How to Choose the Right Optic

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With the variety of choices available, it can be a daunting task to specify and choose the right optic for a given application. Even off-the-shelf catalogue components have many features which should be taken into consideration before an order is placed. Of significant concern are beam size, damage threshold, bandwidth, angle of incidence, polarization and reflectivity.

The Shape

Most optical substrates are offered in an array of shapes and sizes. What may seem to be an easy decision can end up being the wrong decision if factors such as clear aperture, angle of incidence and access to suitable mounts are not taken into consideration. For example, a typical 1″ diameter optic will have a clear aperture of about 22mm at normal incidence, accommodating any beam smaller than that. The same optic used at an incident angle of 45 degrees will only accommodate a round beam up to 15.5mm diameter. The obvious choice might be to use elliptical or rectangular substrates for applications at 45 degrees, but the polishing costs are often higher for substrates in shapes other than round (fig 1) and the selection of mounts is limited. Unless there is a spatial constraint to the optical set-up, a suitably large round substrate will usually meet the requirements at a lower cost and faster lead time.

Figure 1 Round optics are easier and more economical to manufacture.

Lenses and other curved substrates add another factor to the equation because radius of curvature also has to be considered. Using the simple lens equation for a plano-convex singlet lens where focal length $f = R/(\eta-1)$ it is clear that for any material with an index near 1.5, like crown glass or fused silica, the focal length will be approximately twice the radius of curvature. Also, because the physical diameter of a positive singlet lens cannot be more than twice the radius of curvature, it follows that the diameter of a lens cannot be more than the approximate focal length of the lens, unless you switch to a higher index glass material like SF11. And again, fabrication costs (and therefore selling price) will vary depending on the size and shape of the lens. A short focal length lens which has to be polished one-at-a time will cost more than a lens with a longer radius of curvature that can be manufactured in lot sizes of 19 or more. Similarly it may be more economical to polish a batch of bi-convex lenses where R1 & R2 approximately equal the focal length of the lens than a batch of plano-convex lenses with a shorter radius that limits the lot size to only 3 or 7 parts per polishing block. These are important concepts to remember when considering the price, quality and performance of a lens.

Surface Quality

Surface quality and surface figure need to be clearly defined to meet damage threshold, wavefront and low-scatter requirements. Most laser systems require substrates with a surface quality of 10-5 or better, meaning that the polished surfaces will have no scratch greater than 10 microns in width and no dig greater than 5 microns in diameter. An uncoated fused silica lens polished to a 10-5 surface can withstand energies of more than 40J/cm^2 at 1064nm. Commercial grade optics with a scratch/dig spec of 60-40 or 40-20 cost less and may be perfectly suitable for research and low energy applications.

The performance of an optic is also affected by reflected and/or transmitted wavefront distortion (TWD), which are primarily determined by the surface figure. For lenses, a true calculation cannot be done without taking into consideration diffraction limits and spherical aberration theory, but in general, a long focal length singlet lens will have less spherical aberration and therefore a better TWD than one with a short radius of curvature on one or both sides. Most laser quality optics are polished to a surface figure of $\lambda/10$ waves p-v at 632.8nm, or tenth-wave flatness. To achieve this on a window or other flat substrate, it is important to allow for enough physical thickness to maintain a suitably low diameter-to-thickness aspect ratio; for BK7 (borosilicate crown glass) the preferred maximum value is 6:1 and for fused silica it is 10:1. TWD is dependent on both material homogeneity and surface flatness so thinner substrates are better; one inch diameter substrates made from grade A BK7 glass are typically available with $\lambda/10$ TWD in thicknesses ranging from 1.5 to 10mm.

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Substrate Materials

Because of availability and optical quality, BK7 and fused silica have emerged as the most common substrate materials utilized in the ultra-violet (UV) to near-infrared (NIR) wavelength regions. For uses in the visible and NIR, BK7 is a low-cost glass with good homogeneity and good manufacturability, suitable for many applications as either a transmissive or reflective component. When an application requires increased thermal stability, very high damage threshold or exposure to UV light, fused silica is the better option. Fused silica is an amorphous form of silicon dioxide glass and is readily available in a variety of grades and material classes with high transmittance as low at 193nm. VUV grade calcium fluoride (CaF_2) transmits from 157nm to about 8 microns in the infrared, so is a good choice for either IR or Deep UV applications; care must be taken when specifying this material however since issues such as birefringence, cost and surface quality limitations must all be taken into consideration.

Coatings

Coatings can be used to enhance the performance and lifetime of an optical component. For transmissive optics such as lenses, windows, waveplates and prisms, a thin film dielectric anti-reflection (AR) coating can increase the overall transmission through the optic by as much as 4% per surface. AR coatings also help minimize stray light and back reflections throughout the system.

Fresnel's equation can be used to calculate the reflectance in air ($\eta = 1.0$) off an uncoated glass surface at normal incidence:

$$R = ((\eta-1)/(\eta+1))^2$$

where η is the refractive index of the substrate material. For BK7 at 633nm, $\eta = 1.5151$ so $R = 4.2\%$; this results in a total loss of more than 8% of the initial power. An AR coating can reduce the reflectance per surface to 0.1-2.0% depending on the design chosen.

Antireflection Coatings

Three types of AR coatings designs are most often used. A multi-layer V-Coating is both durable and damage resistant and can be designed for use at almost any UV-NIR wavelength to achieve better than $R < 0.25\%$ per surface at normal incidence (fig 2). Broadband multi-layer AR coatings are typically applied to optimize transmission over several wavelengths or wavelength regions within a limited range; average reflectance of < 0.5% per surface over 100-200nm can be expected depending on the substrate material and wavelength region being covered, improving overall transmission by more than 7%. The third common choice is a single layer magnesium fluoride (SLMF) AR coating which is the most broadband of the readily available options. With an index of about 1.38, the SLMF coating is an excellent and inexpensive coating choice for use on high index materials such as sapphire and SF10 glass. Normal incidence reflectance of < 0.25% can easily be achieved on these materials without sacrificing either durability or bandwidth.

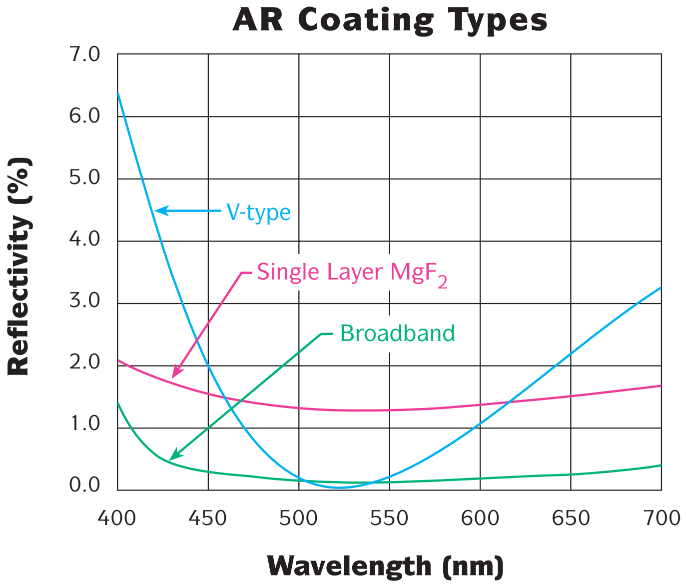

Figure 2 Graph showing reflectivity vs wavelength performance of the three most common AR coating types: V-type, single-layer MgF_2, and broadband.

Dielectric & Metal Coatings

Dielectric and metal coatings can be applied to flat and curved substrates in order to reflect, redirect or focus light. Metal coatings such as gold, silver and aluminum are primarily used for reflecting very broadband light sources with low energies (< 100mJ/cm^2) at almost any angle of incidence from 0 to 60°. These coatings often have a protective dielectric layer to increase the durability and lifetime of the coating and can be enhanced with a multi-layer dielectric stack to increase reflectivity in the UV or visible regions. Metal coatings are still sensitive to moisture and/or scratches so are generally not used in abrasive environments or systems in which the optics have to be frequently cleaned or handled.

High energy laser mirrors use dielectric coating stacks to achieve very high reflectivity at a single wavelength or over a narrow bandwidth and incidence angle. Depending on the substrate material and wavelength of operation, damage thresholds of 10-20J/cm^2 and reflectivity of greater than 99.5% are standard for normal incidence mirrors (fig 3). At 45 degrees, S-polarization reflects more and is more broadband than P-polarization, so it is important to identify the correct component and polarization state when ordering or determining optic specifications.

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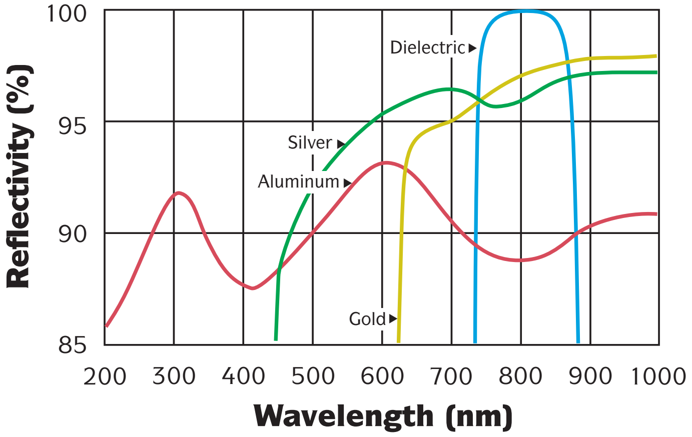

Figure 3 Gold, silver, and aluminum coatings provide broadband performance, while dielectric coatings achieve very high reflectivity at a single wavelength or over a narrow bandwidth and incident angle.

When bandwidth is a higher priority than damage threshold, alternate coating materials can be used in the visible and NIR to create highly reflective mirrors with low dispersion and minimal pulse distortion. Coating designs can also be modified to create mirrors with high reflectivity at two distinct wavelengths or over much broader bandwidths than can be achieved with "single-stack" designs.

Polarization

When polarization is a concern, linear and birefringent polarizers can be used to remove, reflect or refract one of the polarization components (fig 4). Whether or not to choose a calcite (Glan Thompson or "Glan Laser") polarizer, a thin film plate polarizer or a polarizing beamsplitter cube depends on the bandwidth and energy levels of the input light. A cemented beamsplitter cube works well for low energy applications in which both components of light are to be utilized. These are available at many wavelengths from the UV to the NIR, in both narrow and broadband varieties with damage thresholds up to 100mJ/cm^2 and transmitted extinction ratios of 1000:1. Higher extinction ratios on the order of 10^5:1 over very broad bandwidths can be achieved using birefringent calcite or magnesium fluoride (MgF_2) Rochon polarizers. Damage thresholds vary from 10mJ to 1J/cm^2 depending on whether the rejected beam is absorbed or removed through an escape window, and whether the assembly is cemented or air-spaced.

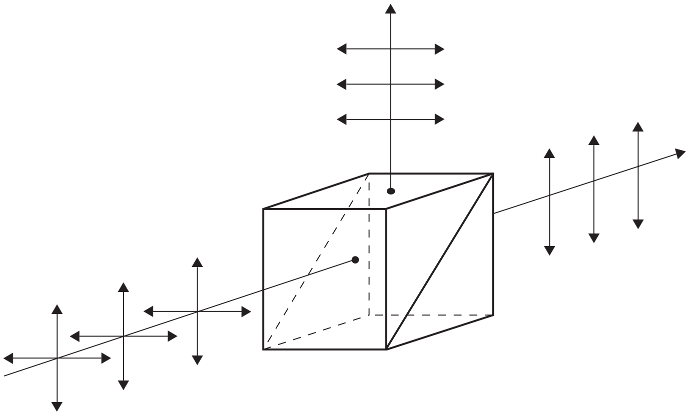

Figure 4 Example of a Polarizing Beamsplitter Cube.

For fluences of a joule or more, a plate polarizer or an optically contacted polarizing beamsplitter cube can be used to avoid damage due to cement or tracking within calcite material; both types of polarizers reflect the S-polarized light and can be used for high energy laser applications. Plate polarizers exhibit low group velocity dispersion so are often used in ultrashort femtosecond systems, but usually need to be angle tuned for maximum transmission and extinction ratio. Polarizing beampslitter cubes require no angle tuning and the transmitted and reflected beams are separated by 90^o but are often more expensive and limited to dimensions of an inch or less.

Therefore

In summary, to get the most from your optical component budget, consideration should be given to functionality and manufacturability as well as the mechanical and optical specs of each component.

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