which risks introducing scratches and surface imperfections if mishandled. Dirt and dust trapped within the wedge also limits the resolution. Additionally, a different curved reference piece is required for every different radius of curvature, which is very costly. The aforementioned Fizeau interferometer is therefore a preferable choice as it has a much larger air gap, eliminating the risk of damaging the test or reference pieces. Fizeau interferometers only required a limited number of transmission spheres to measure a variety of spherical surfaces, making them far less costly in that respect. Due to the air gap a Fizeau interferometer generally requires a collimation system. The reference surface is placed in front of the test piece.

The interference principles in a Fizeau interferometer are similar to that of a Newton interferometer. The reference and test pieces are brought close (but not into contact) to each other, the size of the air gap is varied to calibrate and adjust the interferogram.

A fringe pattern consisting of straight lines implies that the test optic is flat otherwise if aberrations or defects are present the pattern is distorted. 2 examples of aberrations are given in figure 3. The subject of aberrations is discussed in the previous chapter.

Through analysis of interferograms an optical component can be brought into its final shape. Aberrations, scratches and other defects can be identified and selectively removed via the selective pitch polishing of substrates. The measurement and subsequent correction of such features is vital in the production of precision optics to assure high LIDT and no unwanted scattering or redirection of light.

Interferometry can also be utilised to measure the Group Delay Dispersion or GDD of an optic. Light is reflected off the mirror under study and interferes with a test wave. By measuring the interference pattern across a range of wavelengths a GDD curve can be extracted making interferometry invaluable in the production and testing of ultrafast mirrors.

Through careful interferometry and polishing, MPO is able to offer optics and substrates polished to ångström scale levels of smoothness, highly suitable for all your precision optic needs.

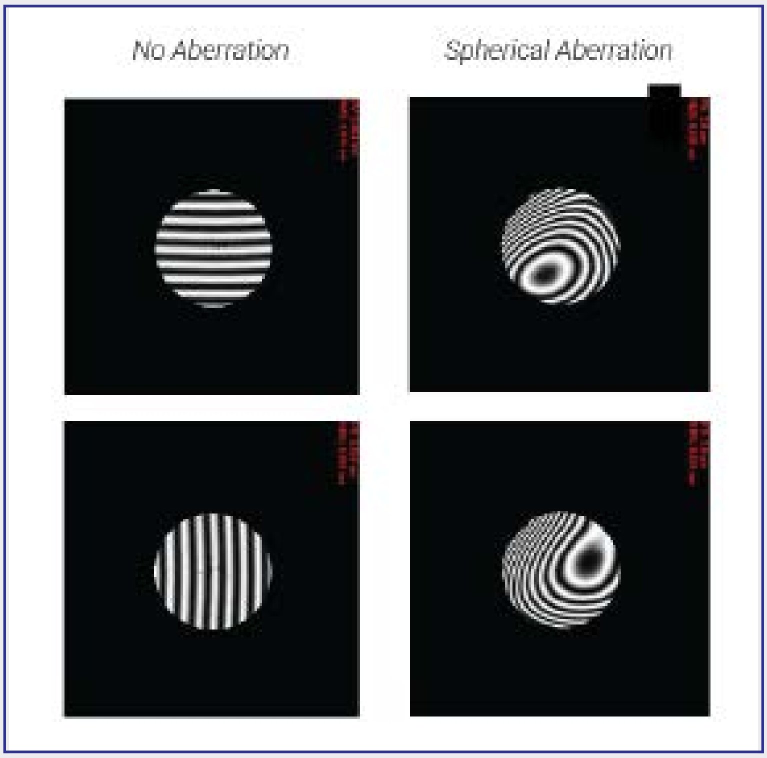

Figure 3: Comparison of fringe patterns between an optic with No aberrations and one with Spherical

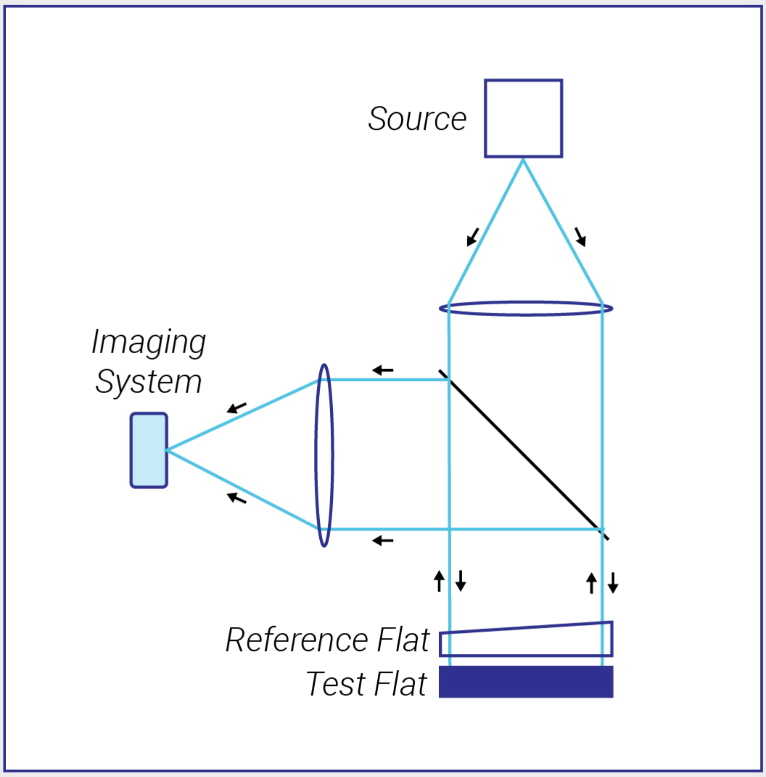

Figure 4: A typical Fizeau interferometer setup for measuring flat test pieces.

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Technical Guide

Optical Coatings

Coating Materials

Different materials are best deposited under different conditions and techniques as properties such as melting and sublimination points all differ greatly. Oxides in particular tend to be deposited under oxygen rich conditions as to encourage oxidisation or re-oxidisation of the material as it grows on the substrate.

An important property of all coating materials is the purity, often a purity of at least 99.99% is required for losses due to impurities to become neglible with respect to other scatter and absorption losses. Additionally, impurities can also have a marked effect on the coating process. Below is a brief overview of some common thin film materials as well as tables of optical properties and melting points.

Diaelectric Materials

Dielectric materials are transparent materials with an extinction coefficient of zero, though in reality many are transparent over a certain bandwidth of electromagnetic radiation over which they have a negligible coefficient of extinction. Due to the chemical diversity of dielectric compounds they cover a wide range of refractive indices and are therefore viable materials for a huge array of optical coatings, though they are limited by factors such as adhesion and deposition technique. The oxides are a notable sub-type of dielectric coating material in that most are high index and tend to require reactive deposition techniques. On the upside they tend to be very hardy as well.

Magnesium Fluoride (MgF2)

Magnesium Fluoride is a classic low index material for anti-reflection coatings. It has a refractive index of around 1.39 in the visible and is transparent from around 150nm into the far-infrared with low dispersion. It is however prone to spitting unless the purity of the material is extremely high, and MgF2 films tend to have high stress meaning that they are unsuitable for complex multilayers.

Zinc sulphide (ZnS)

Zinc Sulphide is an easy to handle material that sublimes rather than melts. It has a high index 2.35 at nm, though it is not very robust. It has a very large transparency bandwidth stretching from the visible to very far into the infrared, though it is absorbing in the near UV.

Cryolite (Na3AlF6)

Cryolite, like ZnS is also an easy to handle material sublimes rather than melts not being terribly robust. Unlike ZnS it is a low index material with an index of 1.35 and is more useful in the near UV as it is transparent over that bandwidth in addition to the visible and near infrared.

Silicon Dioxide (SiO2)

Silicon dioxide or silica is an excellent low index (1.46 in the visible, lowest of the oxides) dielectric material for coating due to its very low dispersion and generally amorphous thin film structure. It is common to find many optics with SiO2 overcoats as it is hard and resistant to scratches. It is transparent from around nm to into the far infrared and requires electron-beam deposition and magnetron sputtering due to its high melting point.

Aluminium Oxide (Al2O3)

Aluminium Oxide is an absorption free material from around the far UV, throughout the visible and well into the infrared with a refractive index of around 1.62 at 600nm, though it becomes highly absorbing moving further into the UV. Additionally, it possesses low dispersion It adheres very well to substrate glasses, oxides and metals making it suitable as a buffer or protective layer for metal mirrors. The refractive index makes it suitable as a middling layer in multilayer ARs as it is higher than the refractive index of many glass substrates, but below that of “high” index materials..

Zirconium Dioxide (ZrO2)

ZrO2, also known as Zirconia (or fake diamond) is a tough, high index material (n=2.17 at 532nm) with a wide bandwidth over which it is transparent, stretching from the near-UV into the far infrared though it quickly becomes absorbing moving further into the UV. The combination of large usable bandwidth, low dispersion, high index and excellent durability makes it ideal for a variety of broadband coatings among many other coating types. It is generally deposited via sputtering or electron beam deposition due to its high melting point.

Tantalum Oxide (Ta2O5)

Tantalum Oxide is a very high index material (2.16 at 550nm) with low losses, high stability and an exceptionally large transparency range stretching into the infrared. It is best deposited via energetic deposition techniques with IAD.

Titanium Dioxide (TiO2)

Titanium Dioxide is a resilient and robust material among the oxides. In the visible it has an exceptionally large refractive index though absorption at wavelengths below 350nm into the near-UV limits its applications. The refractive index of TiO2 can be as high as 2.65 but it largely depends upon the deposition process as the index is highly structure dependent. As a result, TiO2 is best deposited under energetic conditions in carefully controlled, reactive processes.

Hafnium Dioxide (HfO2)

Hfo2 or Hafnium oxide is a high index material with a similar refractive index (2.0 at 500nm) to ZrO2 and wide transparency bandwidth. Also, like ZrO2 it possesses high adhesion and is very hard, making it ideal for a variety of laser applications and an overall good alternative. It is deposited with electron beam deposition or through reactive sputtering.

Material	Melting Point °C	Refractive index @550nm	Transparency Bandwidth
MgF2	1261	1.38	150nm - 8µm
ZnS	1850	2.35	400nm - 14µm
Na3AlF6	1000	1.35	200nm - 14µm
SiO2	1720	1.46	200nm - 9µm
Al2O3	2000	1.62	190nm - 7µm
ZrO2	2800	2.1 yb	230nm - 7µm
HfO2	2750	2.0	230nm - 8µm
TiO2	1850	2.2-2.7	400nm - 8µm
Ta2O5	1862	2.16	350nm - 10µm

AR Coatings

Uncoated optical surfaces reflect a percentage of incoming light due to Fresnel Reflectivity. The exact amount reflected depends upon the refractive index of the substrate material and the refractive index of the medium (for air). In optical systems containing a large number of surfaces, the various orders of reflection can drastically reduce the contrast of the projected image in an imaging system, and lead to unacceptable losses in transmission. The various orders of reflection are depicted in figure 1.

If we assume the substrates in figure 1 are made of glass with refractive index 1.52 then at first order approximately 4% of light is reflected, then at second order 0.16%, at 3rd order 0.0064% and so on. If we consider a complex optical system consisting of many surfaces such as within a camera then it is easy to imagine how losses mount. Even if we consider a single glass component for use in transmission, we lose just under 8% or so of the light due to Fresnel reflectivity off both sides of the optic. Worse still, the reflected light may produce unwanted interference. In a high-power laser system such losses are unacceptable.

Modern coating technology allows for significant reductions in the residual reflectivity of a surface or can eliminate it in some cases. So-called anti-reflection ('AR') coatings can, depending on circumstances, reduce the reflectivity of a surface to less than 0.1%. They are generally available for single and multiple wavelengths (where, for example, the application involves discrete laser wavelengths) or entire spectral wavelength bands .

AR coatings operate on the principles of interference in thin films. Thin film interference is covered in more detail in other technical notes but essentially coating a substrate with a thin layer of some material with a different refractive index than the medium or substrate separates the reflected light into components of opposing phase. They destructively interfere, eliminating the reflection. For a single quarter wave layer sitting atop a substrate of refractive index n_s , 100% transmission is achieved if the refractive index of this layer is given by:

$$n_l = n_s^{½}$$

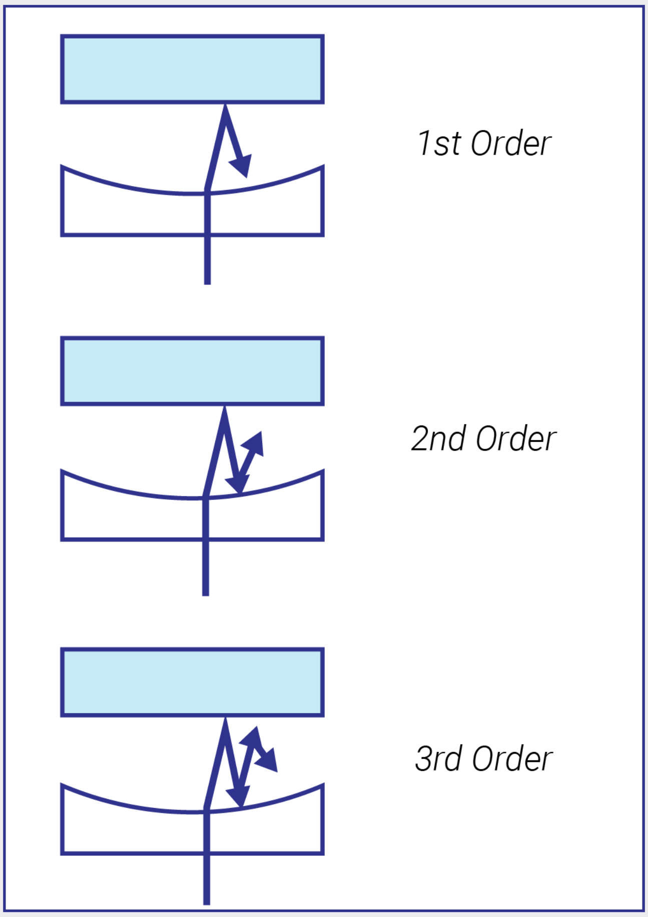

Figure 1: Orders of reflection. For a glass substrate around 4% of light is reflected at each reflection.

Assuming the incident medium is air. For crown glass of index n_s =1.52 this corresponds to an index of around n_l = 1.23. Unfortunately, no such material exists that can be easily coated onto glass. The next best thing is MgF2, Magnesium Fluoride which has an index of around 1.38. MgF2 coatings are nonetheless quite common as they still reduce residual reflectivity to about 1.3% per surface, a drastic improvement over 4%.

A system of multilayers can however improve the reflection further. Multilayer coatings tend to consist of at least three layers but generally no more than seven. Due to the spectral performance of these coatings they are sometimes referred to as "V" coatings. Layer thicknesses can be varied by computer optimisation procedures to generate more complex, high

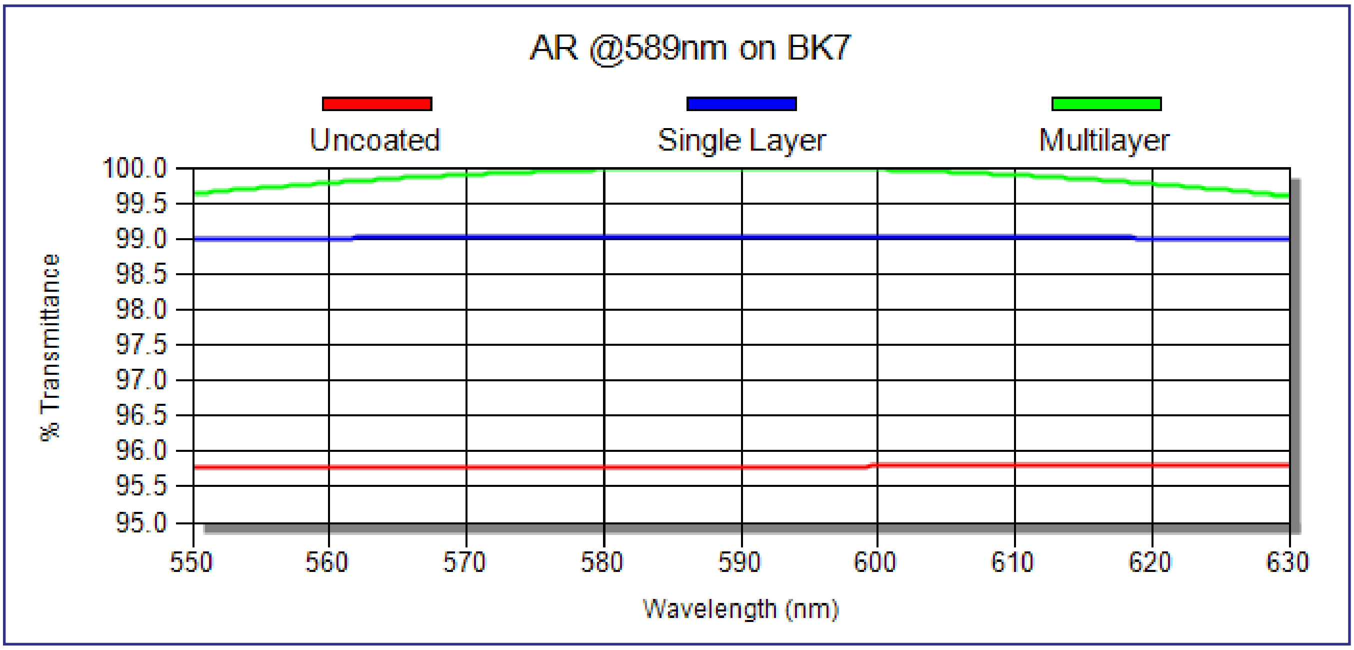

Figure 2: AR-coating performance on BK7 at 589nm (red: uncoated BK7, blue: single layer AR, green: multi layer AR "V" coating)

performance anti-reflection coatings such as broadband coatings (e.g. low reflection across the visible spectrum) or multi-wavelength coatings. Figure 1 below illustrates the performance of a single- and multilayer AR coating compared to an uncoated surface of a BK7 substrate at 589nm.

As a general rule of thumb, the more wavelengths need to be covered or the broader the required bandwidth for the AR coating is, the lower the specification has to be. As the coating materials are dielectric, the performance of an AR coating is also dependent on polarisations and therefore the angle of incidence. Manx Precision Optics offers a range of standard AR coatings, but where a specific specification is required, the company will work with the customer to find the best solution.

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Furthermore, the refractive index of the substrate material is important. Where an AR coating for several different substrate materials is required, the highest performance will be achieved with AR coatings designed specifically for each substrate material. This, however, can be very expensive and very often it is possible to find suitable solution by designing an optical coating that can be applied to different substrates at only limited reduction in performance.

At Manx Precision Optics Ltd. (MPO) we have got vast experience in AR coatings and are always happy to work with our customers in finding the best solution. We manufacture traditional e-beam and sputter coated AR coatings. The latter are very often the coating of choice for machine vision applications and to enable rapid prototyping, MPO can offer a quick turnround (3-5 working days) on many substrate sizes and wavelength ranges while also offering highly competitive pricing.

High Reflection Coatings, Interference Filters and Bandpass Filters.

The quarter wave stack is an elegantly simple yet incredibly versatile dielectric multilayer system that forms the basis of optical coatings from high reflection coatings to edge filters and beyond. The quarter wave stack is an optical assembly composed of alternating layers of high and low index dielectric materials with an optical thickness equal to a quarter of a specified design wavelength.

At the design wavelength a quarter wave stack is highly reflecting. The initial reflection of the first layer changes the phase of the first reflected wave by 180degrees as $n_{Air} < n_H$. The refracted beam reflects off the second layer and does not undergo a phase change as $n_L < n_H$ but it does travel an extra half wavelength which changes its phase by 180degrees. It therefore constructively interferes with the first reflected wave. At the interface between the second and third layer, the refracted beam travels a full wavelength but undergoes a phase change upon reflection meaning it again constructively interferes. Considering these reflections and refractions iteratively we see that the reflected beams interfere constructively, maximising reflection. The reflectivity of such an arrangement is given by equation:

$$R = \left(\frac{1 - \left(\frac{n_H}{n_L}\right)^{2p} \frac{n_H{}^2}{n_s}}{1 + \left(\frac{n_H}{n_L}\right)^{2p} \frac{n_H{}^2}{n_s}} \right)^2$$

Where n_s is the index of refraction of the substrate and 2p+1 is the number of layers. It is easy to see that if the term containing the indices is larger than 1 then increasing the number of pairs of layers increases the reflectivity. Theoretically we could deposit an infinite number of films to achieve absolute reflectance but this would not be feasible in the real world as coating stress, scatter losses etc would outweigh any potential benefit. In reality approximately 30 layers are generally sufficient.

The behaviour of the film over a broad band of wavelengths is given by figure 2.

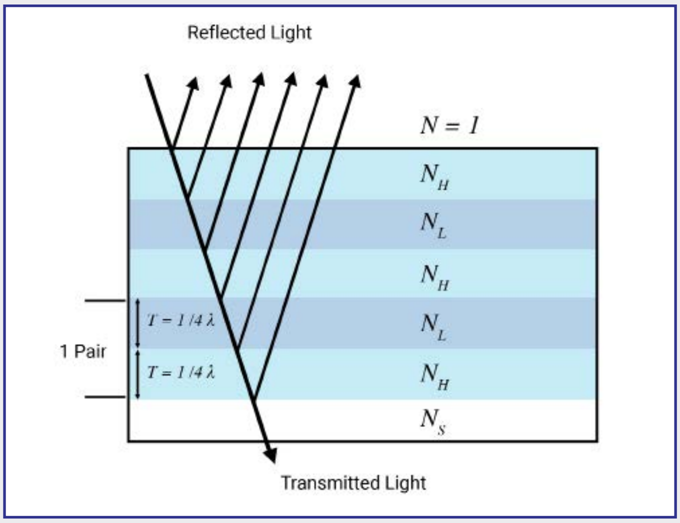

Figure 1: A quarter wave stack consisting of alternating layers of equal thickness and refractive indices N_H and N_L (where H denotes the "high" index and L denotes the "low" index).

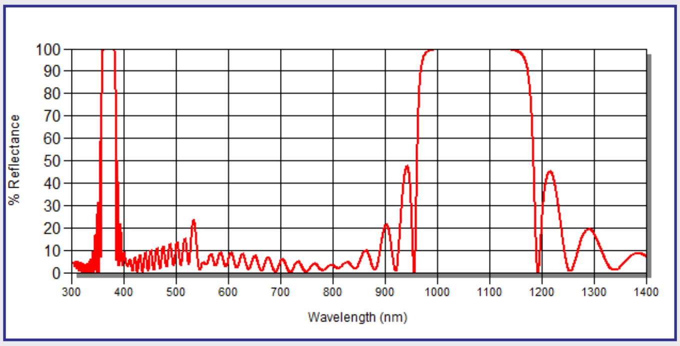

Figure 2: Quarter Wave Stack High Reflector designed for λ = 1064nm. Note the extra peak around λ/3 = 355nm and the shorter peak at λ/2 = 532nm.

Close to the design wavelength the high reflectivity is sustained with the breadth of the reflectivity band dictated by the ratio of the refractive indices of the materials used. The bigger the ratio, the wider the reflectivity band. This rapidly drops off into high transmission oscillations though additional high reflection peaks occur at wavelengths where the layers are an odd number of quarter wavelengths thick. The reflective properties and bandwidth can be further improved if we deviate from the design and modify the thickness' in accordance with a geometric or arithmetic series.

As indicated, this behaviour makes the quarter wave stack adaptable for use as an edge filter that filters out a section of the electromagnetic spectrum above or below a specified wavelength. These are referred to as long-pass and short-pass filters respectively. The oscillatory behaviour referred to in literature as the "ripple" is however undesirable and the quarter wave stack requires adjustments to reduce it such as the inclusion of matching layers between the multilayer and the substrate/air, or via design optimisation methods. Unwanted reflection bands can also be suppressed to extend high transmission zones.

Additionally, a pronounced reflectance peak sometimes referred to as the "2nd harmonic" tends to show up at $\lambda/2$ as seen in figure 2. This poses an obvious problem if a quarter wave stack is to be used as a low-pass filter. The peak is sensitive to variations in layer thickness and so can be suppressed by tweaking the design. On the other hand, it can be difficult to remove fully due to very small thickness deviations in the actual coating and in some cases a broadband transmission filter may be specified with an average transmission over the region rather than a lower bound on performance.

Quarter wave stacks or edge filters can additionally be implemented in band-pass filters, which consist of regions of high transmission bounded by regions of rejection. Broad band-pass filters can be achieved via stacking of a long-pass and short-pass filter on the same substrate with spacer layers to suppress interference between the two stacks.

Similar techniques and combinations of stacks can be used in the design of high reflectance dielectric mirrors with multiple design wave-lengths. These kinds of designs are more challenging however due to the number of layers and interference between stacks. Though spacer layers will suppress interference, small errors in layer thickness may reintroduce unwanted transmission or reflection peaks.

At MPO we work with our customers to determine the most suitable optical coatings for their specific applications. With years of experience and an intimate knowledge of thin film coatings design we can produce bespoke, quality coatings according to the specifications you require.

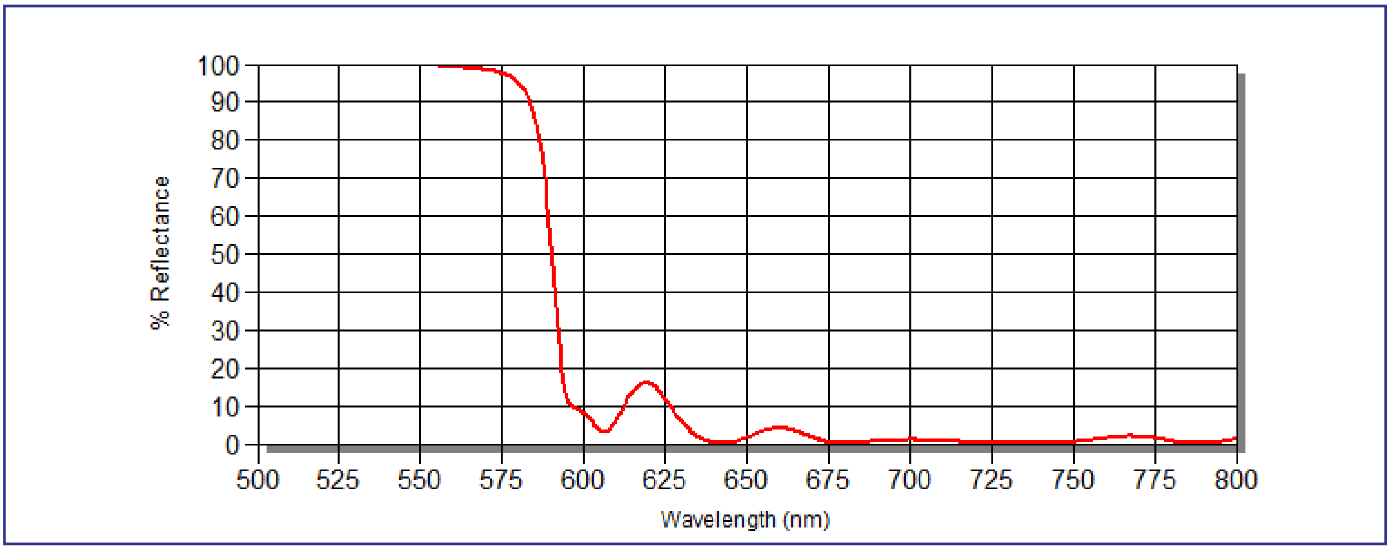

Figure 3: An example of a long-pass edge filter with a boundary between zones at λ = 580nm.

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Technical Guide

Specialised Optics

Ultrafast Coatings

In the nano-second pulse regime the effects of dispersion on pulse structure is neglible and LIDT is well understood to follow various scaling laws. However, the situation is different in the femto-second (10^{-15}s) or "ultra-short" pulse regime as averse dispersive effects become unavoidable and different laser damage mechanisms dominate. There are hence significant design challenges that must be overcome in this regime.

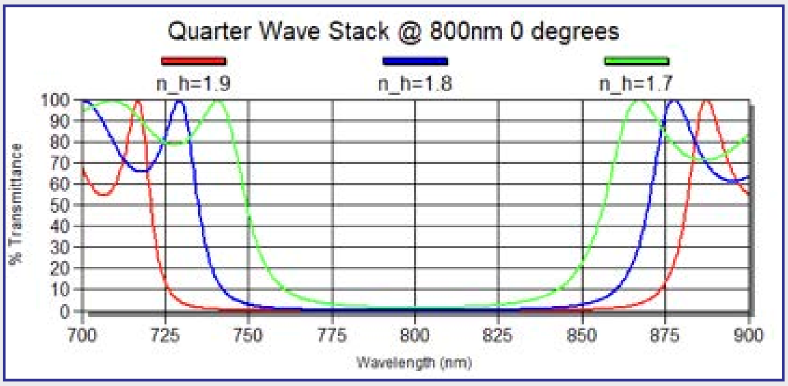

Figure 1: Transmittance of a highly reflector (HR) quarter wave stack at different values of the refractive index of the higher index material.

Optical coatings for femto-second pulses (ultrafast coatings) must fulfil the criteria of possessing a sufficiently wide bandwidth, allow for dispersion control, high LIDT in the femto-second regime and maintain high reflectivity across the bandwidth.

The staple Dielectric Ultrafast mirror was first developed in 1994 as an alternative to installing pairs of negative GDD prisms for counteracting the positive intracavity dispersion of ultrashort pulse lasers such as Ti:sapphire lasers. Residual higher order dispersion within the prisms presented a major limitation on ultrashort pulse generation due to pulse broadening. With their compact design and comparatively smaller higher order dispersions over large bandwidths, ultrafast mirrors quickly became and remain an industry staple, allowing for simpler cavity design, greater control over dispersion and more reliable ultra-short laser pulse systems.

From an optical design point of view, the requirements of ultra-fast coatings raise specific challenges. A standard laser line, high-reflecting mirror design (Bragg reflector) is usually a stack of alternating coating layers of high and low refractive index, each with an optical thickness of lambda/4. Apart from a high LIDT and reflectivity, the advantage of such a design is also the relatively good GDD performance. In such a design the breadth of the reflectivity band is determined by the ratio of the refractive indices of the low and high refracting materials. This is illustrated in fig 1 below which depicts the reflectivity of a quarter wave stack at various relative refractive index values.

When dealing with ultrafast pulses it also becomes apparent that the LIDT of a coating material decreases as the refractive index increases.

Combing three coating materials over 2 partial stacks is a solution that allows for the mirror to maintain an acceptable performance and a broader reflectivity band than a standard, high LIDT design based on two coating materials. However, the disadvantage of such a design is that the higher stress in the coating can lead to coating damage under vacuum (crazing due to stress in the coating), especially when used on larger mirrors. Furthermore, the LIDT depends very much on the power distribution in the laser pulse.

MPO has undertaken in-depth research and development to find a solution that offers excellent vacuum compatibility and broad reflectivity band while maintaining a superior GDD performance and LIDT.

Essential for this research and development is MPO's white light interferometer which allows the measurement of the GDD of all ultrafast optics manufactured and provides customers with measured, rather than theoretically calculated curves.

MPO Mirrors

MPO refers to ultrafast standard quarter wave mirrors as TTS (Tunable Ti:Sapphire Standard). However, the

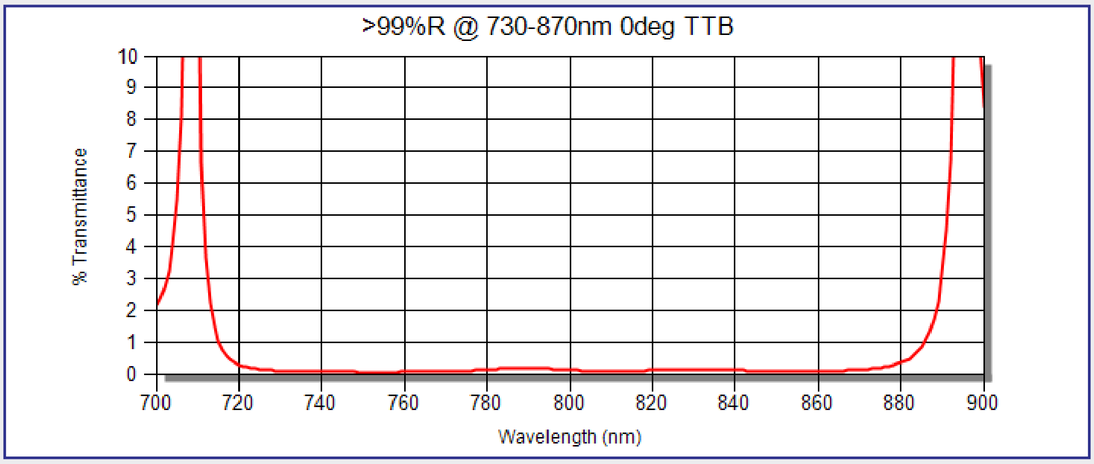

Figure 2: Transmittance of a TTB mirror. The breadth of the reflection band is much greater than that of the Bragg reflector in figure 1.

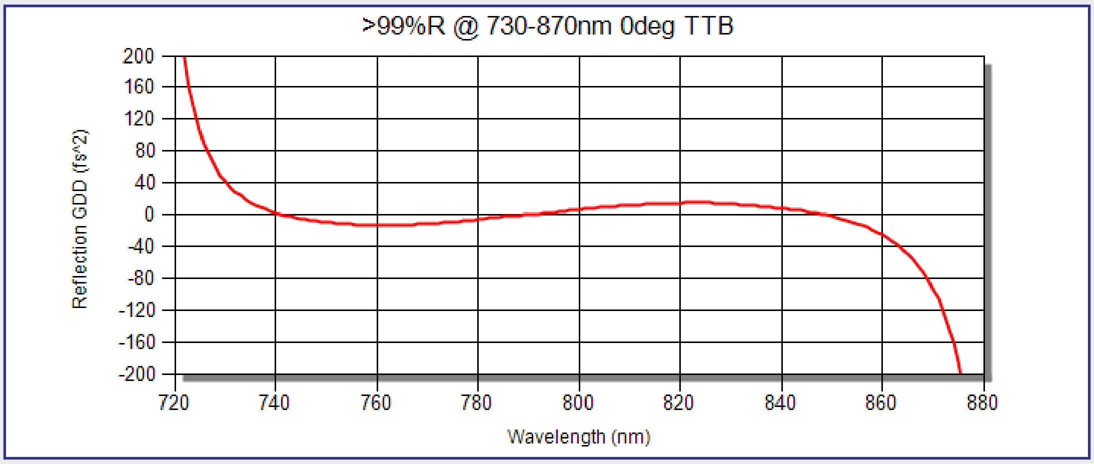

Figure 3: Group Delay Dispersion (GDD) of a TTB mirror. Across the 120nm bandwidth from 740nm to 860nm the GDD remains extremely close to zero and is approximately linear with wavelength.

performance of this coating is insufficient to properly generate or maintain ultra-short pulses. For example, a 10fs pulse at 800nm has a minimum spectral width of around 110nm, clearly the Bragg reflector given in figure 1 does not suffice. MPO has therefore developed further lines of very high performance, optimised ultra-fast mirrors for dispersion control, the TTB, TTW (Broad, Wide), protected metal and TTMH (Metal Hybrid). TTB and TTW are lines of dielectric mirrors that have been computer optimised to achieve additional band-width and even lower GDD compared to TTS mirrors.

Ultrafast metal mirrors represent a separate class of mirrors with unique properties owing to their material properties. Protected metal mirrors consist of a single thicker metal layer and a dielectric overcoat that protects the metal from corrosion and scratches. Metals possess very high reflectivity over very broad bandwidths and because the protected metal mirror does not rely on interference effects the GDD tends to be very low. On the other hand, the LIDT of metal mirrors suffers due to high absorption. For example, a silver metal mirror may have a typical LIDT of around 2:5Jcm2 at 1064nm in 10ns whereas a dielectric mirror can withstand around > 35Jcm2, though performance improves in the femto-second regime. Metal mirrors are also less versatile as their optical properties are fixed.

TTMH or "Metal Hybrid" mirrors are a unique design that combines the high base broadband reflectivity of metals with the versatility, durability and low losses of dielectric designs. These mirrors consist of a single metal layer overcoated with a dielectric stack, reinforcing the natural reflectivity of the metal with the interference properties of the dielectric layers. The result is an extremely broad reflectivity bandwidth with a much higher performance specification than an ordinary bare or protected metal mirror.

Laser Induced Damage Threshold (LIDT)

LIDT stands for "Laser Induced Damage Threshold" and is defined as the "highest quantity of laser radiation incident upon the optical component for which the extrapolated probability of damage is zero" by ISO 21254, or in other words it is an estimate of how powerful a laser has to be before it begins to cause damage in an optic. LIDT is typically defined in units of fluence, J/cm^2.

ISO 21254 describes the methodology, principles and terminology of laser damage tests. Laser damage tests are typically performed in the format of 1:1 or S:1 tests. 1:1 tests consist of exposing a previously unexposed site to a single laser shot with a specified fluence. S:1 tests consist exposing a previously unexposed site to multiple consecutive laser shots with a specified fluence. ISO specifies that at least 10 sites are tested in order to gain a better representation of the LIDT.

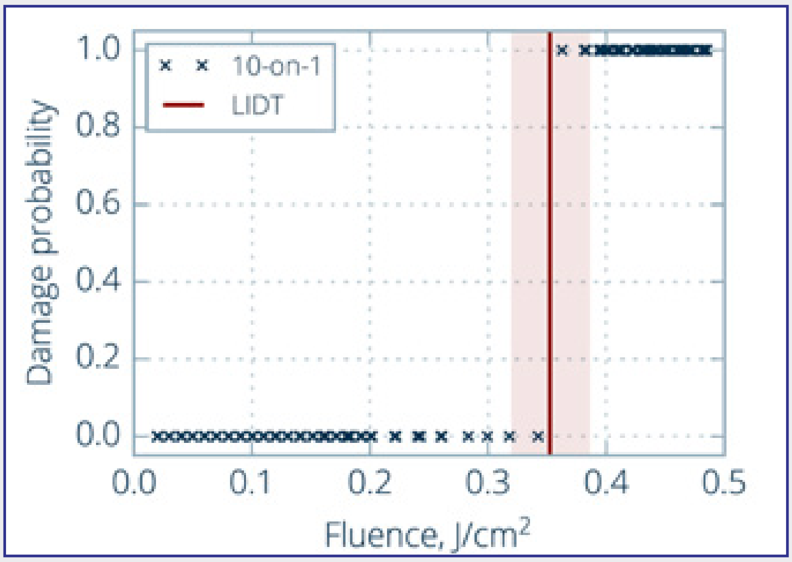

Figure 1: A typical damage probability plot. Fluences below the LIDT typically cause no damage until they approach it.

The LIDT is estimated by increasing the fluence and observing resultant changes in the coatings. In some cases any observable change in the coatings is considered a failure.

The LIDT is estimated by increasing the fluence and observing resultant changes in the coatings. In some cases any observable change in the coatings is considered a failure. An example is given below in figure 1.

Estimates of LIDT may be influenced by a number of factors such as the cleanliness of the testing facility as well as effects such as laser conditioning. The pulse diameter and duration are also significant factors, and so LIDTs are often given with specified pulse characteristics. There are approximate methods that can be used to scale LIDT for lasers with different specifications. Within the nanosecond/microsecond regime one can estimate LIDT for a certain wavelength, diameter and pulse duration from an LIDT given with a different set of parameters. The scaling law is given by the equation (right).

$$LIDT_{New} = \sqrt{\frac{\tau_{New}}{\tau_{Old}}} \times \left(\frac{\lambda_{New}}{\lambda_{Old}}\right) \times \left(\frac{D_{Old}}{D_{New}}\right)^2 \times LIDT_{Old}$$

Sub-nanosecond scale pulses do not obey this scaling law however as different damage mechanisms dominate for such short pulse durations.

The exact nature of laser damage is still being actively researched. The main culprits are defects/contamination within the optical coating and the response of the coating to high electric field densities. For example, absorbing defects can be heated to a plasma state causing a circular pit to form as the top-most layers fail. Nodule defects formed during the coating progress can be ejected by the pulse leaving pits that penetrate deeply into the coating. These mechanisms can be mitigated in a multitude of ways, a common method is the addition of a silica overcoat. Another technique is to modify layer thickness' in such a way that peaks of standing wave electric fields are reduced in high index materials as these standing waves are responsible for a number of damage mechanisms. Additionally, one can aim to reduce contamination and defects by maintaining a clean coating environment and making use of energetic coating methods.

Etalons

Etalons are optical components based on the principle of the Fabry-Perot Interferometer. They are effective narrowband filters, transmitting only light of specific, periodic frequencies with tight bandwidths. They are commonly used in applications such as telecommunications, lasers and spectroscopy.

An Etalon consists of two flat, partially reflecting plates separated by a distance. The gap between them, either in vacuum or filled with air or some solid substrate forms an optical cavity. These two types are known as “Air Spaced” and “Solid” Etalons respectively and possess different advantages and disadvantages.

An Etalon consists of two flat, partially reflecting plates separated by a distance. The gap between them, either in vacuum or filled with air or some solid substrate forms an optical cavity. These two types are known as “Air Spaced” and “Solid” Etalons respectively and possess different advantages and disadvantages.

Etalons function as multiple beam interferometers, incident light passes through the first plate and into the cavity at which point it undergoes multiple internal reflections resulting in the transmission of light with many different phases through the whole assembly. Assuming no absorption in the component and equal reflectance off both interfaces in the cavity the resulting transmission is given by the equation:

$$F = \frac{4R}{(1-R)^2}$$

Where

$$FSR = \frac{\lambda^2}{2nd}$$

Where R is the reflectance of both surfaces of the cavity and δ is the phase acquired by light passing through the cavity once. F is sometimes known as the “coefficient of finesse”, and is related to an important quantity known as the “Finesse” of an etalon. The transmission curve is given below by figure 2. The multiple beam interference due to reflections within the cavity results

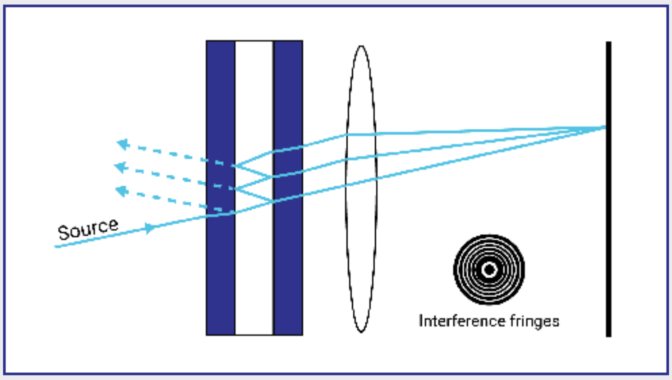

Figure 1: Ray diagram depicting the multiple interference principles of Etalons/Fabry-Perot interferometers

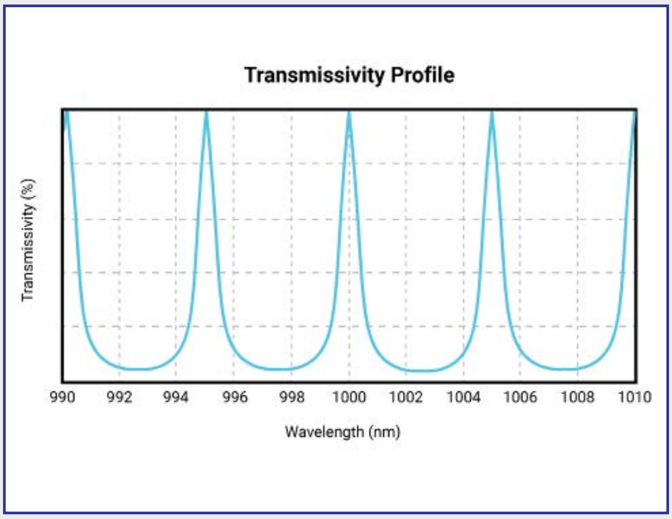

Figure 2: Transmission profile for an ideal etalon

in a transmission profile with peaks at $\delta = m\pi$ where m is an integer. This corresponds to when (at normal incidence) the optical length of the cavity is $m\lambda/2$ where λ is the wavelength of the incident light. With increasing F the width of the fringes become increasingly narrow.

An important part of the specification of an Etalon is the Free Spectral Range (FSR) which is the separation between the adjacent peaks. FSR for incoming light at normal incidence is given by:

$$T = \frac{1}{1 + F\sin^2\delta}$$

Where n is the refractive index of the cavity and d is the separation of the plates. The ratio of the FSR with the Full Width Half Maximum (an expression for the bandwidth of the transmission peaks, FWHM) is called the "finesse" $\mathscr{F}$. For sufficiently small δ finesse is given by

$$\mathscr{F} = \frac{FSR}{FWHM} = \frac{\pi F^{\frac{1}{2}}}{2} = \frac{\pi R^{\frac{1}{2}}}{(1-R)}$$

Roughly speaking, the Finesse parametrises the performance of the Etalon as a narrowband filter, with a higher finesse resulting in narrower transmission bands. For high finesse applications dielectric coatings with high reflectance are coated onto the cavity interior to boost reflectance. A high finesse is desirable in spectroscopy and spectrum analysis as the Etalon can possess both a large Free Spectral Range and a small resonator bandwidth allowing for a high spectral resolution. The finesse as a function of plate reflectivity is given by figure 3 below.

As with all equations in physics, the above all assumes a perfect situation. In reality the actual finesse will be lower than the theoretical reflectivity finesse due to defects and the physical limitations and quality of the assembly components.

Figure 4 depicts the three main Etalon defect types. All three defect-types introduce variations in the ideally fixed distance between the Etalon plates, resulting in reduced finesse, peak shifts and lowered resolution. A distinction between the theoretical "reflectivity finesse" and "effective finesse" is then made, the latter quantity representing the finesse of the system taking into account defects. Aside from depending on surface flatness and component tolerances the effective finesse also depends on the clear surface aperture, a smaller aperture leading to a higher finesse.

Another consideration is inhomogeneity in the refractive index of the plates which has a similar effect to flatness limitations and surface irregularity due to deformation in the transmitted wave-front, and the problem worsens the thicker the Etalon plates are. As a result, it is advisable to consider purchasing glass plates with an inhomogeneity grade of 4 or more (as per ISO 10110 Part 4).

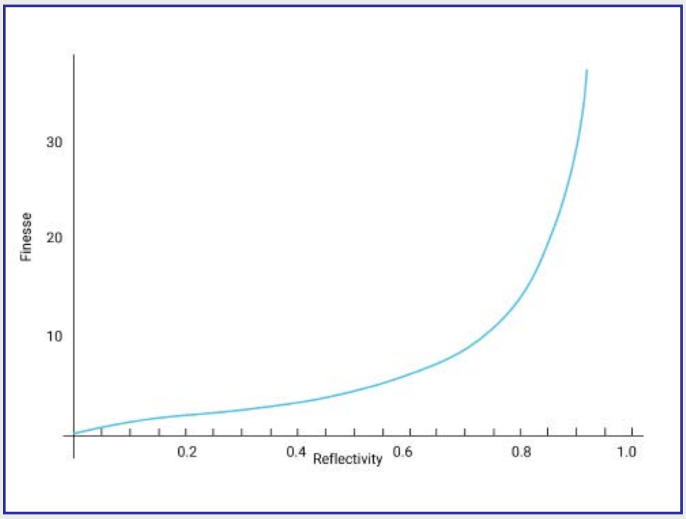

Figure 3: Finesse as a function of reflectance

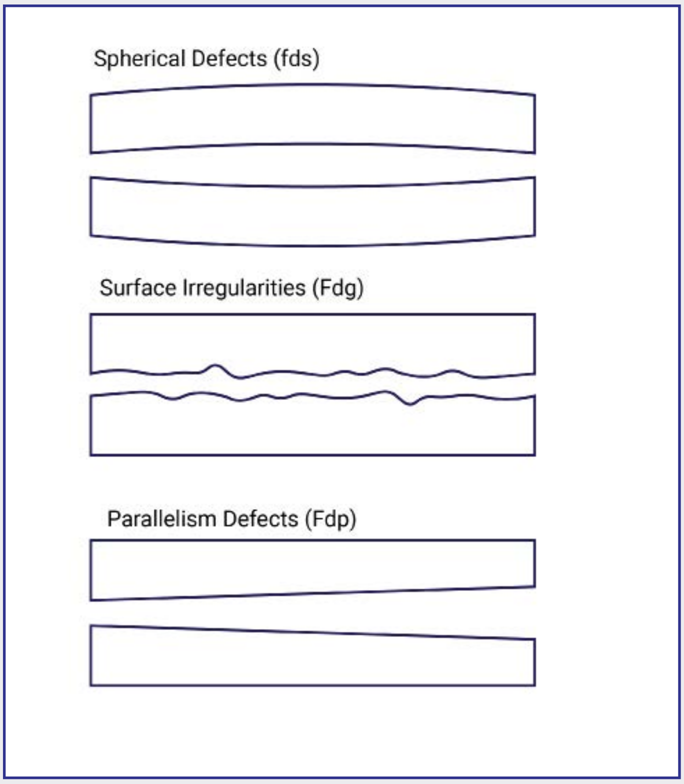

Figure 4: The three principle defects

Waveplates

Waveplates, also known as retarders are handy optical components that allow for the manipulation of the polarisation state of an incident electromagnetic wave without introducing deviation in its path or attenuating it. They are typically constructed from birefringent materials such as crystalline quartz and introduce phase shifts between the orthogonal polarisation states of incident radiation to modify the overall polarisation as desired.

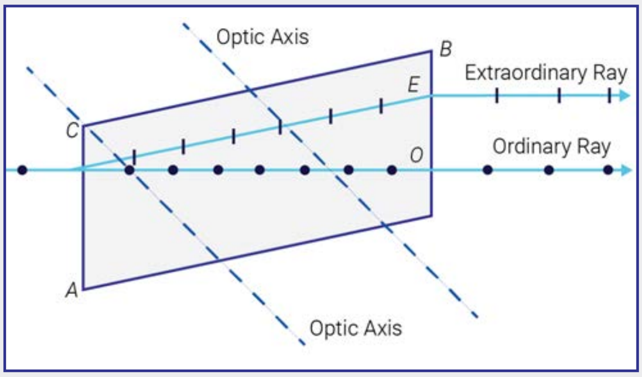

Figure 1: Birefringence in a uniaxial material. The linearly polarised beam splits into two components, an ordinary ray perpendicular to the optical axis and an extraordinary ray parallel to it. The difference in refractive indices causes phase lag between the two emerging beams

Dimensional Specification

Waveplates principally rely on the phenomena of birefringence to achieve polarisation control. A birefringent material is optically anisotropic i.e. it exhibits a refractive index that is dependent on the direction of incident of an electromagnetic wave, as well as its polarisation. This behaviour is defined by an optical axis (uniaxial) or two axes (biaxial) along which the polarisation components experience the same refractive index, n_0. A beam passing through oblique to this axis is split into two orthogonally polarised beams travelling in different directions. There is always a polarisation component perpendicular to the plane of the optical axis and direction of propagation which emerges as the ordinary beam and experienced a refractive index n_0 whereas the plane parallel component is referred to as the extraordinary beam and experiences a larger index with its most extreme value being n_e at 90degrees to the optical axes. The axes of propagation of these two beams are sometimes referred to as the fast (low index) and slow (high index) axes as a higher index means a lower propagation speed.

Birefringent materials which include but are not limited to Crystalline Quartz, Calcite, Mica (Muscovite) and even some plastics when under stress (stress birefringence). Quartz is especially prevalent in precision optics due to its suitability for high power applications and low dispersion. These materials have been favoured for their unusual optical properties for centuries, for example the Vikings are thought to have used birefringent calcite to locate the sun on a cloudy day to aid with navigation.

Construction of Waveplates

Waveplates are optical components that act as a means for controlling the polarisation of incident radiation. They are commonly made by cutting out discs out birefringent material such that the optical axis is perpendicular to the face of the waveplate. The polarisation components oscillating along the slow and fast axes (relative to the optical axis) experience different indices of refraction (n_0 and n_e as the light propagates at 90deg to the optical axis) and hence experience phase lag (sometimes referred to as retardation), modifying the overall polarisation state.

Because the optical path difference depends upon the thickness of the waveplate a waveplate can be tailored to achieve a particular polarisation at a given wavelength or wavelength range. For example, Mica is a popular material as it can be split into thin sheets easily and has very low dispersion. A Mica waveplate designed for a wavelength λ=550nm has approximately the same retardation across the whole visible spectrum (400nm<λ<700nm).

Waveplates tend to come in two varieties across different sectors. These are the half-waveplates and quarter-waveplates, so-called because they are sufficiently thick as to introduce a phase difference equivalent to half or quarter of a wavelength (π and $\pi/2$) respectively. The half-wave plate will convert an incident linearly polarised beam into a beam of another linear polarisation but rotated by an angle 2θ where θ is the angle between the optical axis and the initial plane of polarisation. The quarter-waveplate converts linear polarisation into elliptical polarisation, acting as a circular polariser when θ=45°. The principles of half and quarter-waveplates are depicted in figure 3.

$$d = \left(\frac{\Delta\phi}{2\pi} + m\right)\frac{\lambda}{\Delta n}$$

Where $\Delta\Phi$ is the phase change (π or $\pi/2$), λ is the wavelength of incident radiation, Δn is the difference between the ordinary and extraordinary refractive indices and m is the (integer) order of the waveplate.

Due to the periodic nature of phase change there is a range of thicknesses that satisfy the condition for quarter and half-waveplates hence the integer dependence. Waveplates of a thickness such that m>0 are referred to as "multi-order waveplates". In practise zero-order waveplates, whilst far less sensitive to angle of incidence, temperature and wavelength variations compared to their multi-order brethren, are very difficult to manufacture and handle as d can be very thin (for example a zero order quarterwave-plate composed of quartz may only be a few tens if microns thick).

However pseudo-zero order wave-plates are possible by combining two thicker waveplates into one with the optical axes at right angles to eachother. This means that one plate compensates for the other, and the resultant polarisation arises from the difference in the thicknesses of the two wave-plates. Nonetheless, true zero order waveplates are necessary for purposes when high stability in the retardation is required, or perhaps an achromatic waveplate which is composed of individual waveplates of different materials.

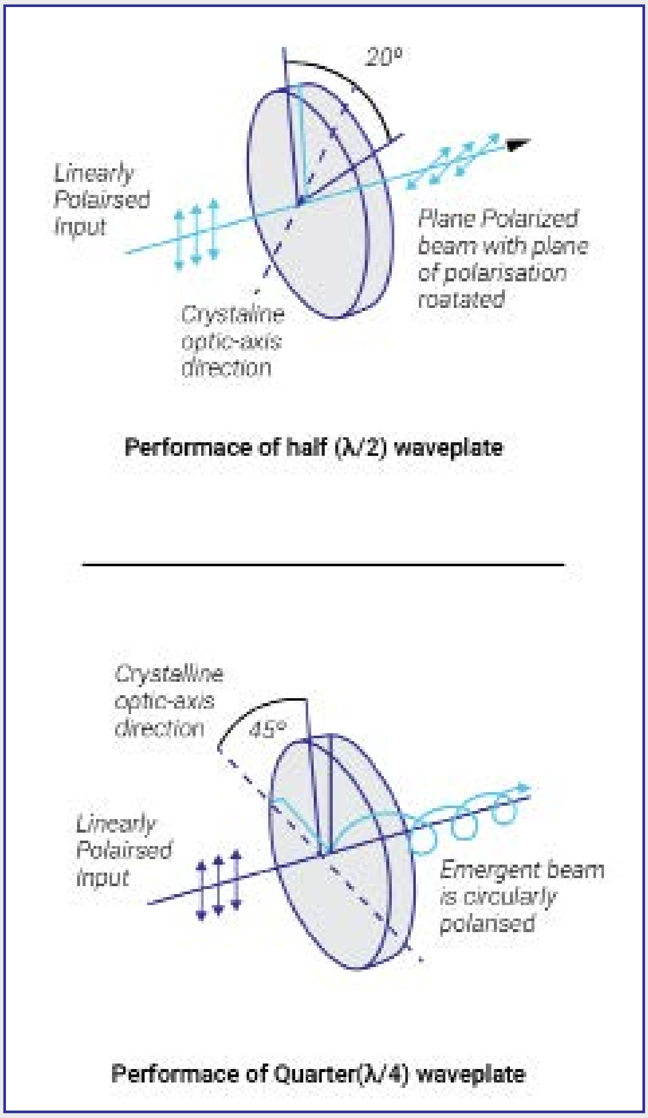

Figure 2: The principles of half and quarter-waveplates. A linearly polarised input can be converted to any other linear polarisation with a half-waveplate or any elliptical (including circular) polarisation with a quarter-waveplate via mere rotation

References & Further Reading

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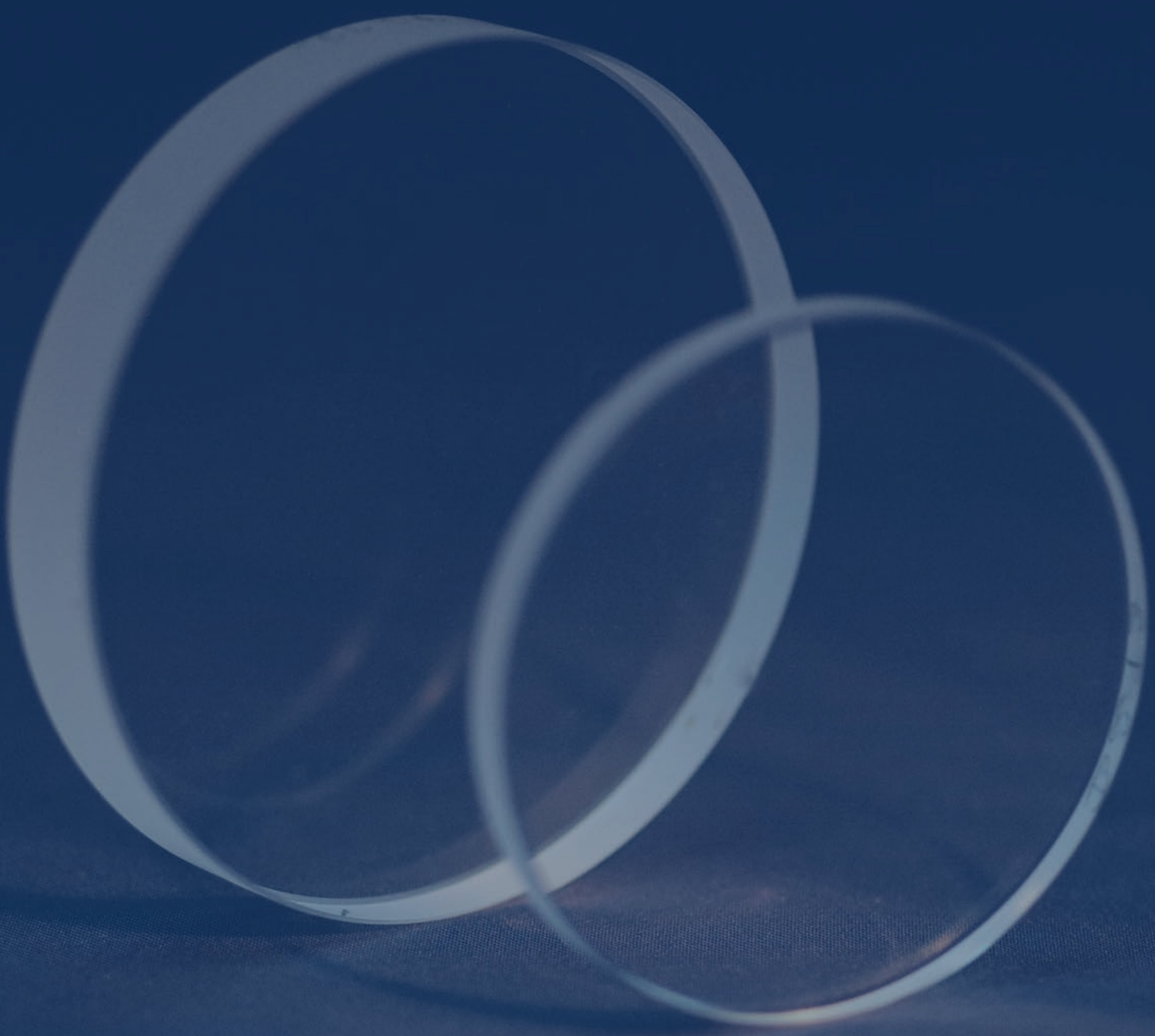
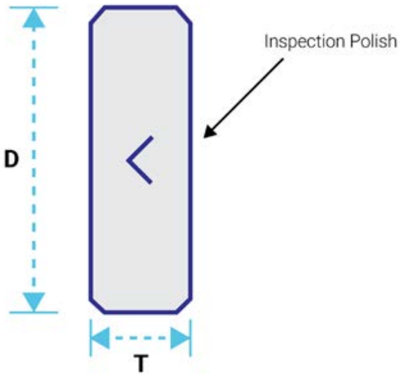
Products

Uncoated Optics



Mirror Substrates



Material	UV Fused Silica
	BK7
Diameter Tolerance	+ 0 / -0.25mm
Thickness Tolerance	± 0.25mm
Surface Flatness	λ/10
Front Surface Quality	10-5 Scratch-dig
Rear Surface Quality	Inspection Polish
Parallelsim	<than 5 arc min parallel

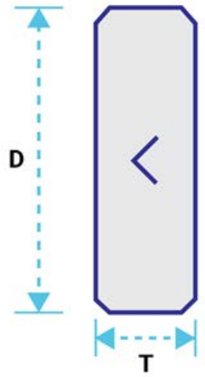
Wedged Optics have a 30arc min (+/-5 arc min) wedge, thickness specified for thick side

BK7 MIRROR SUBSTRATES	DIAMETER	THICKNESS
BK7-FMR-12.7-6.35	12.7mm	6.35mm
BK7-FMR-25.4-6.35	25.4mm	6.35mm
BK7-FMR-38.1-9.52	38.1mm	9.52mm
BK7-FMR-50.8-9.52	50.8mm	9.52mm
BK7-FMR-76.2-12.7	76.2mm	12.7mm
BK7-FMR-101.6-12.7	101.6mm	12.7mm
BK7-FMR-152.4-25.4	152.4mm	25.4mm
BK7-WMR-25.4-6.35-30MIN	25.4mm	6.35mm
BK7-WMR-50.8-9.52-30MIN	50.8mm	9.52mm

FUSED SILICA MIRROR SUBSTRATES	DIAMETER	THICKNESS
FS-FMR-12.7-6.35	12.7mm	6.35mm
FS-FMR-25.4-6.35	25.4mm	6.35mm
FS-FMR-38.1-9.52	38.1mm	9.52mm
FS-FMR-50.8-9.52	50.8mm	9.52mm
FS-FMR-76.2.-12.7	76.2mm	12.7mm
FS-FMR-101.6-12.7	101.6mm	12.7mm
FS-FMR-152.4-25.4	152.4mm	25.4mm
FS-WMR-25.4-6.35-30MIN	25.4mm	6.35mm
FS-WMR-50.8-9.52-30MIN	50.8mm	9.52mm

Other sizes and specifications are available upon request- please contact us

Window Substrates



Material	UV Fused Silica
	BK7
Diameter Tolerance	+ 0/ -0.25mm
Thickness Tolerance	±0.25mm
Transmitted Wavefront	λ/10
Front Surface Quality	10-5 Scratch-dig
Rear Surface Quality	10-5 Scratch-dig
Parallelsim	<than 10 sec paralllism

Wedged Optics have a 30arc min (+/-5 arc min) wedge, thickness specified for thick side

BK7 WINDOW SUBSTRATES	DIAMETER	THICKNESS
BK7-FWD-12.7-6.35	12.7mm	6.35mm
BK7-FWD-25.4-6.35	25.4mm	6.35mm
BK7-FWD-38.1-9.52	38.1mm	9.52mm
BK7-FWD-50.8-9.52	50.8mm	9.52mm
BK7-FWD-76.2-12.7	76.2mm	12.7mm
BK7-FWD-101.6-12.7	101.6mm	12.7mm
BK7-FWD-152.4-25.4	152.4mm	25.4mm
BK7-WWD-25.4-6.35-30MIN	25.4mm	6.35mm
BK7-WWD-50.8-9.52-30MIN	50.8mm	9.52mm

FUSED SILICA WINDOW SUBSTRATES	DIAMETER	THICKNESS
FS-FWD-12.7-6.35	12.7mm	6.35mm
FS-FWD-25.4-6.35	25.4mm	6.35mm
FS-FWD-38.1-9.52	38.1mm	9.52mm
FS-FWD-50.8-9.52	50.8mm	9.52mm
FS-FWD-76.2.-12.7	76.2mm	12.7mm
FS-FWD-101.6-12.7	101.6mm	12.7mm
FS-FWD-152.4-25.4	152.4mm	25.4mm
FS-WWD-25.4-6.35-30MIN	25.4mm	6.35mm
FS-WWD-50.8-9.52-30MIN	50.8mm	9.52mm

Other sizes and specifications are available upon request- please contact us

Spherical Substrates/Lenses

Lens Specification

Diameter Tolerance	+ 0/ -0.25mm
Thickness Tolerance	±0.25mm
Both Sides	λ/10 surface figure
	10-5 Scratch-dig
Focal Length Tolerance	± 0.5%

Mirror Specifications

Diameter Tolerance	+ 0 / -0.25mm
Thickness Tolerance	±0.25mm
Front Surface	λ/10 surface figure
	10-5 Scratch-dig
Rear Surface	Inspection Polish
ROC tolerance	± 1%

Plano - Concave Substrates
25.4mm Diameter : 6.35mm edge thickness

Plano - Convex Substrates
25.4mm Diameter : 6.35mm centre thickness

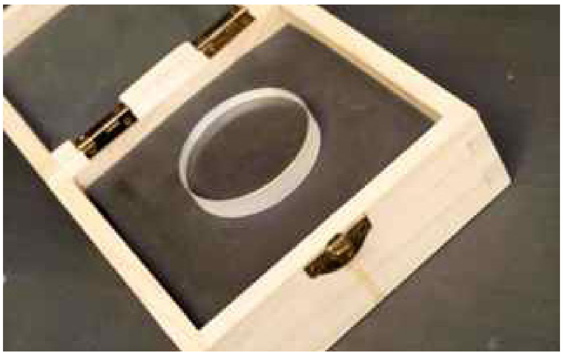
FUSED SILICA MIRROR SUBSTRATES	DIAMETER	RADIUS OF CURVATURE
FS-SMR-25.4-6.35-1.0M-CC	25.4mm	1000mm concave
FS-SMR-25.4-6.35-1.5M-CC	25.4mm	1500mm concave
FS-SMR-25.4-6.35-3.0M-CC	38.1mm	3000mm concave
FS-SMR-25.4-6.35-5.0M-CC	50.8mm	5000mm concave

FUSED SILICA LENSES PLANO - CONVEX	DIAMETER	NOMINAL FOCAL LENGTH AT 1064NM
******FS-SPW-25.4-6.35-46.5-CX	25.4mm	100mm
******FS-SPW-25.4-6.35-56.6-CX	25.4mm	125mm
******FS-SPW-25.4-6.35-68.3-CX	25.4mm	250mm
FS-SPW-25.4-6.35-112.4-CX	25.4mm	250mm
FS-SPW-25.4-6.35-135.6-CX	25.4mm	300mm
FS-SPW-25.4-6.35-226.9-CX	25.4mm	500mm
FS-SPW-25.4-6.35-454.4-CX	25.4mm	1000mm

BK7 - LENSES PLANO - CONVEX	DIAMETER	NOMINAL FOCAL LENGTH AT 1064NM
BK7-SPW-25.4-6.35-46.5-CX	25.4mm	90mm
BK7-SPW-25.4-6.35-112.4-CX	25.4mm	220mm
BK7-SPW-25.4-6.35-226.9-CX	25.4mm	450mm
*****BK7-SPW-25.4-6.35-454.4-CX	25.4mm	900mm

Other sizes and specifications are available upon request- please contact us

Reference Flats



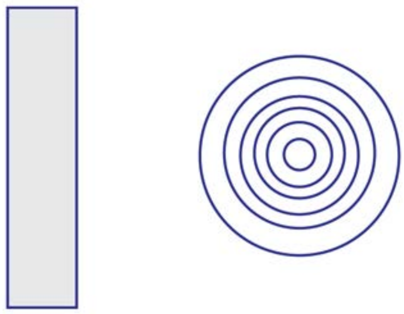
Diameter Tolerance	+ 0/ - 0.25mm
Thickness Tolerance	±0.25mm
Front Surface	λ/20 Flatness
	20-10 scratch-dig
Rear Surface	Inspection Polish
Parallelism	<than 5 arc min parallel

Uncoated supplied in a wooden box

PART NUMBER	MATERIAL	DIAMETER	THICKNESS (T)
ZER-REF1-25.0-12.0-L/20	Zerodur	25.0mm	12.0mm
ZER-REF1-50.0-15.0-L/20	Zerodur	50.0mm	15.0mm
ZER-REF1-100.0-19.0-L/20	Zerodur	100.0mm	19.0mm
FS-REF1-25.0-12.0-L/20	Fused Silica	25.0mm	12.0mm
FS-REF1-50.0-15.0-L/20	Fused Silica	50.0mm	15.0mm
FS-REF1-100.0-19.0-L/20	Fused Silica	100.0mm	19.0mm

Etalons

Solid Etalons



Material	UV Fused Silica
Diameter Tolerance	+ 0/ - 0.25mm
Thickness Tolerance	± 5% of thickness up to 2mm
Clear Aperture	≥ 80%
Surface Flatness	λ/20
Surface Quality	10-5 Scratch-dig
Parallelsim	<than 1 arc sec paralllism

PART NUMBER	DIAMETER	THICKNESS
ET-FS-25.4-0.2	25.4mm	0.2mm
ET-FS-25.4-0.3	25.4mm	0.3mm
ET-FS-25.4-0.5	25.4mm	0.5mm
ET-FS-25.4-0.1.0	25.4mm	1.0mm
ET-FS-25.4-0.2.0	25.4mm	2.0mm

Air-Spaced Etalons

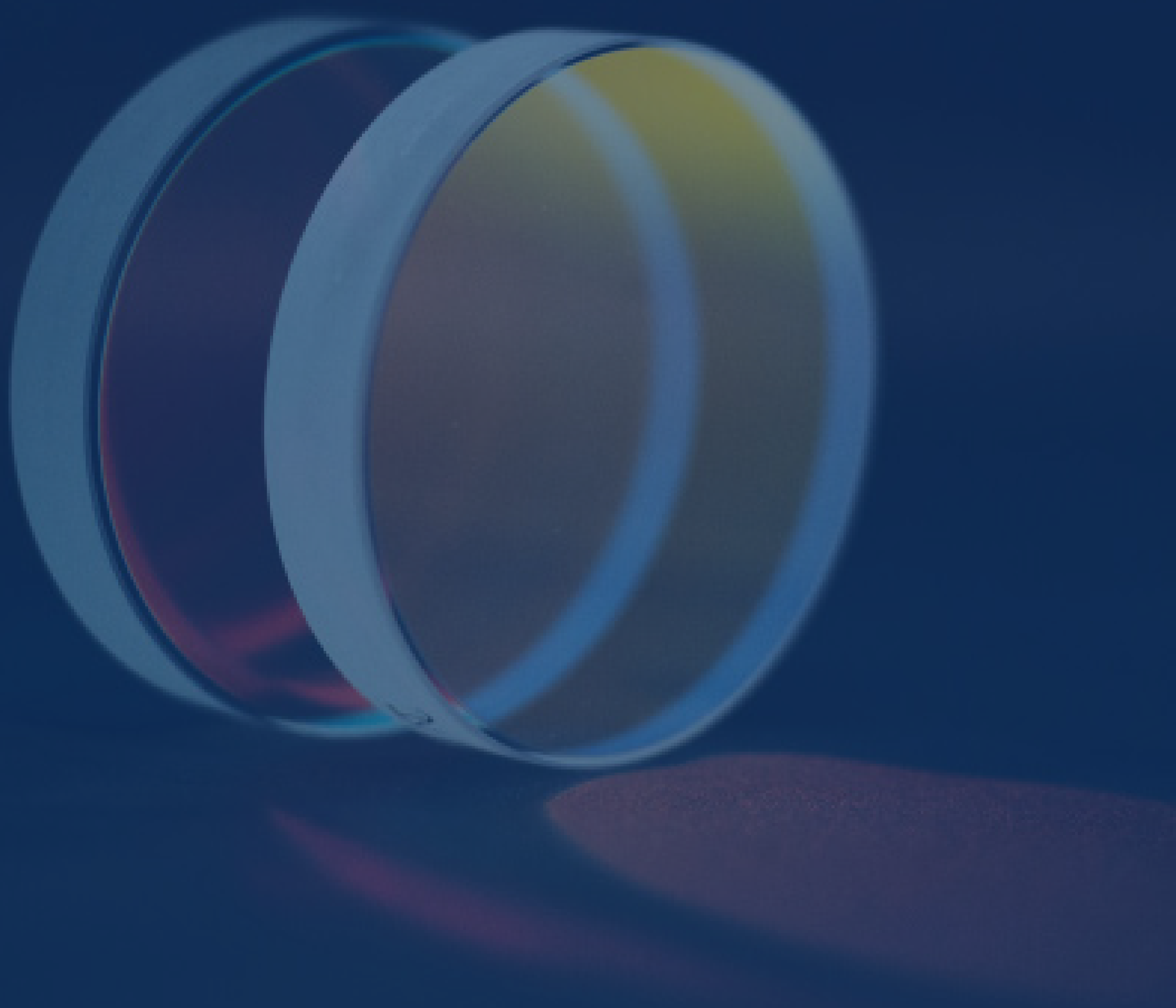
Please contact us for further details about air-spaced etalons. We can manufacture traditional airspaced etalons (with three spacer legs) and ring-spaced etalons (for applications that require very rigid etalons. We hold stock of 30mm diameter (20mm clear aperture) etalon plates and also carry a vast selection of ready-made spacers in stock. With our in-house software we can find the best specification for your application.

Virtually Imaged Phase Array (VIPA) Etalons

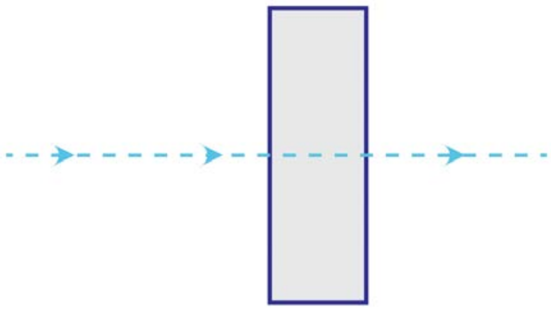
Manx Precision Optics manufactures a wide range of VIPA Etalons. Please contact us for further information.

Products

Coated Optics



AR Coated Windows



Material	UV Fused Silica
Diameter Tolerance	+ 0/ - 0.25mm
Thickness Tolerance	± 0.25mm
Transmitted Wavefront	λ/10
Surface Quality (both faces)	10-5 scratch-dig
Parallelsim	< than 10 sec paralllism

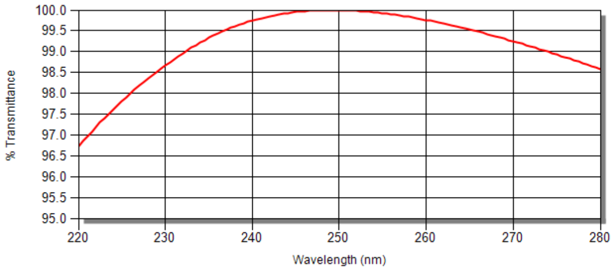
All single wavelength AR coatings give 0.25%R for the respective wavelength.

The broadband AR coatings for 245nm-410nm give (<%1R avg.) while all other listed broadband AR coatings give (<0.5%R avg.)

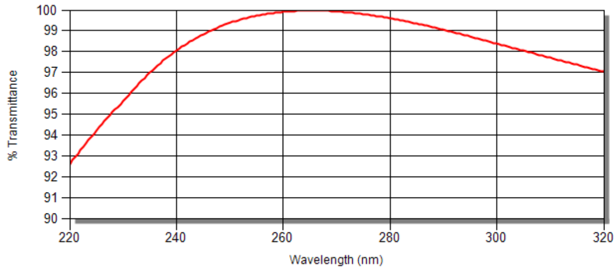
PART NUMBER	DIAMETER	THICKNESS	COATING WAVELENGTH
FS-FWD-25.4-6.35-AR/AR-248-0	25.4mm	6.35mm	248nm
FS-FWD-25.4-6.35-AR/AR-266-0	25.4mm	6.35mm	266nm
FS-FWD-25.4-6.35-AR/AR-355-0	25.4mm	6.35mm	355nm
FS-FWD-25.4-6.35-AR/AR-532-0	25.4mm	6.35mm	532nm
FS-FWD-50.8-9.52-AR/AR-532-0	50.8mm	9.52mm	532nm
FS-FWD-25.4-6.35-AR/AR-1030-0	25.4mm	6.35mm	1030nm
FS-FWD-50.8-9.52-AR/AR-1030-0	50.8mm	9.52mm	1030nm
FS-FWD-25.4-6.35-AR/AR-1064-0	25.4mm	6.35mm	1064nm
FS-FWD-50.8-9.52-AR/AR-1064-0	50.8mm	9.52mm	1064nm
FS-FWD-25.4-6.35-AR/AR-245-440-0	25.4mm	6.35mm	245nm-410nm
FS-FWD-50.8-9.52-AR/AR-245-440-0	50.8mm	9.52mm	245nm-410nm
FS-FWD-25.4-6.35-AR/AR-400-700-0	25.4mm	6.35mm	400nm-700nm
FS-FWD-50.8-9.52-AR/AR-400-700-0	50.8mm	9.52mm	400nm-700nm
FS-FWD-25.4-6.35-AR/AR-630-1100-0	25.4mm	6.35mm	630nm-1100nm
FS-FWD-50.8-9.52-AR/AR-630-1100-0	50.8mm	9.52mm	630nm-1100nm

Other sizes and specifications are available upon request- please contact us

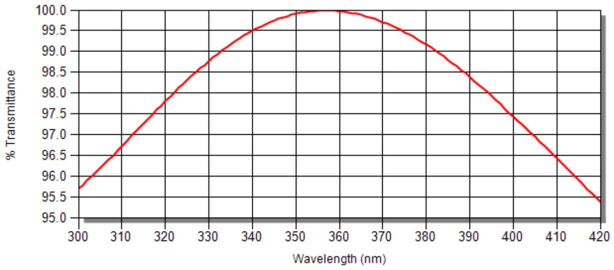
AR @248nm /0°



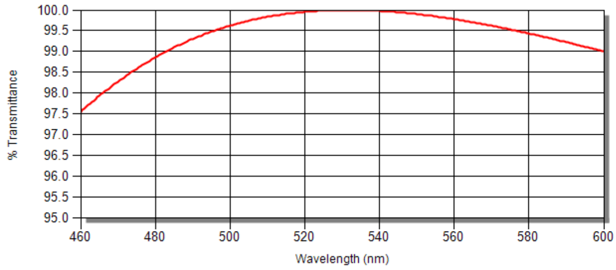
AR @266nm /0°



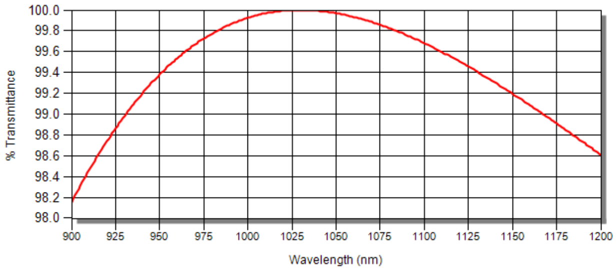
AR @355nm /0°



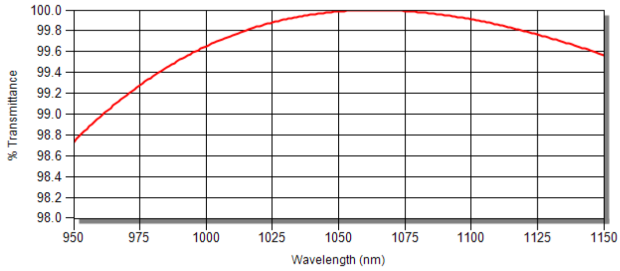
AR @532nm /0°



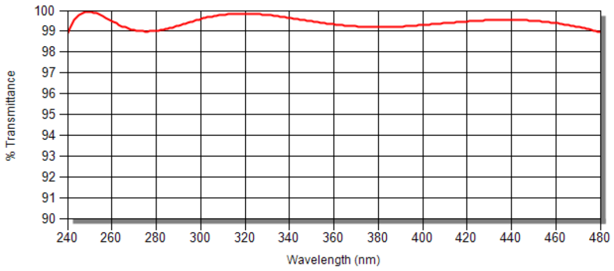
AR @1030nm /0°



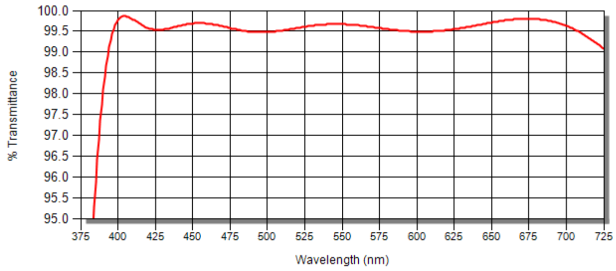
AR @1064nm /0°



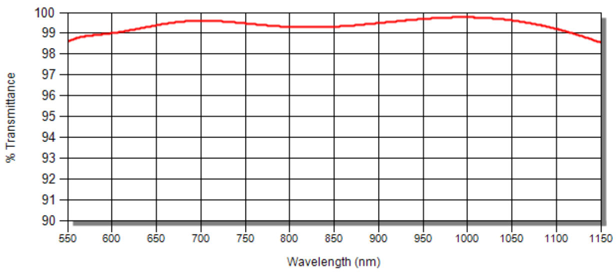
AR @245-440nm /0°



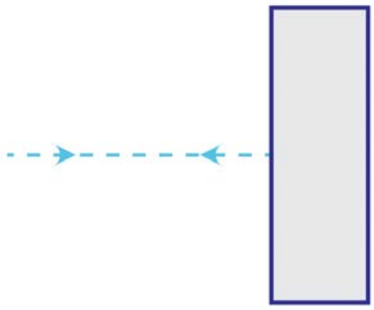
AR @400-700nm /0°



AR @630-1100nm /0°



Laser Line Mirrors 0° Incidence



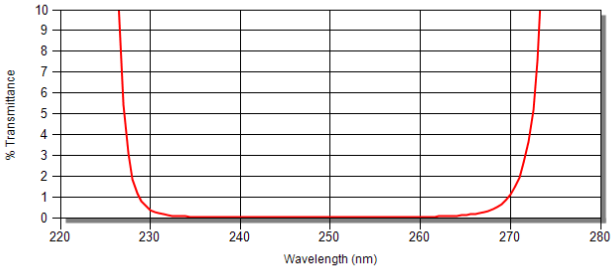
Material	UV Fused Silica
Diameter Tolerance	+ 0/ - 0.25mm
Thickness Tolerance	± 0.25mm
Front Surface	λ/10 Flatness
	10-5 scratch-dig
Rear Surface	Inspection polish

All coatings will give >99.7%R at the respective wavelength.

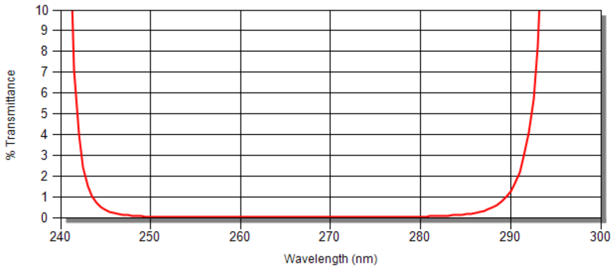
PART NUMBER	DIAMETER	THICKNESS	COATING WAVELENGTH
FS-FMR-25.4-6.35-HR-248-0	25.4mm	6.35mm	248nm
FS-FMR-50.8-9.52-HR-248-45	50.8mm	9.52mm	248nm
FS-FMR-101.6-12.7-HR-248-0	101.6mm	12.7mm	248nm
FS-FMR-25.4-6.35-HR-266-0	25.4mm	6.35mm	266nm
FS-FMR-50.8-9.52-HR-266-0	50.8mm	9.52mm	266nm
FS-FMR-101.6-12.7-HR-266-0	101.6mm	12.7mm	266nm
FS-FMR-25.4-6.35-HR-355-0	25.4mm	6.35mm	355nm
FS-FMR-50.8-9.52-HR-355-0	50.8mm	9.52mm	355nm
FS-FMR-101.6-12.7-HR-355-0	101.6mm	12.7mm	355nm
FS-FMR-25.4-6.35-HR-532-0	25.4mm	6.35mm	532nm
FS-FMR-50.8-9.52-HR-532-0	50.8mm	9.52mm	532nm
FS-FMR-101.6-12.7-HR-532-0	101.6mm	12.7mm	532nm
FS-FMR-25.4-6.35-HR-1030-0	25.4mm	6.35mm	1030nm
FS-FMR-50.8-9.52-HR-1030-0	50.8mm	9.52mm	1030nm
FS-FMR-101.6-12.7-HR-1030-0	101.6mm	12.7mm	1030nm
FS-FMR-25.4-6.35-HR-1064-0	25.4mm	6.35mm	1064nm
FS-FMR-50.8-9.52-HR-1064-0	50.8mm	9.52mm	1064nm
FS-FMR-101.6-12.7-HR-1064-0	101.6	12.7mm	1064nm

Other sizes and specifications are available upon request- please contact us

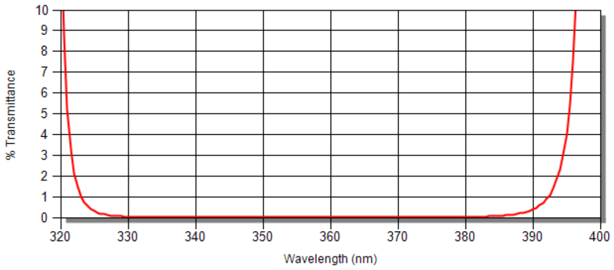
HR @248nm /0°



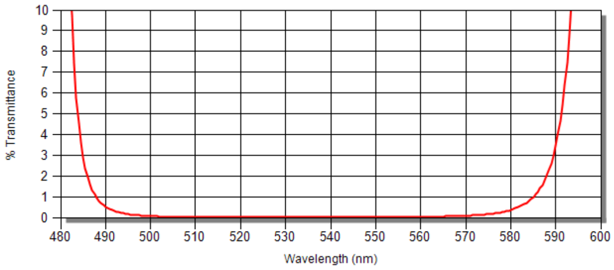
HR @266nm /0°



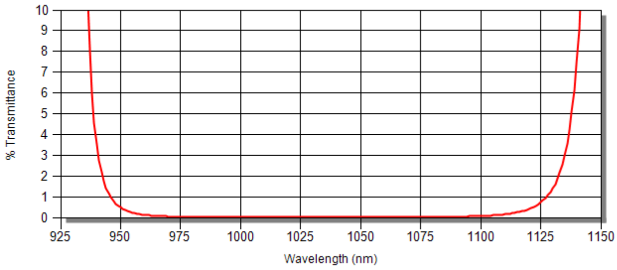
HR @355nm /0°



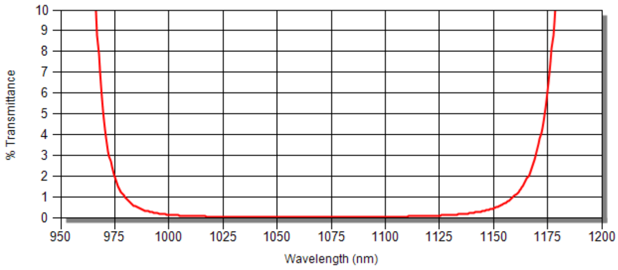
HR @532nm /0°



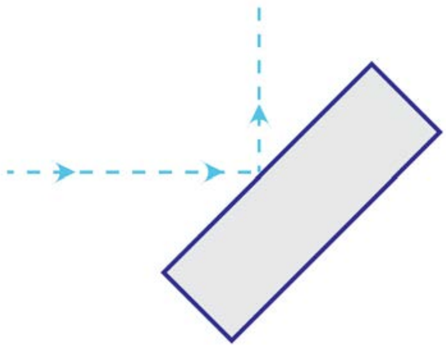
HR @1030nm /0°



HR @1064nm /0°



Laser Line Mirrors 45° Incidence



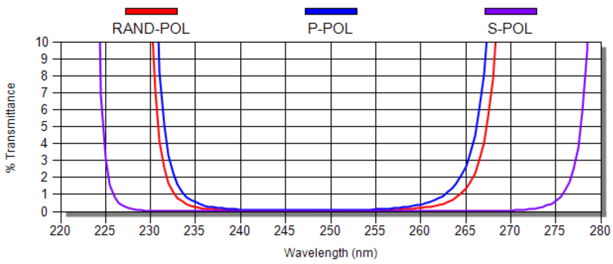
Material	UV Fused Silica
Diameter Tolerance	+ 0/ - 0.25mm
Thickness Tolerance	± 0.25mm
Front Surface	λ/10 Flatness
	10-5 scratch-dig
Rear Surface	Inspection polish

All coatings will give >99.3%R in rand. -POL at the respective wavelength.

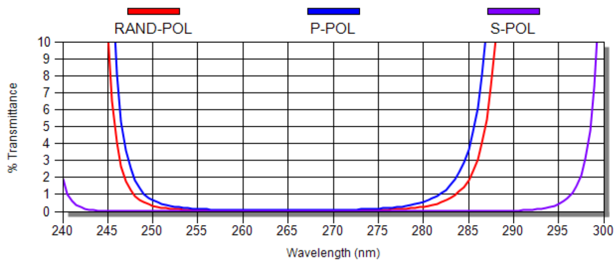
PART NUMBER	DIAMETER	THICKNESS	COATING WAVELENGTH
FS-FMR-25.4-6.35-HR-248-45	25.4mm	6.35mm	248nm
FS-FMR-50.8-9.52-HR-248-45	50.8mm	9.52mm	248nm
FS-FMR-101.6-12.7-HR-248-45	101.6mm	12.7mm	248nm
FS-FMR-25.4-6.35-HR-266-45	25.4mm	6.35mm	266nm
FS-FMR-50.8-9.52-HR-266-45	50.8mm	9.52mm	266nm
FS-FMR-101.6-12.7-HR-266-45	101.6mm	12.7mm	266nm
FS-FMR-25.4-6.35-HR-355-45	25.4mm	6.35mm	355nm
FS-FMR-50.8-9.52-HR-355-45	50.8mm	9.52mm	355nm
FS-FMR-101.6-12.7-HR-355-45	101.6mm	12.7mm	355nm
FS-FMR-25.4-6.35-HR-532-45	25.4mm	6.35mm	532nm
FS-FMR-50.8-9.52-HR-532-45	50.8mm	9.52mm	532nm
FS-FMR-101.6-12.7-HR-532-45	101.6mm	12.7mm	532nm
FS-FMR-25.4-6.35-HR-1030-45	25.4mm	6.35mm	1030nm
FS-FMR-50.8-9.52-HR-1030-45	50.8mm	9.52mm	1030nm
FS-FMR-101.6-12.7-HR-1030-45	101.6mm	12.7mm	1030nm
FS-FMR-25.4-6.35-HR-1064-45	25.4mm	6.35mm	1064nm
FS-FMR-50.8-9.52-HR-1064-45	50.8mm	9.52mm	1064nm
FS-FMR-101.6-12.7-HR-1064-45	101.6mm	12.7mm	1064nm

Other sizes and specifications are available upon request- please contact us

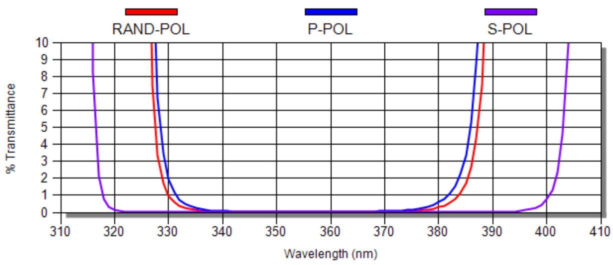
HR @248nm /45°



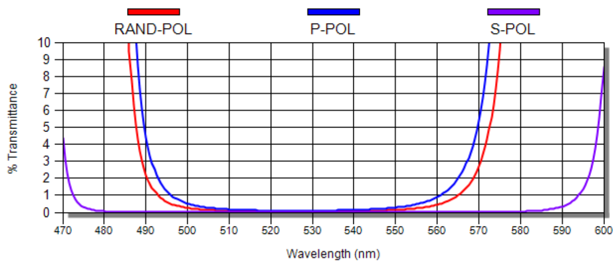
HR @266nm /45°



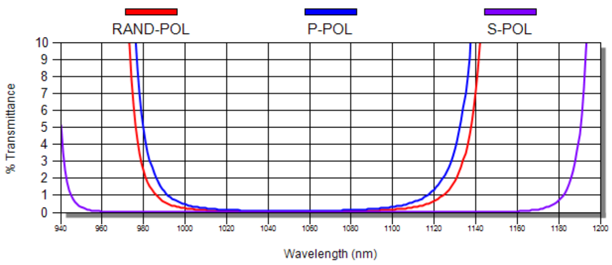
HR @355nm /45°



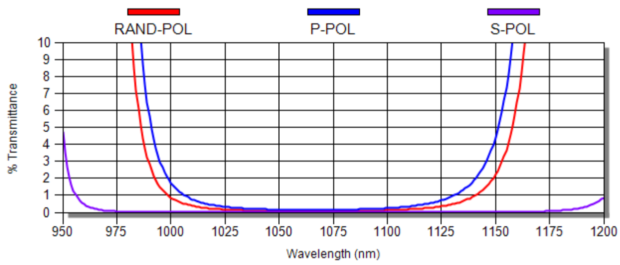
HR @532nm /45°



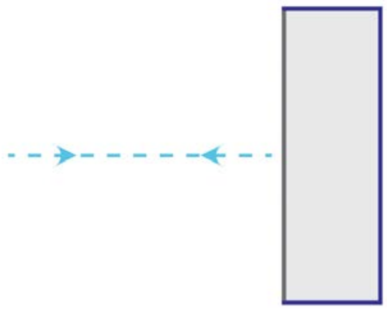
HR @1030nm /45°



HR @1064nm /45°



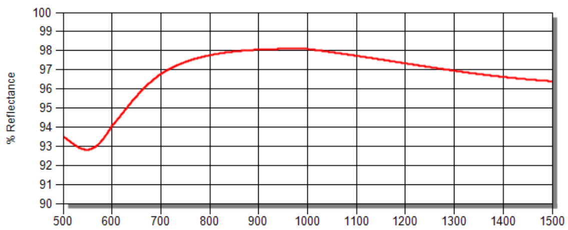
Metal Coated Mirrors



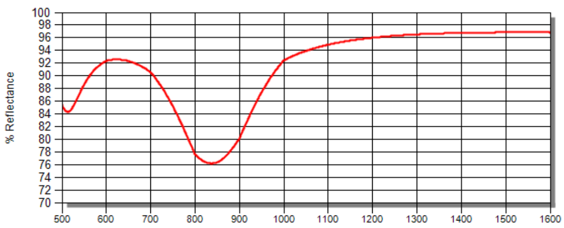
Material	N-BK7
Diameter Tolerance	+ 0/ - 0.25mm
Thickness Tolerance	± 0.25mm
Front Surface	λ/10
	10-5 scratch-dig
Rear Surface	Inspection polish

PART NUMBER	DIAMETER	THICKNESS	COATING MATERIAL
BK7-FMR-25.4-6.35-PAG	25.4mm	6.35mm	Protected Silver
BK7-FMR-50.8-9.52-PAG	50.8mm	9.52mm	Protected Silver
BK7-FMR-101.6-12.7-PAG	101.6mm	12.7mm	Protected Silver
BK7-FMR-25.4-6.35-PAL	25.4mm	6.35mm	Protected Aluminium
BK7-FMR-50.8-9.52-PAL	50.8mm	9.52mm	Protected Aluminium
BK7-FMR-101.6-12.7-PAL	101.6mm	12.7mm	Protected Aluminium

Protected Silver, 0°



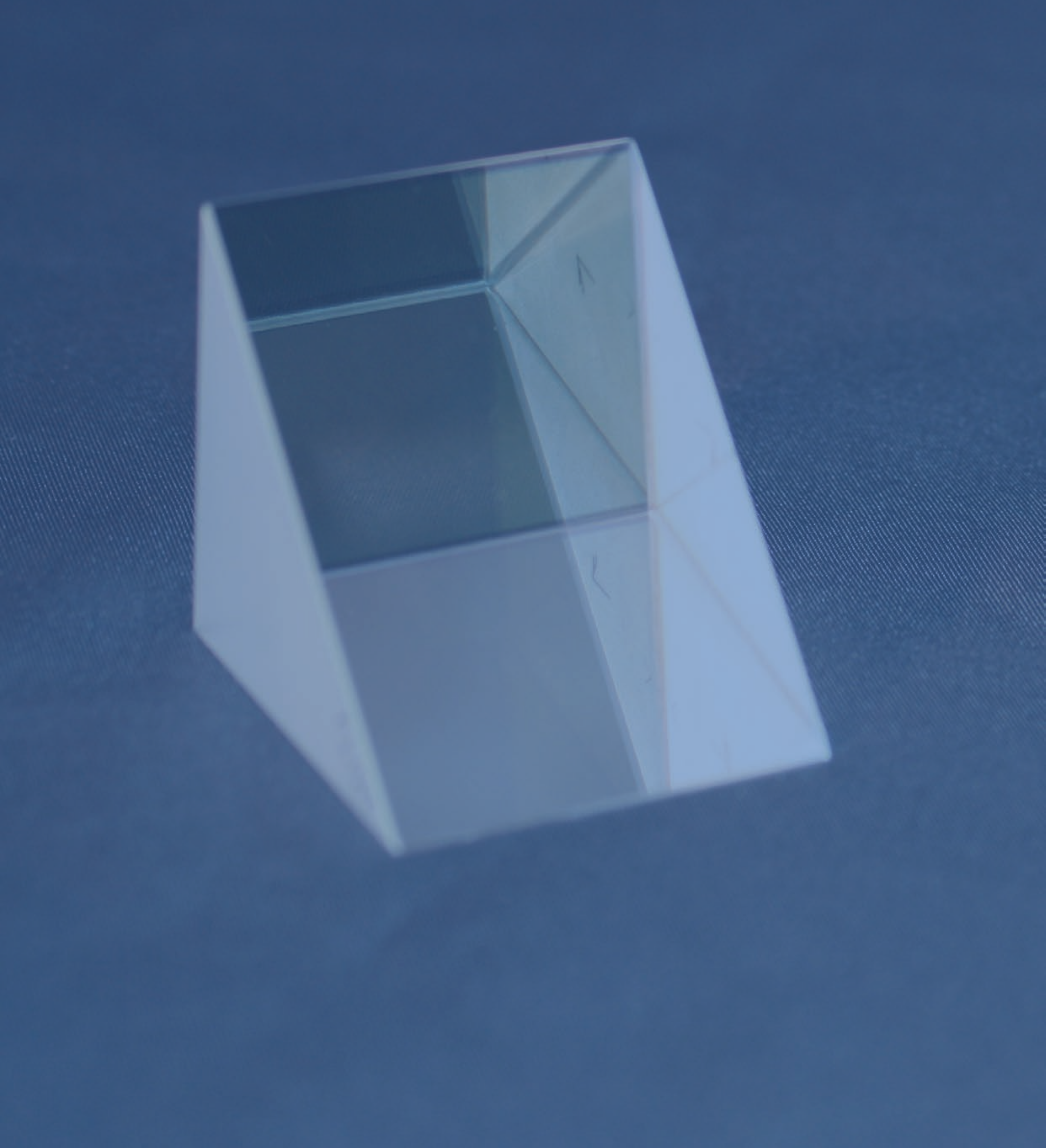
Protected Aluminum, 0°



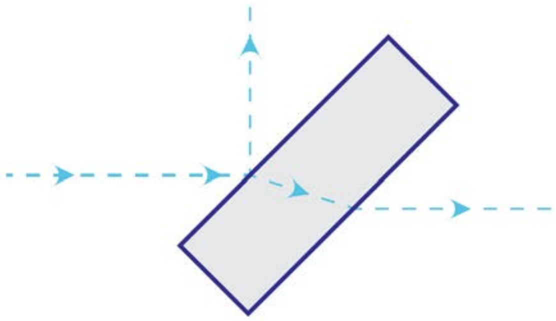
Other sizes and specifications are available upon request- please contact us

Products

Polarisation Optics



Beamsplitter Coatings



Please select the required beamsplitter coating from the table of standard splitting ratios / AR coatings below, applicable to substrates up to 101.6mm (4”) in diameter.

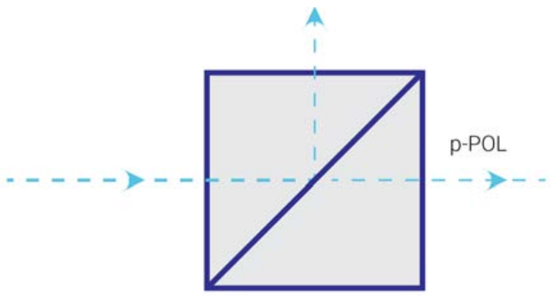
If you need beamsplitters larger than 4” (101.6mm) in diameter or if you cannot find the coating you require in the table, please do not hesitate to contact us for a quotation. We might even have a suitable optic readily available from stock.

COATING TYPE	WAVELENGTH – 355 nm/ 532 nm / 633 nm / 800 nm / 1030 nm or 1064 nm
Partial reflector – splitting ratio 20% / 50% / 80% 90% / 95% or 98% at 0º or 45º rand.-POL	Standard coating for 1” – 4” diameter substrate
Anti reflection (AR) coating for 0º or 45º rand. -POL	Standard coating for 1” – 4” diameter substrate

Partial reflectors reflectivity tolerance:
+/- 3% for 20%R and 50%R
+/- 2% for 80%R and 90%R
+/- 1% for 95%R
+/- 0.75%R for 98%R

Anti-reflection coatings: <0.25%R for 0º and <1%R for 45º rand.-POL

Cube Polarisers



Material	Fused Silica Cube
Dimensional Tolerance	+ 0/ - 0.25mm
Transmission	λ/8
Surface Quality	20-10 Scratch-dig

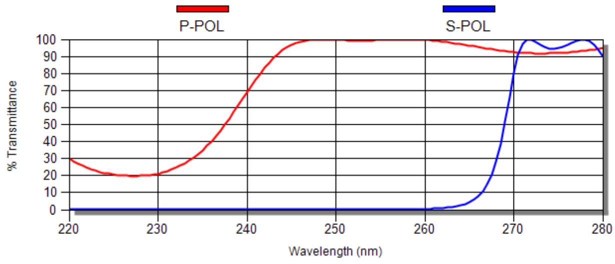
Polarising coating immersed to give >99.5%R s-POL & >95%T p-POL @operational wavelength.

All outside faces AR (<0.25%R) coated at operational wavelength.

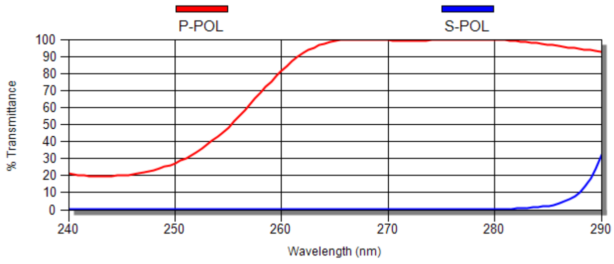
PART NUMBER	SIZE	COATING WAVELENGTH
FS-CPOL-25.4-248	25.4mm x 25.4mm x 25.4mm	248nm
FS-CPOL-25.4-266	25.4mm x 25.4mm x 25.4mm	266nm
FS-CPOL-25.4-355	25.4mm x 25.4mm x 25.4mm	355nm
FS-CPOL-25.4-532	25.4mm x 25.4mm x 25.4mm	532nm
FS-CPOL-25.4-1030	25.4mm x 25.4mm x 25.4mm	1030nm
FS-CPOL-25.4-1064	25.4mm x 25.4mm x 25.4mm	1064nm

Other sizes and specifications are available upon request- please contact us

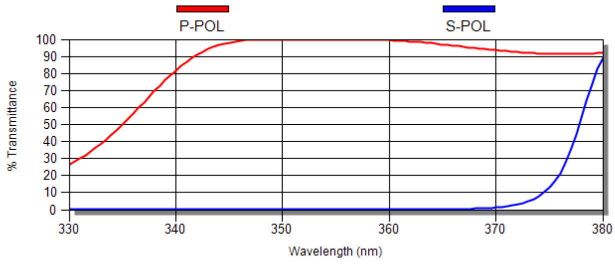
FS-CPOL-25.4 @248nm



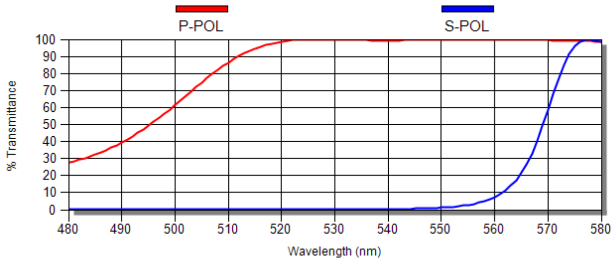
FS-CPOL-25.4 @266nm



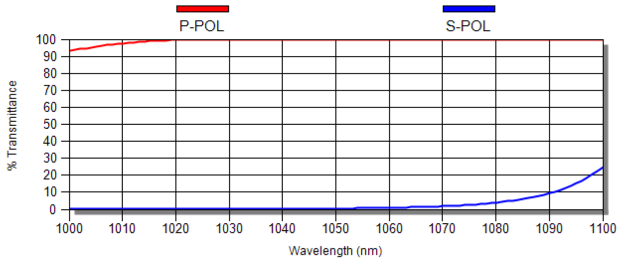
FS-CPOL-25.4 @355nm



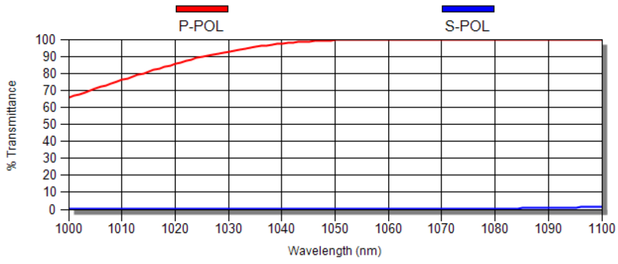
FS-CPOL-25.4 @532nm



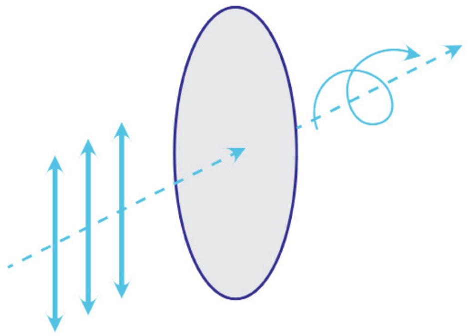
FS-CPOL-25.4 @1030nm



FS-CPOL-25.4 @1064nm



Waveplates



Material	Crystal Quartz
Diameter Tolerance	+ 0/ - 0.25mm
Thickness Tolerance	±0.25mm
Transmitted Wavefront	λ/10
Surface Quality (Both Faces)	10-5 scratch-dig
Parallelism	<than 0.5 arc sec
Clear Aperture	%85
Retardation Tolerance	λ/100 - λ/600

Both faces AR (<0.25%R) Coated at operational wavelength

Standard Diameters

25.4mm (1inch)
50.8mm (2inch)

Both available with quarter and half wave retardation

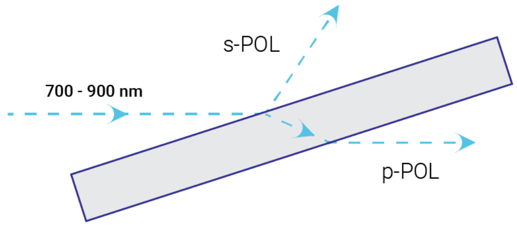
STANDARD OPERATIONAL WAVELENGTHS IN NM				
248	257	266	308	355
400	405	488	514	532
633	670	694	780	800
810	1030	1047	1053	1064
1315	1319	1550		

All waveplates can also be mounted. Waveplates for other than standard operational wavelengths, different waveplate diameters and uncoated waveplates are also available - please contact us.

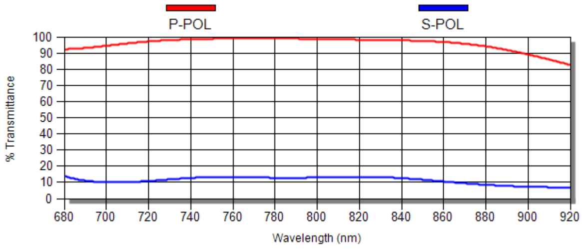
Products

Components for Ultrafast Applications

Ultrafast Polarisers



PPOL-700-900-72



FS-FWD-28.6-14.3-3.175-PPOL-700-900-72

Fused Silica window, 28.6mm x 14.3mm (+0/-0.25mm), 3.175mm (+/-0.25mm) thick, λ/10 transmitted wavefront distortion, 10-5 scratch-dig

Coating side 1: >85%R (av.) s-POL & >85%T (av.) p-POL @700-900nm / 72°

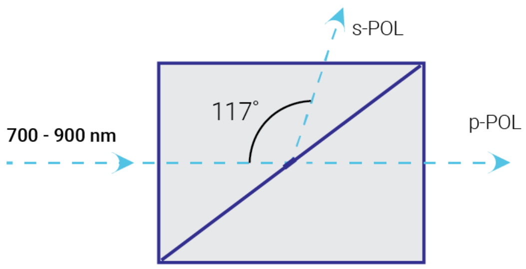
Coating side 2: AR (<2%R avg.) @ 700-900m / 72° p-POL

FS-RWD-60.0-20.0-3.175-PPOL-700-900-72

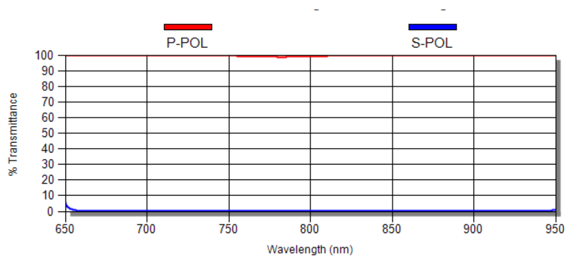
Fused Silica window, 60.0mm x 20.0mm (+0/-0.25mm), 3.0mm (+/-0.25mm) thick, λ/4 transmitted wavefront distortion, 10-5 scratch-dig

Coating side 1: >85%R (av.) s-POL & >85%T (av.) p-POL @ 700-900nm / 72°

Coating side 2: AR (<2%R avg.) @ 700-900m / 72° p-POL



ECPOL-700-900



FS-ECPOL-25.4-700-900

Fused Silica cube polariser, optically contacted 25.4mm x 25.4mm x 35.0mm. λ/8 transmitted wavefront distortion, 20-10 scratch-dig, Polarising Coating immersed

Coating Immersed: <99.5%R sPOL & >95%T p-POL @700-900nm / 54° low GDD coating

Coating side 2: AR (<0.5%R) @700-900nm / 0°

FS-ECPOL-50.8-700-900

Fused Silica cube polariser, optically contacted 50.8mm x 50.8mm x 70mm. λ/8 transmitted wavefront distortion, 20-10 scratch-dig, Polarising Coating immersed

Coating Immersed: <99.5%R sPOL & >95%T p-POL @700-900nm / 54° low GDD coating

Coating side 2: AR (<0.5%R) @700-900nm / 0°

TTS Range

The TTS range of mirrors is designed to offer an uncomplicated, low coating stress design suitable for a wide range of applications and is aimed at very high power applications. At 800nm, mirrors from the TTS range achieve an LIDT of >=0.75 J/cm² in 150fs. For LIDTs relating to other pulse durations please do not hesitate to contact us, we are happy to advise you.

Material	UV Fused Silica
	N-BK7
Diameter Tolerance	+ 0/ - 0.25mm
Thickness Tolerance	± 0.25mm
Front Surface	λ/10 flatness
	10-5 scratch-dig
Rear Surface	Inspection polish

Coating Specifications

400nm mirrors 0deg angle of incidence:
>99.3%R @ 370-430nm /0deg

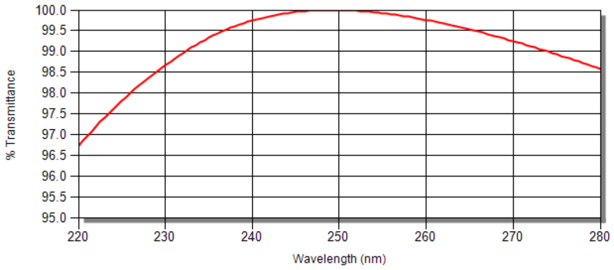
400nm mirrors 45deg angle of incidence:
>99.7%R @ 360-440nm /45deg s-POL&
>99%R @ 380-420nm /45deg p-POL

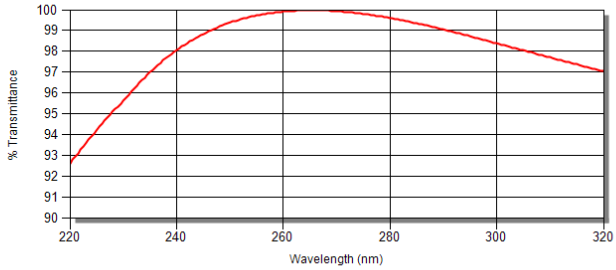
800nm mirrors 0deg angle of incidence:
>99.3%R @ 740-860nm /0deg

800nm mirrors 45deg angle of incidence:
>99.7%R @ 730-870nm /45deg s-POL
>99%R @ 765-835nm / 45deg p-POL

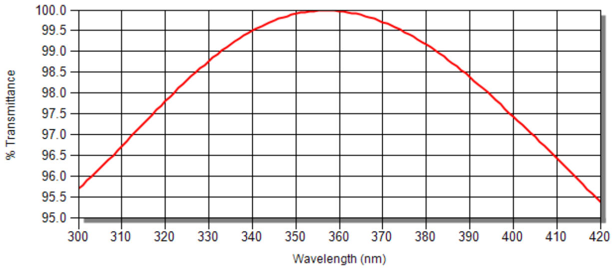
PART NUMBER	DIAMETER	THICKNESS	COATING CENTRE WAVELENGTH	ANGLE OF INCIDENCE
TTS-25.4-6.35-400-0	25.4mm	6.35mm	400nm	0 Degrees
TTS-50.8-9.52-400-0	50.8mm	9.52mm	400nm	0 Degrees
TTS-25.4-6.35-400-45	25.4mm	6.35mm	400nm	45 Degrees
TTS-50.8-9.52-400-45	50.8mm	9.52mm	400nm	45 Degrees
TTS-25.4-6.35-800-0	25.4mm	6.35mm	800nm	0 Degrees
TTS-50.8-9.52-800-0	50.8mm	9.52mm	800nm	0 Degrees
TTS-76.2-12.7-800-0	76.2mm	12.7mm	800nm	0 Degrees
TTS-101.6-12.7-800-0	101.6mm	12.7mm	800nm	0 Degrees
TTS-25.4-6.35-800-45	25.4mm	6.35mm	800nm	45 Degrees
TTS-50.8-9.52-800-45	50.8mm	9.52mm	800nm	45 Degrees
TTS-76.2-12.7-800-45	76.2mm	12.7mm	800nm	45 Degrees
TTS-101.6-12.7-800-45	101.6mm	12.7mm	800nm	45 Degrees

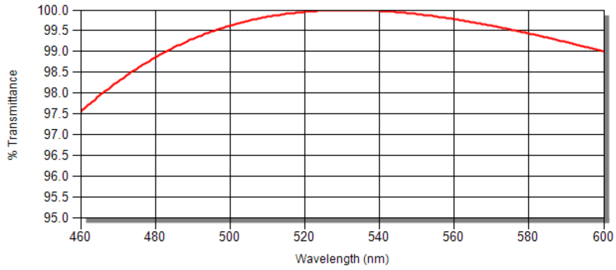
TTS-type mirror for 400nm /0deg



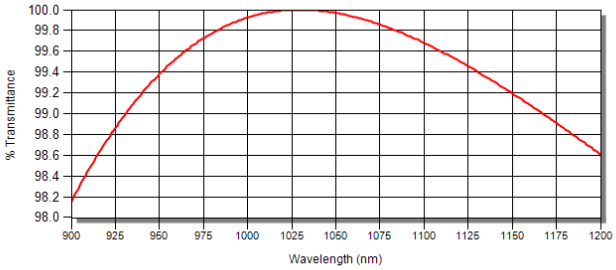


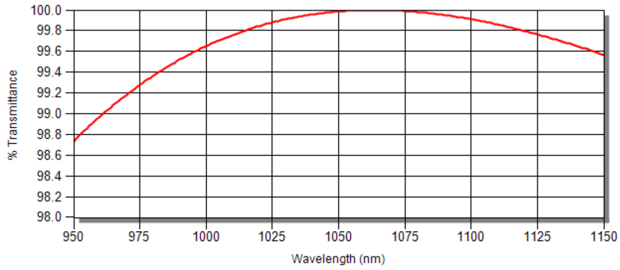
TTS-type mirror for 400nm /45deg



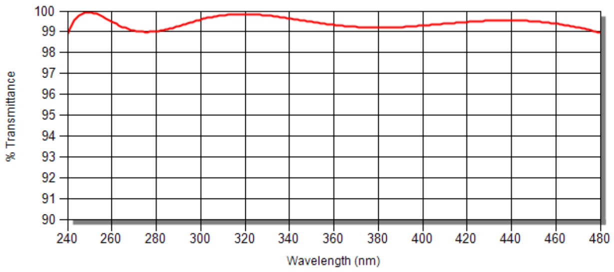


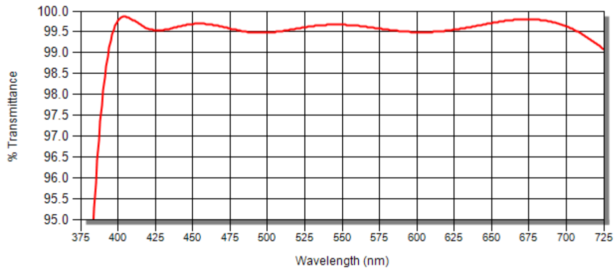
TTS-type mirror for 800nm /0deg





TTS-type mirror for 800nm /45deg





TTB Range

The TTB range of mirrors is based on a specialist coating design to offer a broader reflectivity bandwidth than the TTS range while maintaining a good Group Delay Dispersion (GDD) and high Laser-induced damage threshold (LIDT). At 800nm,mirrors from the TTB range achieve an LIDT of >=0.45 J/cm2 in 25fs and >=1.15 J/ cm2in 500fs.

Material	UV Fused Silica
	N-BK7
Diameter Tolerance	+ 0/ - 0.25mm
Thickness Tolerance	± 0.25mm
Front Surface	λ/10 flatness
	10-5 scratch-dig
Rear Surface	Inspection polish

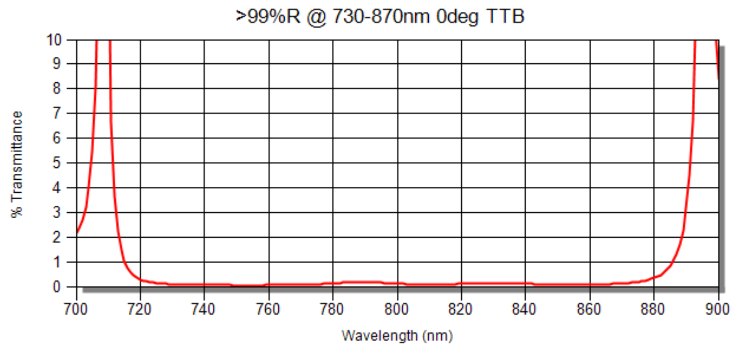
Coating Specifications

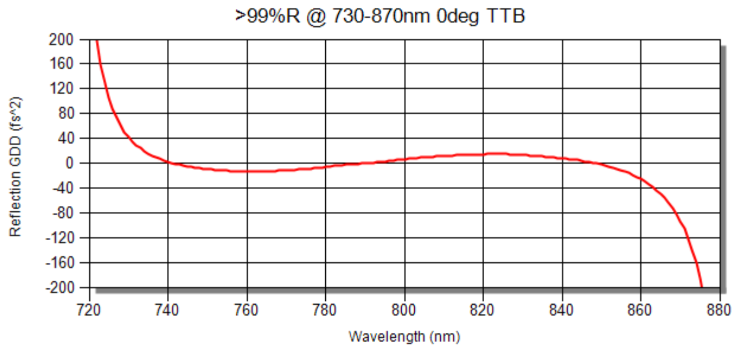
800nm mirrors 0deg angle of incidence:
>99.3%R @ 730-870nm /0deg

800nm mirrors 45deg angle of incidence:
>99.5%R @ 710-890nm /45deg s-POL
>99%R @ 750-850nm / 45deg p-POL

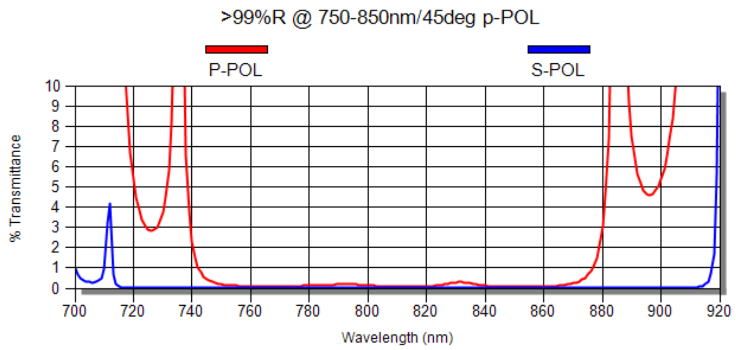
PART NUMBER	DIAMETER	THICKNESS	COATING CENTRE WAVELENGTH	ANGLE OF INCIDENCE
TTB-25.4-6.35-800-0	25.4mm	6.35mm	800nm	0 Degrees
TTB-50.8-9.52-800-0	50.8mm	9.52mm	800nm	0 Degrees
TTB-76.2-12.7-800-0	76.2.mm	12.7mm	800nm	0 Degrees
TTS-101.6-12.7-800-0	101.6mm	12.7mm	800nm	0 Degrees
TTB-25.4-6.35-800-45	25.4mm	6.35mm	800nm	45 Degrees
TTB-50.8-9.52-800-45	50.8mm	9.52mm	800nm	45 Degrees
TTB-76.2-12.7-800-45	76.2mm	12.7mm	800nm	45 Degrees
TTB-101.6-12.7-800-45	101.6mm	12.7mm	800nm	45 Degrees

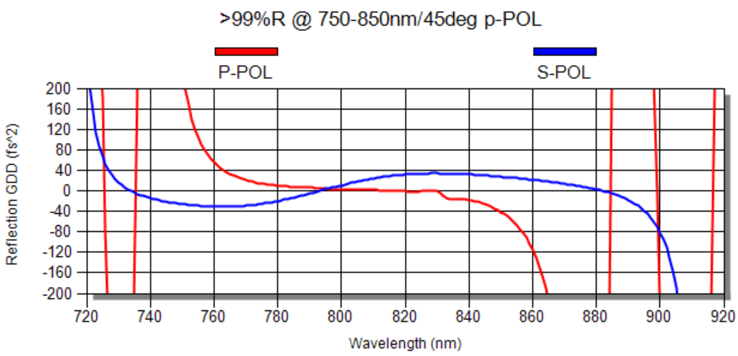
TTB-type mirror for 800nm /0deg





TTB-type mirror for 800nm /45deg





TTW Range

The TTW range of mirrors, like the TTB range, is based on a specialist coating design to offer a very broad reflectivity bandwidth based only on dielectric coating materials while maintaining a good Group Delay Dispersion (GDD) and high Laserinduced damage threshold (LIDT).

Material	UV Fused Silica
	N-BK7
Diameter Tolerance	+ 0/ - 0.25mm
Thickness Tolerance	± 0.25mm
Front Surface	λ/10 flatness
	10-5 scratch-dig
Rear Surface	Inspection polish

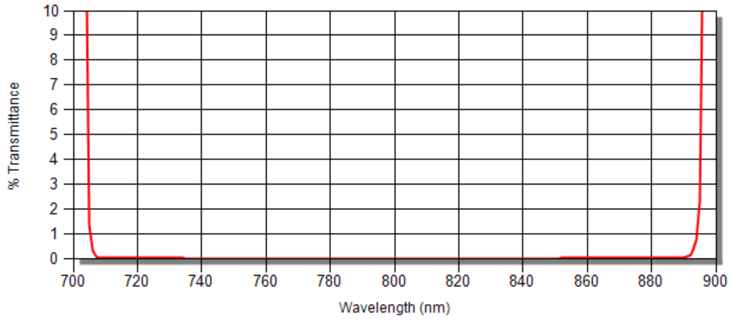
Coating Specifications

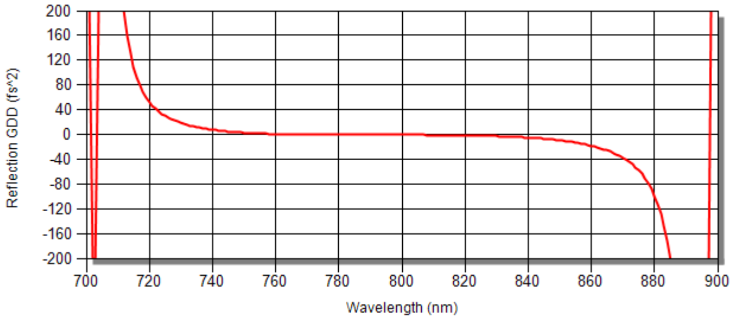
800nm mirrors 0deg angle of incidence:
>99.3%R @ 720-880nm /0deg

800nm mirrors 45deg angle of incidence:
>99.3%R @ 700-900nm /45deg s-POL
>99.3%R @ 740-860nm / 45deg p-POL

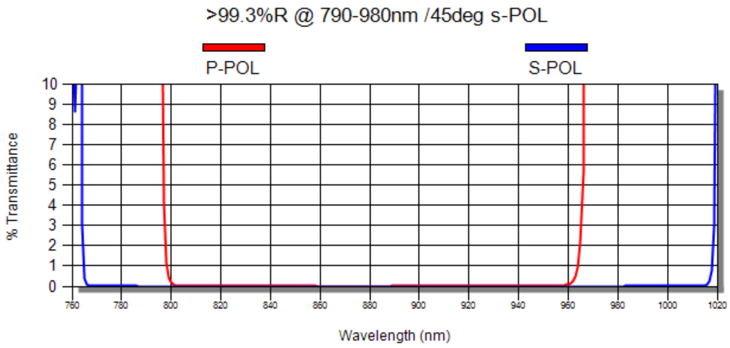
PART NUMBER	DIAMETER	THICKNESS	COATING CENTRE WAVELENGTH	ANGLE OF INCIDENCE
TTW-25.4-6.35-800-0	25.4mm	6.35mm	800nm	0 Degrees
TTW-50.8-9.52-800-0	50.8mm	9.52mm	800nm	0 Degrees
TTW-76.2-12.7-800-0	76.2.mm	12.7mm	800nm	0 Degrees
TTW-101.6-12.7-800-0	101.6mm	12.7mm	800nm	0 Degrees
TTW-25.4-6.35-800-45	25.4mm	6.35mm	800nm	45 Degrees
TTW-50.8-9.52-800-45	50.8mm	9.52mm	800nm	45 Degrees
TTW-76.2-12.7-800-45	76.2mm	12.7mm	800nm	45 Degrees
TTW-101.6-12.7-800-45	101.6mm	12.7mm	800nm	45 Degrees

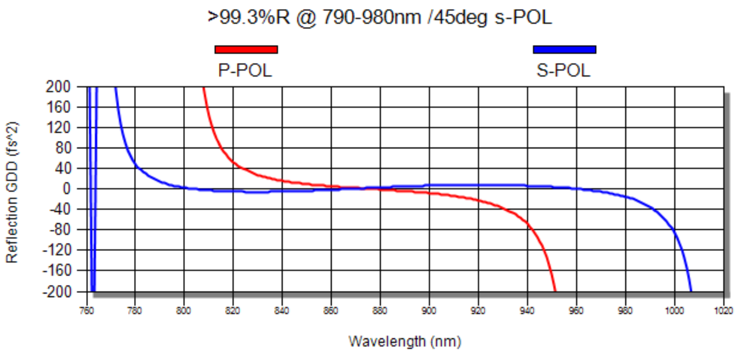
TTW-type mirror for 800nm /0deg





TTW-type mirror for 800nm /45deg





TTMH Range

Using a specially designed metal-dielectric hybrid coating, MPO's TTMH-type mirrors are able to achieve a very high LIDT and offer high reflectance over a 200nm bandwidth (700-900nm) under 45deg p-polarisation.

The coating has been designed with a low group delay dispersion (GDD) in mind and can be applied to optics up to 450mm diameter.

Material	UV Fused Silica
	N-BK7
Diameter Tolerance	+ 0/ - 0.25mm
Thickness Tolerance	± 0.25mm
Front Surface	λ/10 flatness
	10-5 scratch-dig
Rear Surface	Inspection polish

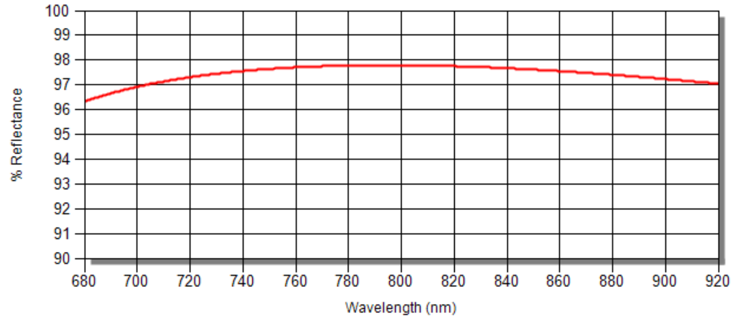
Coating Specifications

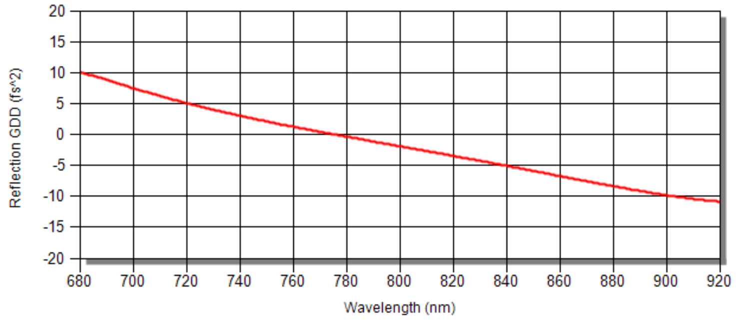
800nm mirrors 0deg angle of incidence:
>97%R @ 700-900nm / 45deg s-POL &

800nm mirrors 45deg angle of incidence:
>97.5%R @ 700-900nm /45deg s-POL
>96%R (avg.) @700-900nm / 45deg p-POL

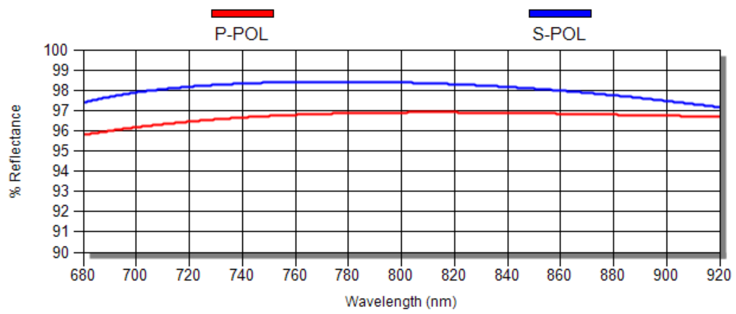
PART NUMBER	DIAMETER	THICKNESS	COATING CENTRE WAVELENGTH	ANGLE OF INCIDENCE
TTMH-25.4-6.35-800-0	25.4mm	6.35mm	800nm	0 Degrees
TTMH-50.8-9.52-800-0	50.8mm	9.52mm	800nm	0 Degrees
TTMH-76.2-12.7-800-0	76.2.mm	12.7mm	800nm	0 Degrees
TTMH-101.6-12.7-800-0	101.6mm	12.7mm	800nm	0 Degrees
TTMH-25.4-6.35-800-45	25.4mm	6.35mm	800nm	45 Degrees
TTMH-50.8-9.52-800-45	50.8mm	9.52mm	800nm	45 Degrees
TTMH-76.2-12.7-800-45	76.2mm	12.7mm	800nm	45 Degrees
TTMH-101.6-12.7-800-45	101.6mm	12.7mm	800nm	45 Degrees

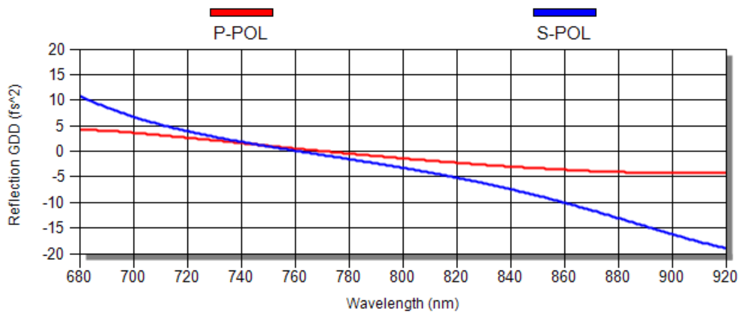
TTMH-type mirror for 800nm /0deg



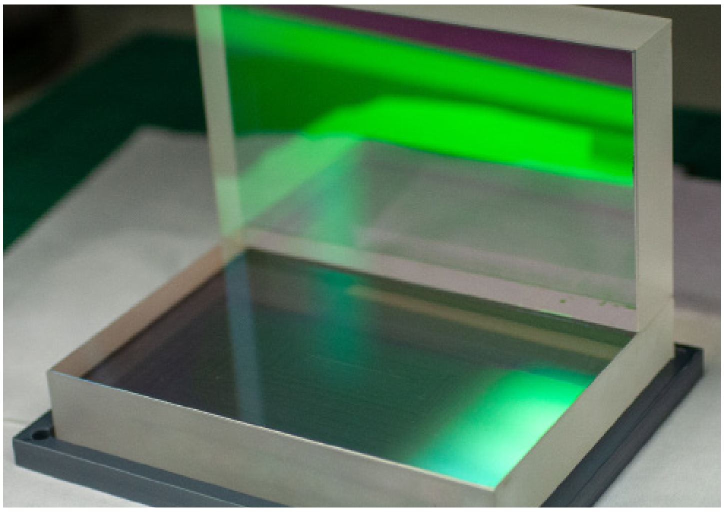


TTMH-type mirror for 800nm /45deg



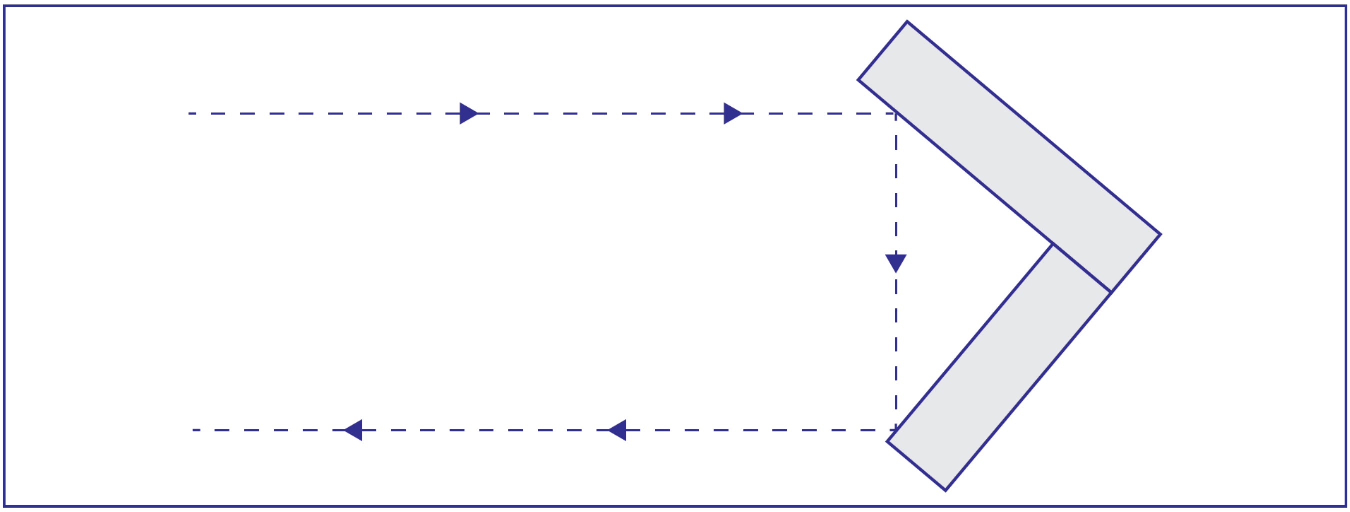


Roof Mirrors



All coatings can also be applied to optically contacted roof mirrors for beam delay lines. Due to the two reflecting mirrors being optically contacted together these mirrors are comparatively easy to mount and to adjust as the two reflecting mirrors maintain their angle and orientation towards each other.

Please contact us for further information.



Useful Information

Useful Equations

Speed of Light: c = 299792458 km/s

Snell's Law:

$$\frac{\sin \alpha}{\sin \beta} = \frac{n_2}{n_1}$$

Focal length of a curved mirror:

$$f = \frac{r}{2}$$

r: radius of curvature

Lensmaker's Equation
(approximate focal length of a thin lens):

$$\frac{1}{f} \approx (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2}\right]$$

f: focal length, R1, R2: radii of curvature of the lens surfaces

Fresnel reflection of a surface at 0°:

$$R = \frac{n_2 - n_1}{n_2 + n_1}$$

Optical Density OD:

T: Transmission

$$OD = \log_{10} \frac{1}{T}$$

f-stop number N:

$$N = \frac{f}{D}$$

Manx Precision Optics- Quality Policy

Manx Precision Optics Ltd. operates to BS EN ISO 9001:2015 offering high quality optical components, systems and integrated solutions to customers within the photonics industry.

Manx Precision Optics Ltd. focuses on meeting customer requirements through the provision of sound advice. The company encourages all employees to participate in a process of continuous improvement and to adopt a systematic approach to processes in manufacturing and problem solving, working in partnership with its suppliers.

Manx Precision Optics Ltd. adopts the following principles for its operations:

- Creation and maintenance of trusted relationships with suppliers and customers
- Focus on customer requirements and meeting commitments made
- Encourage a work ethic that ensures all employees feel responsible for quality and maintain the highest level of craftsmanship
- Meeting legal and statutory requirements
- Adopting a proactive approach to continual improvement of its quality systems
- Setting a quality objectives program to encourage continuous improvement

Dr Helmut Kessler
Managing Director

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