DESCRIPTIONS & NOMENCLATURE

Bandpass Filters

555XX30

CWL (center wavelength) Filter Design FWHM/Bandwidth

3RD550-580

Cut-on Cut-off

Note: Full Width Half Max (FWHM) is defined by the region of the passband where the transmission of the filter is 50% of the maximum transmission.

Filter Design – Our nomenclature and descriptors define the performance characteristics of filter designs.

- **BP – Bandpass filter**: Bandpass filters transmit light within a defined spectral band. Coating designs range from 2 to 6 cavities.
- **QM – QuantaMAX™**: Surface coated, single substrate designs provide steep edges, very high transmission and minimal registration shift.
- **3RD – 3RD Millennium**: Filters are manufactured using proprietary ALPHA coating technology and Omega's patented, hermetic assembly, and defined by the critical cut-on and cut-off requirement.
- **AF – ALPHA Filter**: Alpha filter designs are manufactured using Omega's proprietary technology resulting in extremely steep edges, precise edge placement, and theoretical attenuation >OD10. Defined by the critical cut-on and cut-off requirement.
- **DF – Discriminating Filter**: These filter designs have 6 or more interfering cavities, resulting in a rectangular bandpass shape, very steep edges, and very deep blocking up to optical density (OD) 6 outside the passband.
- **WB – Wideband Filter**: Wideband filters are 4 & 5 cavity designs with FWHM greater than 30nm, up to several hundred nanometers.
- **NB – Narrowband**: Narrowband filters are 2-cavity designs with FWHM typically between 0.2 and 8nm.

Dichroic Filters

505DRLP

Cut-on Filter Design

675DCSPXR

Cut-off Filter Design

Note: Cut-on or cut-off wavelength is defined as the wavelength at which the dichroic is at 50% of its maximum transmission.

Filter Design – Dichroics are filters that highly reflect one specified spectral region while optimally transmitting another. These filters are often used at non-normal angles of incidence, typically 45 degrees.

- **DC – Dichroic**: These filters provide wide regions of both transmission and reflection, exhibiting a high degree of polarization along with a somewhat shallow transition slope.
- **DR – Dichroic Reflector**: These designs provide a steeper slope than typical DC filters, low polarization, a wide range of transmission and a limited region of reflection.
- **DCXR – Dichroic Extended Reflector**: A design that provides extended reflection regions.
- **DCSP / DCLP / DRSP / DRLP**: These designations dictate those portions of the spectrum that will be transmitted and reflected. The "SP" (shortpass) nomenclature means the filter will be transmitting wavelengths below the defined cut-off region. The "LP" (longpass) nomenclature defines the region of transmission as wavelengths above the defined cut-on region.

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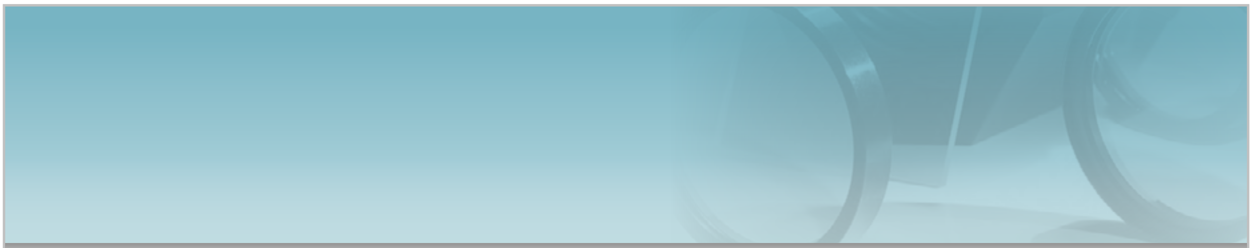

Longpass & Shortpass Filters

515ALP

Cut-on Filter Design

680ASP

Cut-off Filter Design

3RD650LP

Filter Design Cut-on

Note: Cut-on or cut-off wavelength is defined as the wavelength at which the filter is at 50% of its maximum transmission.

- **LP – Longpass**: These filters transmit wavelengths longer than the cut-on and reflect a range of wavelengths shorter than the cut-on.
- **SP – Shortpass**: These filters transmit wavelengths shorter than the cut-off and reflect a range of wavelengths longer than the cut-off.

Multi-band Filters

- **DB – Dual Band**: Filters are designed to have two passbands and two rejection bands.
- **TB – Triple Band**: Filters are designed to have three passbands and three rejection bands.
- **QB – Quad Band**: Filters are designed to have four passbands and four rejection bands.

Filter Product Line Codes

XA – Analytical Filters
XB – Bandpass Filters
XC – Microscope Filter Holders
XCC – Clinical Chemistry
XCY – Flow Cytometry Filters
XF – Fluorescence Filters
XL – Laser Line Filters (not blocked)
XLD – Laser Diode Clean-up
XLK – Laser Line Filters (fully blocked)
XLL – Laser Line Filters
XMV – Machine Vision
XND – Neutral Density Filters
XRLP – Raman Longpass Filters
XUV – UV Filters

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LASER COMPONENTS®

COATING TECHNOLOGY

◗ **QuantaMAX™ – for high performance interference filters**

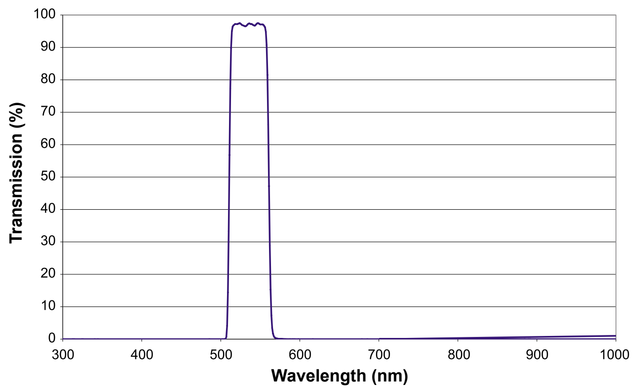
Outstanding spectral characteristics on a wide variety of substrate materials utilizing our state-of-the-art deposition technology, *Dual Magnetron Reactive Sputtering (DMRS).*

QuantaMAX

◗ Transmission

For today's most sensitive instruments, **QuantaMAX™ optical coatings** provide exceptional throughput. As seen in Figure 1, a standard 510-560 interference filter achieves transmission in excess of 97%. Combined with deep out of band attenuation, **QuantaMAX™ optical coatings** make every photon count.

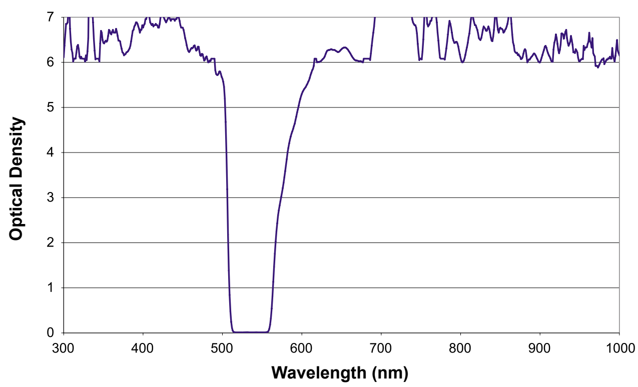
Figure 1 – *actual performance* **Transmission of a standard 510-560 interference filter**



◗ Optical Density

For many applications, the out of band blocking at the detector is as important as the overall transmission. Figure 2 shows the out of band blocking from 300-1000nm and the optical density average of > 6.0. A filter with these characteristics operating in a system with an ideal light source and detector could be expected to have a signal/noise ratio of exceeding 10,000:1, while collecting all available signal.

Figure 2 – *actual performance* **Optical Density of a standard 510-560 interference filter**



04/22 / V01 / BG-IF / omega/application-notes-filters

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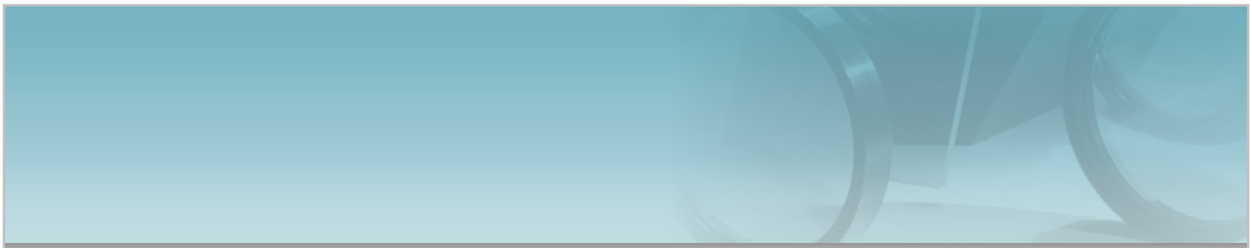
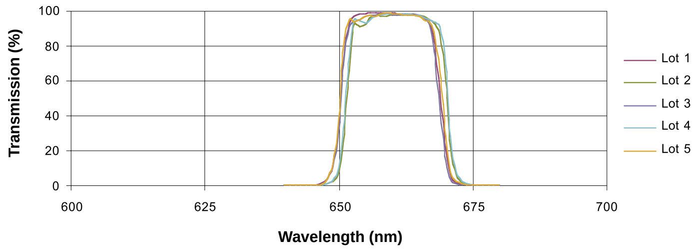


Lot to Lot Reproducibility

With the *Dual Magnetron Reactive Sputtering* (DMRS) process, **QuantaMAX™ optical coatings** employ the latest methods in optical thin-film design and deposition control. Utilizing the DMRS technology we achieve very precise individual layer thickness, along with forward and backward "proof-reading" of layer execution, leading to a high degree of predictability and reproducibility lot-to-lot. As depicted in Figure 3, the edge of the 650-670 bandpass filter varies only 1 nm in either the cut-on or cut-off edges across a sampling of 5 individual deposition lots.

Figure 3 – *actual performance* **Lot to Lot Reproducibility**



Minimized Transmission Band Distortion

The ability to precisely deposit a layer of coating material of optimized optical thicknesses in a stable and highly reproducible manner throughout the deposition cycle provides excellent transmission characteristics with minimal pass-band rippling. Figure 4 and 5 show the typical performance of long-pass and short-pass interference filters.

Figure 4 – *actual performance* **Long Pass Interference Filter**

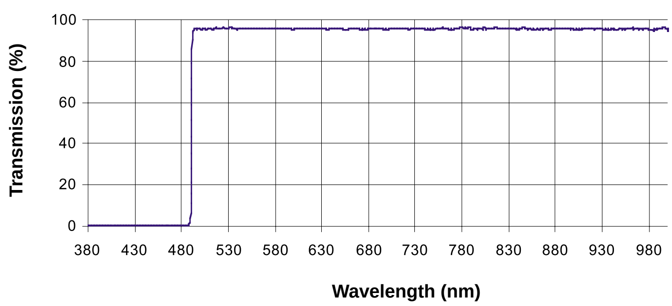
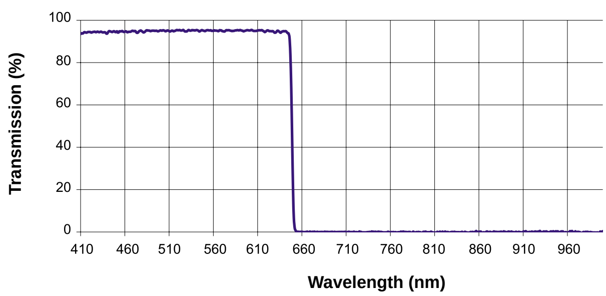


Figure 5 – *actual performance* **Short Pass IR Filter**



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COATING TECHNOLOGY

Viewing Enhancement Coatings

SpectraPlus™ for accurate hue, enhanced saturation, increased color signal-to-noise, and a resulting improved Modulation Transfer Function (MTF). SpectraPLUS coating technology is the deposition of multiple layers of thin film coatings on glass and acrylic lenses for the enhancement of viewing color images to address two primary areas. This technology benefits color imaging systems as well as applications where the eye is the detector. The coating allows transmission of the three bands of pure color—red, green, and blue—while blocking those intermediate wavelengths that distort the perception or recording of color. It also eliminates wavelengths in the ultraviolet and near infrared which are detrimental to an accurate color rendering and visual record.

Two of the more recent and unique technical capabilities developed at Omega have been employed in developing these products. They offer the ability to deposit complex coatings on curved surfaces with control of the thickness distribution over the full usable aperture of the curved optic that makes these features possible. The control of thickness can be either to create uniform thickness where the normal distribution is thinner away from the center, or it can be applied and adjusted to create a thickening coating profile toward the edge to compensate for viewed angular effects that would cause band shifting.

Both of these product developments open many possibilities for new areas of optical device improvement and development.

Photo courtesy of Leybold Optics. Syrus Pro 1510 LION Assisted Electron Beam Custom Opthalmic Coater. Our engineers have worked closely with Leybold Optics of Germany to refine the performance of this large coating tool for the precise deposition of complex multi-layers for Image Enhancement coatings under the SpectraPlus brand.

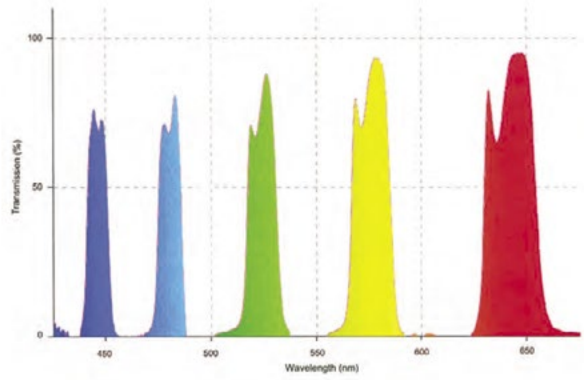
Other enhancements can be integrated into viewing systems. Coatings such as photochromics, or anti-scratch, or hydophobic can be added to produce the highest technology, and performing eyewear world-wide. Applications where these coatings can make the difference between success and failure exist everywhere that excellent vision is a benefit. Typical of these would be dentistry, surgery, sports, high speed maneuvering and viewing in poorly lite situation.

Omega Optical is prepared and anxious to work closely to refine this product line to bring your offer to be the last considered.

SpectraPLUS is protected by U.S. patent #5,646,781.

Depth Defining® series is a totally new approach to displaying and viewing an image with an X and Y impression as well as a clear Z element. The ultra-complex spectral function divides the visible into two visually identical white mixtures which are mutually exclusive.

The left and right viewing eye see distinct images that have been projected spatially or temporally independent. The result is an image with depth that the viewer can experience with clarity.



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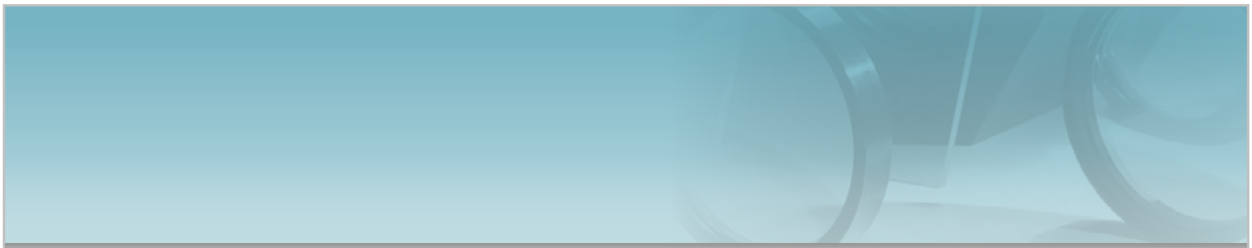
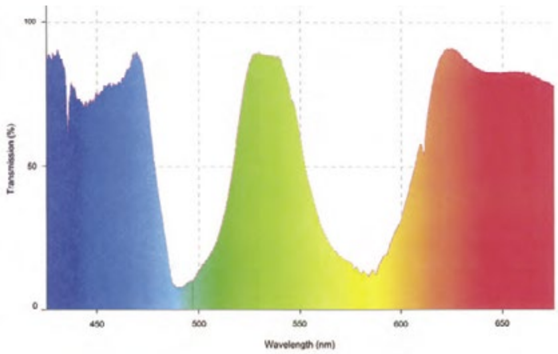


◗ **ColorMAX™** series is intended for spectral refinement with the intended purpose of improving color rendition through saturation and hue. Curved lenses are coated with a complex multi-layer coating that removes harmful UV rays, as well as IR. These coatings further eliminate the colors of light that stimulate multiple cones that result in color confusion. The final product is eyewear that forces all colors to explode from their background.

We offer two ColorMAX filters with SpectraPLUS coatings; XB29 is optimized for digital imaging sensors and XB30 is optimized for the human eye and film. All filters are finished to the highest imaging quality standards and are available in stock and custom sizes.



◗ **XB29 for Digital Imaging Systems and CCD based cameras** blocks the crossover regions between blue/green and green/red centered at 490nm and 600nm respectively. To prevent IR saturation of silicon-based sensors, the coating provides a high degree of attenuation in the near infrared region, from 750nm to 1100nm. XB29 also offers complete attenuation of ultraviolet A and B, and deep blue up to 430nm.

For Digital Imaging Systems:

- Commercial Printing Industry: Pre-press Scanners
- Machine Vision Industry: Camera and Lens Systems
- Office and Home Small Equipment Industry: Desktop Scanners, Color Copiers, Digital Copiers.
- Photography/Video/Film Industry: Video & Digital Cameras and Lenses, Photo Scanners
- Remote Sensing: Camera Systems

◗ **XB29 for Eye and Film** is optimized for applications where the human eye or photographic film is the detector. Color imaging is enhanced with increased saturation, accurate hue, and improved contrast and resolution. This version of the SpectraPLUS filter has two stop band regions centered at 490nm and 580nm for blocking the prime color "crossover" wavelengths between blue/green and green/red in the visible spectrum. The XB30 offers high attenuation of ultraviolet A & B. It also attenuates the near infrared in a band centered at 725nm

For Human Eye and Photographic Film Detection:

- Sports Eyewear Industry: Sunglasses, Ski Goggles, Active Sports Glasses
- Lighting Industry: Medical and Dental Lights, Bulb and Reflector coatings
- Photography/Video/Film Industry: Camera Lens, Video, Film and Slide Projectors, Color and Black&White Film Printers, Enlarger Lens
- Sports Optics Industry: Binoculars and spotting scopes, Rifle Scopes

All sensors - human eye, film, and electro-optical - have limitations in how they "see" and record color. Their receptors significantly overlap, as do the wavelengths for the three prime colors of light: red, green, and blue. A photon of light from within this overlap region can leave an incorrect signal on the receptor so that a green photon, for example, can be perceived or recorded as blue or red.

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COATING TECHNOLOGY

Transparent Conductive Oxides Overview

Transparent Conductive Oxides (TCOs) are a special class of materials that exhibit both transparency and electronic conductivity simultaneously. These materials have widespread applications in flat-panel displays, thin film photovoltaics, low-e windows, and flexible electronics. The requirements of the these materials are not just limited to transparency and conductivity but also include work function, processing and patterning requirements, morphology, long term stability, lower cost and abundance of materials involved. Spectral edges can be generated with the intrinsic properties of one layer of TCOs. This happens with materials like Indium Tin Oxide (ITO) and Aluminum Zinc Oxide (AZO) that have much stronger k values in one spectral band than another band.

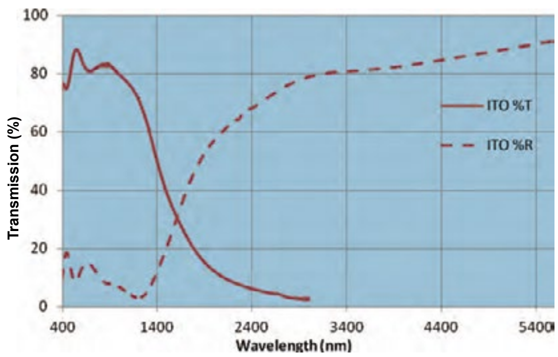

Figure X: Typical ITO Spectral Curve
Curve shows the intrinsic characteristic of ITO to transmit in the visible and reflect like a metal in the IR region. The cross-over frequency (near the plasma frequency) can be moved with changes in deposition parameters.

Description

Currently, ITO is far superior in performance compared to other TCOs and many efforts are being made worldwide to find suitable alternatives. ITO intrinsically has high transparency in the visible and high reflectance in the infrared region. It is commonly used in LCDs and thin film photovoltaic devices. Characteristics of these materials can be widely altered with making changes in deposition parameters. These materials can be integrated with dielectrics to provide wide band IR blocking with thinner layers and low wave-front distortion.

Types

Addressing the wide concern about scarcity and high cost of Indium, Omega is also investigating several other Indium free TCOs, namely,

- Aluminum doped Zinc Oxide
- Fluorine doped Tin Oxide
- Zinc Tin Oxide
- Nickel Oxide and other combinations.

Documentation: Spectrophotometric trace of the attenuation, cut-on, and transmission regions provided. Electronic characteristics such as work function, resistivity and surface roughness are provided upon request.

Specifications

Average Transmission	> 80 % in the visible
Reflectance	High in the IR region
Temperature of Measured Performance	20°C
Operating Temperature Range	-60°C to + 80°C
Humidity Resistance	Per Mil-STD-810E, Method 507.3 Procedure I
Coating Substrates	Optical quality glass
Surface Quality	80/50 scratch/dig per Mil-O-13830A
Sheet Resistance	5-1000 ohms/sq
Surface Roughness	Compatible with the Application
Sizes	Custom dimensions
Barrier Layer	Silicon Dioxide
Process	Ion Assisted Magnetron Sputtering
Work Function	Variable over 4-6eV

In addition to standard specifications, we also produce customized TCO coatings on various kinds of surfaces for many applications.

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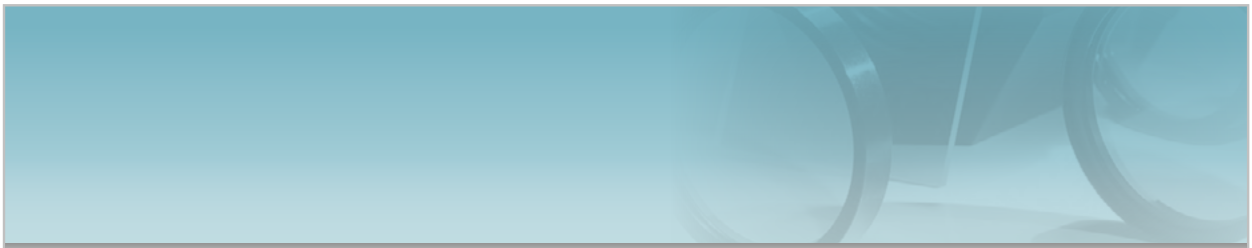

Organic Semiconductor Overview

Organic materials have been used as standard pigments for over 100 years in dyes, inks, food colors and many plastics. One class of organic materials, aromatic hydrocarbons, are known for their stability, insolubility in water and reduces tendency to migrate into other materials. These compounds also exhibit semiconductive properties. Spectral edges can also be generated with the intrinsic properties of organic semiconductors. This is achieved with materials like Copper Phthalocyanine (CuPc) that have a strong k peak in the visible region caused by the so-called Q-band.

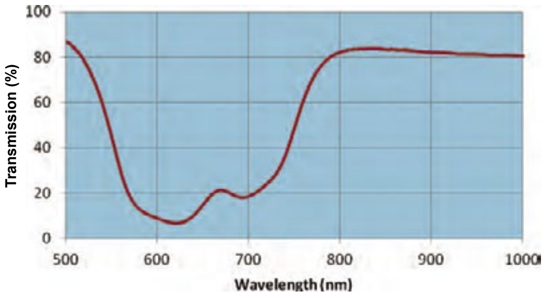

Figure Y: Copper Phthalocyanine Transmission
Typical transmission of CuPc that has significant absorption peak in visible and transmits in IR region.

Description

Organic materials are commonly used in OLEDs, Organic Photovoltaic Devices and Organic FETs. Research is being done worldwide to make these devices commercially available. These materials have significant absorption peaks in the visible and have high transmission in the infrared region. As a result, they can be integrated with other materials to provide blocking with thin layers in optical filters. Other forms of metal-phthalocyanines and perylene derivatives have absorption peaks in different regions of UV, Visible and NIR regions.

Specifications

Blocking	100-150nm wide peaks in visible region
Average Transmission	> 80 % in the IR region
Temperature of Measured Performance	20°C
Operating Temperature Range	-60°C to + 80°C
Humidity Resistance	Per Mil-STD-810E, Method 507.3 Procedure I
Coating Substrates	Optical quality glass
Surface Quality	80/50 scratch/dig per Mil-O-13830A

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LASER COMPONENTS®

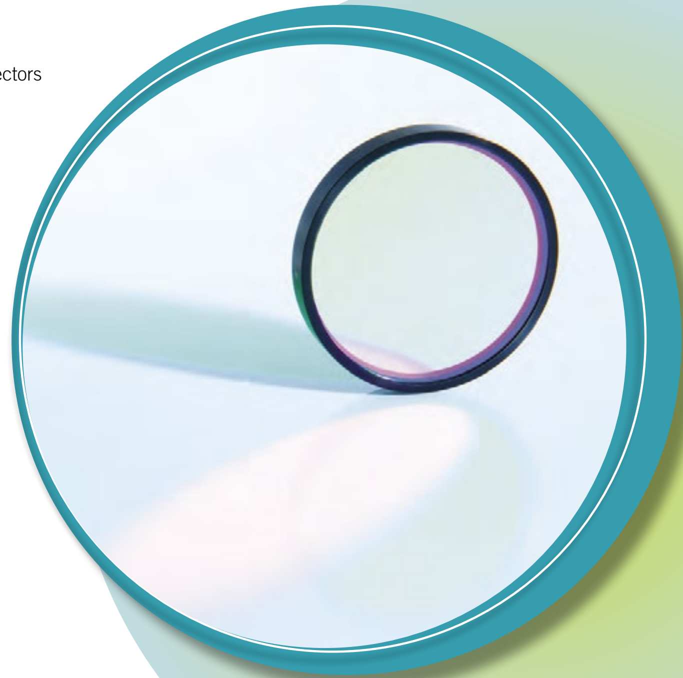
COATING TECHNOLOGY

ALPHA coating technology

ALPHA coating technology is the culmination of Omega's ongoing research and development regarding filter design and deposition techniques. Employing a proprietary method of controlling the coating process, this technology yields filters with exceptionally high signal-to-noise, as well as, steep transition slopes suitable for the most demanding applications. With ALPHA coating technology , optical systems achieve the highest level of spectral discrimination – images are brighter, contrast is enhanced and instruments perform to the limits of detection. Whenever an optical design demands the utmost level of precision, ALPHA coating technology is the obvious choice.

Features/Benefits/Critical Specifications:

- Extremely sharp transitions from stopband to passband
- Precise, repeatable location of cut-on/cut-off wavelengths, tolerances within +/-0.01 to +/-0.005 of the edge 0.3OD - wavelength (50%)
- Transmission 85% avg., 80% minimum, up to 8% gain with anti-reflection coatings
- Tightly controlled ripple at cut-on
- Nearly uniform transmittance across the passband
- Exceptional attenuation of out-of-band signal
- Single surface coatings suitable for PMT and silicon detectors
- Optical quality transmitted wavefront
- Longpass, shortpass and bandpass spectral profiles



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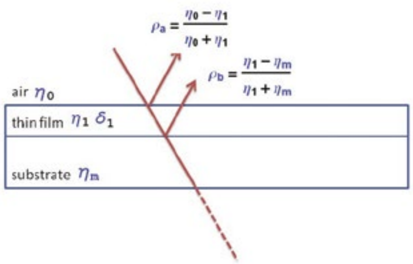
FILTER DESIGN

All boundaries between media are divided into reflected and transmitted portions of the electromagnetic wave. Those portions of the wave not reflected are transmitted across the boundary to a new medium with dissimilar optical properties. These differences cause refraction, or a change in the speed and angle of the wave. A material's refractive index is defined as the ratio of the velocity of light in a vacuum to the velocity of light in that medium. The amount of light reflected is related to the difference between the refractive indices of the media on either side of the boundary; greater differences create greater reflectivity. For non-absorbing media, if there is an increase in refractive index across the boundary, the reflected wave undergoes a phase change of 180°. If there is a decrease no phase change would occur. An optical thin-film coating is a stack of such boundaries, each producing reflected and transmitted components that are subsequently reflected and transmitted at other boundaries. If each of these boundaries is located at a precise distance from the other, the reflected and transmitted components are enhanced by interference.

Unlike "solid" particles, two or more electromagnetic waves can occupy the same space. When occupying the same space, they interfere with each other in a manner determined by their difference in phase and amplitude. Consider what happens when two waves of equal wavelength interfere: when two such waves are exactly out of phase with each other, by 180°, they interfere destructively. If their amplitudes are equal, they cancel each other by producing a wave of zero amplitude. When two such waves are exactly in phase with each other, they interfere constructively, producing a wave of amplitude equal to the sum of the two constituent waves.

An optical thin-film coating is designed so that the distances between the boundaries will control the phase differences of the multiple reflected and transmitted components.



Source: Thin Film Optical Filters by Angus Macleod

When this "stack of boundaries" is placed in a light path, constructive interference is induced at some selected wavelengths, while destructive interference is induced at others.

With the aid of thin-film design software, we apply optical thin-film theory to optimize various coating performance characteristics such as:

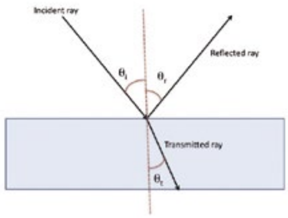
a) The degree of transmission and reflection

b) The size of the spectral range over which transmission, reflection and the transition between them occur

c) The polarization effects at non-normal angles of incidence.
These characteristics are influenced by the number of boundaries, the difference in refractive index across each boundary and the various distances between the boundaries within a coating.

When light does not strike an interference filter at normal (normal is orthogonal to the plane of the filter), the situation becomes a bit more complicated. We now must consider the transmission and reflection of light depending on the orientation of the electric field to the plane of incidence. This orientation of the light's electric field to the plane of incidence is called the polarization of the light. The polarization of incident light can be separated into two perpendicular components called "s" and "p". For a complete treatment of the behavior of light of different polarization, we recommend the classic textbook "Optics" by Eugene Hecht. For now, we'll present Fresnel equations that describe the behavior of the two polarizations of light when they interact with a surface.

The diagram below shows the relevant rays to our discussion. We'll keep the notation used in the diagram for the Fresnel equations below: θ_i is the angle of incidence, θ_r is the angle of reflection and θ_t is the refracted angle of transmission.



First, we can use Snell's Law to determine θ_t from θ_i: $n_1 \sin\theta_i = n_2 \sin\theta_t$

To find the amount of transmitted and reflected light, we use the Fresnel equations:

$$R_s = \left(\frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + n_2 \cos\theta_t}\right)^2 \qquad R_p = \left(\frac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i}\right)^2$$

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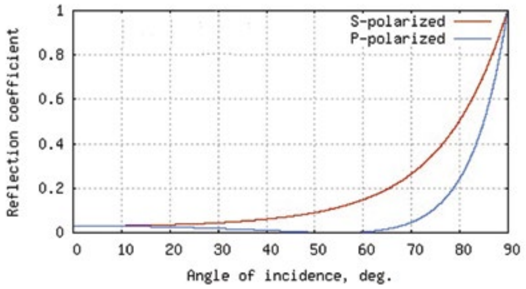
With most of our coatings, absorption is negligible, so transmittance can be found by:

1-R = T.

The following graph shows how the s and p portions of reflectance change as a function of angle of incidence for an air / glass interface:



THE COATING PROCESS

We select coating materials for their refractive and absorptive characteristics at those wavelengths critical to the optical filters application. The coating process requires that materials be selected for their evaporation and condensation properties as well as for their environmental durability.

Our Range of Deposition Chambers includes energetic process systems that rely on sputtering to release the solid to its gas phase (manufactured by Leybold Optics: www.leybold-optics.com). Subsequent to release from the solid, the deposition materials are converted from metal to dielectric in a plasma reaction. These reacted dielectric molecules are then densified in a high power ionic bombardment chamber. This process is repeated in a few milliseconds, so layers are deposited with virtually no defects, and with extreme precision. These Leybold Helios systems are claimed to be the most deterministic in the industry.

Our close work with Leybold Optics has led to enhancements and improvements in the resulting coatings. Additional controls have been added to better define the uniformity of the deposition by both physical and magnetic confinements. Other features have been developed to allow a variety of materials, and precise direct control at nearly any wavelength of light.

With large sputtering targets, and a 1 to 2 meter diameter platen, these deposition chambers have capacity that is unsurpassed. The combination of a vast coating region and extremely precise layer control results in the capability to produce any quantity with nearly indistinguishable spectral function. Furthermore, the precise monitor of dense films make designs of extreme phase thickness a straight-forward process, and the resulting transmission within a small fraction of a percent from theoretical.

Additional deposition chambers include the Leybold SYRUSPro 1510. With 1.5 meters in possible capacity using a LION source for assisted condensation, these chambers provide both complexity and precision in a single system.

These high capacity systems identify Omega Optical as not only the ideal supplier to the labs and research communities, but allow for unlimited production of resulting product developments.

Complementing the energetic process systems are nearly thirty Physical Vapor Deposition (PVD) systems relying on evaporation by resistance or electron beam heating.

Physical Vapor Deposition Coatings are produced in vacuum chambers at pressure typically less than 10-5 torr. The coating materials are vaporized by a resistive heating source, sputter gun (accelerated Ar ions) or an electron beam. With careful control of conditions such as vaporization rate, pressure, temperature and chamber geometry, the vapor cloud condenses uniformly onto substrates, then returning to their solid state. As a layer of material is deposited, its increasing thickness is typically monitored optically.

For example, when zinc sulfide is deposited onto bare glass, the transmission will fall as zinc sulfide builds a layer on the glass. Based on the magnitude of this transmittance level, the precise thickness of the zinc sulfide layer is known. Once the transmittance falls to the point corresponding with the desired layer thickness, the chamber shutter is closed to prevent further deposition of the zinc sulfide. At this point, a second material will typically be added and monitored in a similar fashion. A multi-layer coating is produced by alternating this cycle (typically 20 to 70 times) with two or more materials.

Successful production of a thin film interference filter relies on accurate and precise deposition of the thin film layers. There are a few different methods available to monitor the thickness of deposited layers. The two most commonly employed at Omega are crystal monitors and optical monitors and can be either automated or manual.

Crystal Monitoring Small Crystals (usually quartz) have a natural resonant frequency of vibration. The crystal monitor is placed in the deposition cloud so that the crystal and substrate see directly proportional amounts of deposition regardless of deposition rate, temperature or other factors. As material deposits on the crystal, the vibration of the crystal slows down just like adding mass to an oscillating spring lowers the frequency of oscillation of the spring. Armed with the knowledge of the density of the material we are depositing, we can determine the thickness of the layer deposited.

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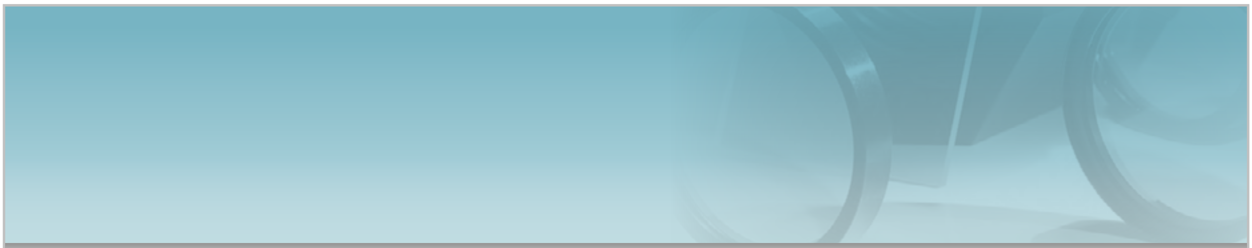

With Optical Monitoring, the intensity of a single color of light passing through the substrate is continually monitored. As the thickness of a layer increases, the transmission of the substrate will change predictably. Even with many tens of layers, the transmission and reflection off a thin film stack is predictable and easily calculable with the benefit of a computer. While we usually optically monitor using transmitted light, it is also possible to optically monitor with reflected light

Several of our deposition chambers have been outfitted for automated manufacturing. The use of a custom written application in "LabView" tells us when to precisely cut layers at the optimal thickness; using optical monitoring of real-time signal.

For optimization of transmission and reflection regions, we employ a number of proprietary commercial packages. These tools allow for the best compromise in performance at all wavelengths in question.

The Quarter-Wave Stack Reflector is a basic building block of optical thin-film products. It is composed of alternating layers of two dielectric materials in which each layer has an optical thickness corresponding to one-quarter of the principal wavelength. This coating has the highest reflection at the principal wavelength, and transmits at wavelengths both higher and lower than the principal wavelength. At the principal wavelength, constructive interference of the multiple reflected rays maximizes the overall reflection of the coating; destructive interference among the transmitted rays minimizes the overall transmission.

Figure 1 illustrates the spectral performance of a quarter-wave stack reflector. Designed for maximum reflection of 550nm light waves, each layer has an optical thickness corresponding to one quarter of 550nm. This coating is useful for two types of filters: edge filters and rejection band filters.

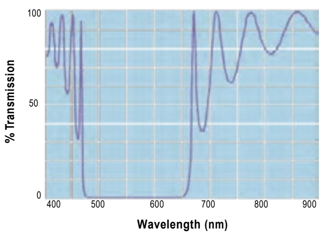

Figure 1 *Quarter-Wave Stack Reflector*

The Fabry-Perot Interferometer, or a single-cavity coating, is formed by separating two thin-film reflectors with a thin-film spacer. In an all-dielectric cavity, the thin-film reflectors are quarter-wave stack reflectors made of dielectric materials.

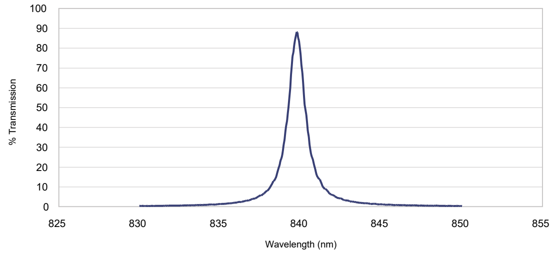

Figure 2 *Single-Cavity Coating*

The spacer, which is a single layer of dielectric material having an optical thickness corresponding to an integral-half of the principal wavelength, induces transmission rather than reflection at the principal wavelength. Light with wavelengths longer or shorter than the principal wavelength will undergo a phase condition that maximizes reflectivity and minimizes transmission. The result is a passband filter. The size of the passband region, the degree of transmission in that region, and the degree of reflection outside that region is determined by the number and arrangement of layers. A narrow passband region is created by increasing the reflection of the quarter-wave stacks as well as increasing the thickness of the thin-film spacer. In a metal-dielectric-metal (MDM) cavity, the reflectors of the solid Fabry-Perot interferometer are thin-films of metal and the spacer is a layer of dielectric material with an integral half-wave thickness. These are commonly used to filter UV light that would be absorbed by all-dielectric coatings.

The Multi-Cavity Passband Coating is made by coupling two or more single-cavities with a matching layer. The transmission at any given wavelength in and near the band is roughly the product of the transmission of the individual cavities. Therefore, as the number of cavities increases, the cut-off edges become steeper and the degree of reflection becomes greater.

When this type of coating is made of all-dielectric materials, out-of-band reflection characteristically ranges from about (.8 x CWL) to (1.2 x CWL). If thin films of metal, such as silver, are substituted for some of the dielectric layers, the metal's reflection and absorption properties extend the range of attenuation far into the IR. These properties cause loss in the transmission efficiency of the band.

As mentioned previously, the choice of materials to be used in a multilayer design is very wide, ranging from metals to the oxides of metals, to the salts and more complex compounds, to the small molecule organics. General features required to be practical include environmental stability, stress, deposition, temperature, transparency, etc. Most of the industry limits the selection to refrac-

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tory oxides. We have experience with a much wider selection. With our wide range of potential materials, coatings of many varieties are possible. We like to use the expression "there is no end in light." By this, we mean we will attempt to satisfy any spectral function as one we can produce, until we have proven otherwise.

List of coating materials:

niobium (V) oxide - Nb_2O_5	zinc sulfide - ZnS
germanium - Ge	cryolite - Na_3AlF_6
magnesium fluoride - MgF_2	aluminum - Al
tantalum (V) oxide - Ta_2O_5	yttrium (III) fluoride - YF_3
hafnium (IV) oxide - HfO_2	silver - Ag
zirconium (IV) oxide - ZrO_2	nickel chromium alloy - Inconel
aluminum oxide - Al_2O_3	silicon dioxide - SiO_2
titanium (IV) oxide – TiO_2	gold - Au

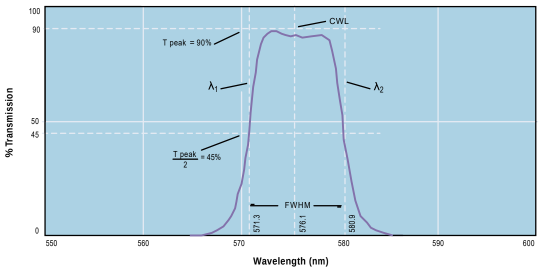

Figure 3 *Multi-Cavity Passband Coating*

Figure 3 illustrates the spectral performance of a 3-cavity bandpass filter. Three features used to identify bandpass filters are center wavelength (CWL), full width at half maximum transmission (FWHM), which characterizes the width of the passband, and peak transmission (%T).

Anti-Reflective Coatings do the opposite of a reflector. At the principal wavelength, it creates destructive interference for the multiple reflected waves, and constructive interference for the multiple transmitted waves. This type of coating is commonly applied to the surfaces of optical components such as lenses, mirrors, and windows. When deposited on the surface of an interference filter, the anti-reflective coating increases net transmission and reduces the intensity of ghost images. It should be noted that a properly designed longpass or shortpass filter is anti-reflective by nature at the relevant wavelengths and doesn't need a second, additional anti-reflective coating.

▸ *See Application Note: Types of Anti-Reflective Treatments and When to Use Them on page 29*

A Partial Reflector, when manufactured from all dielectric materials, is similar to the quarter-wave stack reflector except that fewer layers are employed so that the reflectance is less than complete. Since virtually none of the light is absorbed the portion not transmitted is reflected. Partial beamsplitters often use this partial reflector stack. Here are a couple examples: A 50/50 beamsplitter will reflect 50% and transmit 50% of the incident light over a given spectral range. A 60/40 will reflect 60% and transmit 40%.

Dielectric/Metal Partial Reflector and Neutral Density Metal Filters are two additional types of partial reflectors we offer. The dielectric/metal partial reflector is manufactured with a combination of metal and dielectric materials and absorbs some portion of the incident light. A neutral density filter, coated with the metal alloy "inconel" is a common metal partial reflector.

Front Surface Coatings are employed when light must interact with the coating before passing through the substrate. Reflective surface coatings eliminate multiple reflections in products such as mirrors and dichroic beamsplitters. They also reduce the amount of energy absorbed by the substrate in some products. Anti-reflective coatings that reduce the degree of difference in admittance at the boundary of a filter and its medium are effective on both the front and back surfaces of a filter.

Refractive oxides, fluorides and metals are surface coating materials chosen for their durability. Many optical components are protected by durable surface coatings. Common surface coatings have undergone testing that simulates many years of environmental stress with no observable signs of cosmetic deterioration and only minimal shift in spectral performance. Metal coatings are often over-coated with a layer of oxide or fluoride material to enhance their durability.

Refractive oxide surface coatings are inherently unstable. The reactive coating process for oxides is critically dependent on deposition parameters. Methods such as ion beam sputtering and plasma coating have been developed to improve coating stability through energetic bombardment to produce a more dense coating. Surface coatings are typically more expensive than dielectric coatings due to lengthy manufacturing cycles, but provide extreme durability, excellent transmitted wavefront characteristics and can survive high temperature applications.

Dielectric Coatings may be protected by a cover glass laminated with optical grade cement. This allows use of materials which have wide ranging indices of refraction that result in increasing spectral control at a reasonable cost. A glass-to-glass lamination around the perimeter of the assembly provides moisture protection.

The dielectric materials used to produce these coatings yield the

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highest spectral performance. Research has shown that, although more fragile than refractive oxides, a single pair of dielectric materials permits the most complicated and highest performing interference designs. The benefits of this material include deep out-of-band blocking, very high phase thickness coatings with low residual stress, minimal crazing and substrate deformation, consistent and stable spectral performance, and simplicity of deposition which results in affordable cost.

Extended Attenuation it is often necessary when using a light source or a detector that performs over a broad spectral range to extend the range of attenuation provided by a single-coated surface. Additionally, an increased level of attenuation might be necessary if a high-intensity source or a very sensitive detector is used. While some optical systems may be able to provide space for separate reflectors or absorbers, these attenuating components can often be combined with the principal coating in a single assembly.

Adding attenuating components always results in some loss in transmission at the desired wavelengths. Therefore, optical density blocking strategies are devised for an optimum balance of transmission and attenuation. For example, if a detector has no sensitivity beyond 1000 nm, the filter's optical density blocking is designed only to that limit, conserving a critical portion of the throughput.

Extended attenuation sometimes is achieved by selecting thin film coating materials that absorb the unwanted wavelengths but transmit the desired wavelengths. Absorptive color glasses are commonly used as coating substrates or included in filter assemblies for extended attenuation. Dyes can also be added to optical cement to provide absorption. The choices of absorbing media are many, yet all face their own set of unique limitations. Absorbing media are ideal for some blocking requirements such as the "short wavelength side" of a visible bandpass filter. However, these materials don't provide the best levels of transmission, levels of absorption, or transition slopes in all situations. Furthermore, the temperature increase caused by absorption can be great enough to cause significant wavelength shift or material damage.

Dielectric thin-film coatings, either longpass or shortpass or very wide bandpass, are also commonly used to extend attenuation throughout the required spectral region. Deposited onto substrates

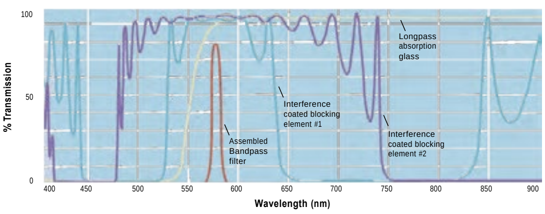

Figure 4 *Bandpass With Extended Attenuation*

they are highly transmissive in the desired spectral region and highly reflective where the principal coating "leaks" unwanted wavelengths.

Figures 4 illustrate how several blocking components increase the attenuation of a principal filter component.

Metal thin-film bandpass coatings extend attenuation to the far IR (>100 microns). This approach is simpler than the all dielectric method in that a single component attenuates a greater range. Metal layers are absorptive however and can reduce transmission at desired wavelengths to levels between 10% and 60%. A comparable all dielectric filter, blocked to the desired wavelength, would allow transmission to 95% in theory, in practice would fall short and not achieve the necessary attenuation range.

Our two most common strategies for extending the attenuation of a single coated surface are referred to as "optimized blocking," for filters used with detectors sensitive only in a limited region, and "complete blocking" for filters used with detectors sensitive to all wavelengths. An optimized blocked filter combines a color absorption glass for the short wavelength side of the passband with a dielectric reflector for the long wavelength side of the passband. A completely blocked filter includes a metal thin-film bandpass coating, which is often combined with a color absorption glass to boost short-wavelength attenuation.

Signal-to-Noise (S/N) ratio is often the most important consideration in designing an optical system. It is determined by:

$S/N = S / (N1 + N2 + N3)$ where:

S = desired energy reaching the detector

N1 = unwanted energy transmitted by the filter

N2 = other light energy reaching the detector

N3 = other undesired energy affecting the output (e.g., detector and amplifier noise)

The optimum interference filter is one that reduces unwanted transmitted energy (N1) to a level below the external noise level (N2 and N3), while maintaining a signal level (S) well above the external noise.

Filter Orientation in most applications is with the most reflective, metallic looking surface toward the light source. The opposite surface is typically distinguished by it's more colored or opaque appearance. When oriented in this way, the thermal stress on the filter assembly is minimized. Spectral performance is unaffected by filter orientation. When significant, our filters are labeled with an arrow on the edge, indicating the direction of the light path. Special markings are made for those customers who require consistency with instrument design.

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Excessive Light Energy can destroy a filter by degrading the coating or by fracturing the glass. Heat-induced glass damage can be avoided by proper substrate selection and by ensuring that the filter is mounted in a heat conducting sink. Coating damage is more complicated and a coating's specific damage threshold is dependent on a number of factors including coating type, wavelength of the incident energy, angle of incidence and pulse length.

Due to the ability to dissipate heat, a surface oxide coating will be the most damage resistant. A protected dielectric coating will be the most susceptible to damage. Surface fluoride, surface metal, and protected metal coatings will fall between these two extremes. Extensive experience with laser applications guides the selection of substrate materials and coating design best suited to meet specific spectrophotometric and energy handling requirements.

Angle of Incidence and Polarization are important considerations when designing a filter. Most interference coatings are designed to filter collimated light at a normal angle of incidence where the coated surface is perpendicular to the light path. However, interference coatings have certain unique properties that can be used effectively at off-normal angles of incidence. Dichroic beamsplitters and tunable bandpass filters are two common products that take advantage of these properties.

The primary effect of an increase in the incident angle on an interference coating is a shift in spectral performance toward shorter wavelengths. In other words, the principal wavelength of all types of interference filters decreases as the angle of incidence increases. For example, in Figure 5 the 665LP longpass filter (50% T at 665nm) becomes a 605LP filter at a 45° angle of incidence.

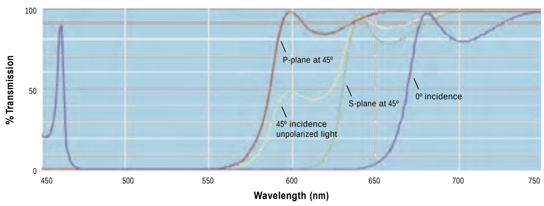

Figure 5 *Angle of Incidence Polarization Effects – Longpass Filter*

The relationship between this shift and angle of incidence is described approximately as:

$$\frac{\lambda_\phi}{\lambda_0} = \frac{\sqrt{N^2 - \sin^2 \phi}}{N}$$

Where:
ϕ = angle of incidence
λ_ϕ = principal wavelength at angle of incidence φ
λ_0 = principal wavelength at 0° angle of incidence
N = effective refractive index of the coating

The effective admittance of a coating is determined by the coating materials used and the sequence of thin-film layers in the coating, both of which are variables in the design process. For filters with common coating materials such as zinc sulfide and cryolite, effective refractive index values are typically 1.45 or 2.0, depending upon which material is used for the spacer layer. This relationship is plotted in Figure 6. The actual shifts will vary slightly from calculations based solely on the above equation (alternating SiO_2 and Nb_2O_5 have values of 1.52 and 2.35).

A secondary effect of angle of incidence is polarization. At angles greater than 0°, the component of lightwaves vibrating parallel to the plane of incidence (P-plane) will be filtered differently than the component vibrating perpendicular to the plane of incidence (S-plane). The plane of incidence is geometrically defined by a line along the direction of lightwave propagation and an intersecting line perpendicular to the coating surface. Polarization effects increase as the angle of incidence increases. Figures 5 and 7 illustrate the effects of polarization on a longpass and a bandpass filter. Coating designs can minimize polarization effects when necessary.

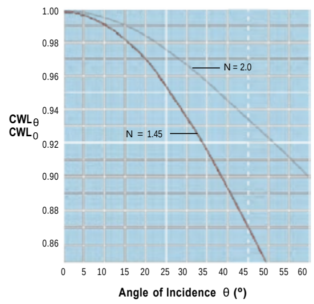

Figure 6
Angle of Incidence Effects

System Speed can have a significant effect on transmission and bandwidth as well as shifting peak wavelength. Faster system speeds result in a loss in peak transmission, an increase in bandwidth and a blue-shift in peak wavelength. These effects can be drastic when narrow-band filters are used in fast systems, and need to be taken into consideration during system design.

When filtering a converging rather than collimated beam of light, the spectrum results from the integration of the rays at all angles

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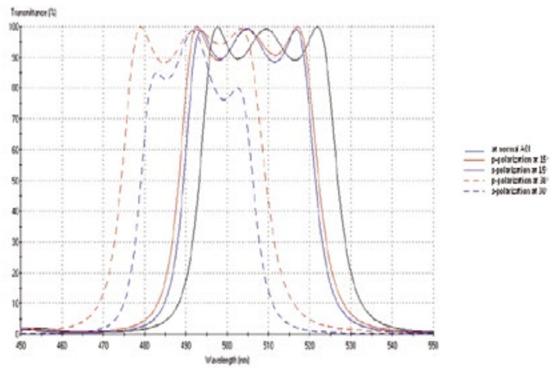

Figure 7 *Angle of Incidence Polarization Effects – Bandpass Filters*

within the cone. At system speeds of f/2.5 and slower (full cone angle of 23° or less), the shift in peak wavelength can be approximately predicted from the filter's performance in collimated light (i.e., the peak wavelength shifts about one-half the value that it would shift in collimated light at the cone's most off-axis angle).

◗ **Temperature Effects** the performance of an interference filter. Wavelength will shift with temperature changes due to the expansion and contraction of the coating materials. Unless otherwise specified, filters are designed for an operating temperature of 20°C. They will withstand repeated thermal cycling assuming temperature transitions are less than 5°C per minute. An operating temperature range between -60°C and +60°C is recommended. For the refractory oxides temperature ranges from -60°C to 120°C. Filters must be specifically designed for use at temperatures above 120°C or below -100°C. Although the shift is dependent upon the design of the coating, coefficients in Figure 8 provide a good approximation.

For applications where the change in performance divided by the change in temperature is to be minimized, the densified refractory oxide materials are preferred. Consideration must be given to maximize temperature as refractory oxides, even when densified through energetic process, will experience a one-time shift in optical thickness. The magnitude of this is <1% but can be of great importance for passband and edge filters.

Laminated interference filters, particularly those with ultra narrowbands, are subject to potential blue shift with age. This tendency is somewhat stabilized through a process of repeated heat cycling, or curing, at moderately high temperatures for short durations during the manufacturing process. For wavelength critical applications, heat cycling should be called out and ideally a temperature controlled oven implemented to maintain temperature. Prolonged exposure to light, particularly short UV wavelengths, results in solarization and reduced transmission.

◗ **Filter Throughput is commonly expressed as Transmission (T) and Optical Density (OD).** Transmission is the portion of the total energy at a given wavelength that passes through the filter. A transmittance value is always a portion of unity (between 0 and 1).

When describing the transmitting performance of a filter (usually when throughput is 1%–99%), the preferred expression is "transmittance" or "transmission".

When describing the attenuating performance of a filter (usually when throughput is less than 1%), the preferred expression is "optical density".

Transmission is most often expressed either as a percentage (90%) or as a decimal (90). Optical density is always expressed as the negative logarithm of transmission. Unit conversions are: OD = $-log^{10}T$ or T = 10^{-OD}

Wavelength Range	Thermal Coefficient
(nm)	(nm of shift per 1° C change)
300 - 400	0,016
400 - 500	0,017
500 - 600	0,018
600 - 700	0,019
700 - 800	0,020
800 - 900	0,023
900 - 1000	0,026

Figure 8 *Wavelength and Thermal Coefficients*

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FILTER DESIGN

Transmitted Wavefront Distortion is measured at the filter's principal wavelength on a Broadband Achromatic Twyman-Green Interferometer or a Shack-Hartmann interferometer. Although many interferometers can measure transmitted wavefront distortion, most are fixed at a single wavelength (often 633nm). For filters that don't transmit this wavelength, these instruments must produce reflected, rather than transmitted, interferograms.

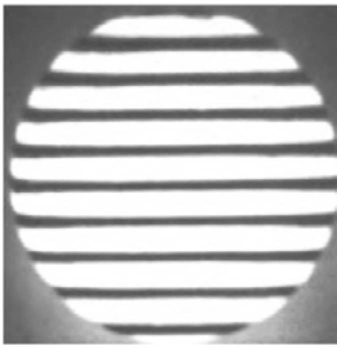

Figure 9

Transmitted wavefront interferogram of a narrow band filter used for telephotometry.

Although reflected interferograms are often used to represent the quality of a transmitted image, there are no reliable means for such interpretation.

▸ *See Application Note: Measuring Transmitted Wavefront Distortion on page 34*

Image Quality Filters: An optical filter's effect on the quality of an image results from the degree it distorts the transmitted wavefront.

In high-resolution imaging systems, filters require multiple layering of various materials (i.e., glasses, coating materials, optical cements, etc.) for high spectral performance. These materials, if used indiscriminately, can degrade a filter's optical performance. This effect can be significantly diminished through material selection, design, process, and testing.

To preserve image quality we select optical grade materials with the highest degree of homogeneity and the best match in refractive index at contacted boundaries. Special coating designs minimize the required number of contacted surfaces that cause internal reflection and fringe patterns. Before coating and assembly, all glasses are polished to requisite flatness and wedge specifications. Our coating and assembly techniques assure uniformity in material as well as spectral properties. With sputtering and other energetic process coatings, very high optical quality can be maintained on monolithic surfaces of fused silica. Multiple substrates of this type may also be assembled to produce a desired spectrum function.

After the filter is assembled, transmitted wavefront distortion can be improved further through a cycle of polishing, evaluating and re-polishing both outer surfaces. Durable anti-reflective coatings are then deposited onto the outer surfaces, reducing the intensity of ghost images while boosting transmission. See Figure 9. The resulting level of performance depends on size, thickness, spectral region and spectral demands of each filter. This approach has been used for filters of the highest standard such as the Space Telescope.

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Types of Anti-Reflective Treatments and When to Use Them

Application Note

While no single solution fits all needs, by appropriately selecting the right anti-reflective technique, nearly any optic can be anti-reflected to meet the needs of the user.

– by Dr. Michael Fink, Project Scientist, Omega Optical

From the benign annoyance of a reflection off your car's instrument panel window to the image-destroying reflections off of multiple optical components in a microscope, unwanted reflections plague our lives. Minimizing reflections has become a multimillion dollar industry. Scientific instruments with several optical components, such as modern confocal microscopes and, more commonly, television cameras, would be far less useful without the benefit of anti-reflective coatings.

Discovery

More than 70 years have passed since the first anti-reflective coating was discovered by a Ukrainian scientist working for Zeiss in Germany. While the anti-reflective coating was first implemented on binoculars in the German military, the new finding quickly expanded to a wide variety of optical elements in the research laboratory.

On Reflections

First, it is probably worthwhile to consider why reflections occur. Reflection of light occurs at any surface between two mediums with different indices of refraction. The closer the two indices of refraction, the less light will be reflected. If an optic could be made out of a material with the same index of refraction as air, then there would be no reflections at all. Of course, lenses would not focus light if they didn't have an index of refraction that differed from that of air (or whatever medium they're immersed in).

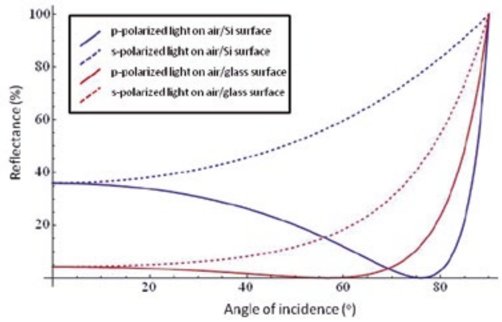

Figure 1 *Percent reflectance of s and p-polarized light off silicon and fused silica surfaces depending on angle of incidence. ($_n$Si = 4.01, $_n$fused silica = 1.46).*

In general, the reflection of light off of a surface will increase as the angle of incidence varies further from normal. However, this is not true for light that is p-polarized. Reflection of p-polarized light will decrease as the angle of incidence increases from normal (0°) to some angle at which there is no reflection. This angle at which there is no reflection of p-polarized light is called Brewster's angle and varies depending on the indices of refraction of the two media. For 1,064 nm light at an interface of air and fused silica, Brewster's angle is approximately 55.4°. Brewster's angle is different depending on the two media that comprise the interface. Figure 1 compares the reflection of s- and p-polarized light for air-fused silica and air-silicon surfaces. At angles of incidence greater than Brewster's angle, the reflection of both s- and p-polarized light increases dramatically as the angle of incidence increases.

Uses and Misuses of Anti-Reflective Treatments

Often, anti-reflective coatings are used to increase transmission of an optic. This is often a valid use of an anti-reflective coating, but it should be noted that this coating does not, by definition, increase transmission. Rather, it only reduces reflections off the incident side of the surface. In some cases, absorptive anti-reflective treatments can actually reduce transmission. In the case of interference filters, an anti-reflective treatment is often superfluous. An interference filter is intentionally reflective at wavelengths that are not being passed, so the total reflection off the optic will not be effectively reduced by an anti-reflective treatment. Furthermore, exposed interference filters are often already anti-reflected at the passed wavelengths, so an extra anti-reflective coating usually has little effect.

In many cases, the enhanced transmission of some anti-reflective coatings is very necessary. In fact, the advent of anti-reflective optics has made new optical instruments containing many-element apparatuses feasible. For example, a modern confocal microscope might have 15 or 20 optical elements in the light path. Borosilicate glass that has not been treated to eliminate reflections typically has a reflectance of about 4% in visible wavelengths per surface. A piece of borosilicate glass with a simple multilayer anti-reflective coating might average 0.7% reflectance per surface. When a single interface is concerned, the difference between 96% transmission and 99.3% transmission seems miniscule. However, in a multi element light path, this difference becomes very significant. If an incident light path crosses 30 air-glass surfaces, the final transmitted light at the end of the path would only be approximately 29% for non-anti-reflection treated optics. An identical path with anti-reflection treated parts would be 81%.

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APPLICATION NOTE Types of Anti-Reflective Treatments and When to Use Them

Anti-Reflective Coatings

The predominant method for causing anti-reflection of an optic is by depositing a layer or several layers of compounds onto the surface of the optic. Deposited anti-reflective coatings vary in complexity from single layer to 10 or more layers. Popular deposition methods of chemical anti-reflective coatings include sputtering, chemical vapor deposition, and spin-coating.

Single-Layer Anti-Reflection

Single-layer anti-reflective coatings are the simplest and often the most sensible solution. With just a single layer of a well-chosen compound, reflection at a specific wavelength can be reduced almost to zero. Additionally, unlike multilayer coatings, there is no wavelength or angle of incidence at which the reflection is greater than is reflected off an untreated substrate.[1]

While the "perfect" compound to make an anti-reflective coating for visible wavelengths does not yet exist, single layer anti-reflective coatings still are often implemented in this range.

To anti-reflect a specific wavelength with one layer of coating, ideally a compound would be used that has an index of refraction that is midway between the indices for air and the optical substrate. Additionally, the optical thickness of the anti-reflective layer is usually chosen to be one-quarter wave. If both of these criteria can be met, the theoretical reflection at that specific wavelength is zero. There are practical considerations that prohibit this in the visible wavelengths.

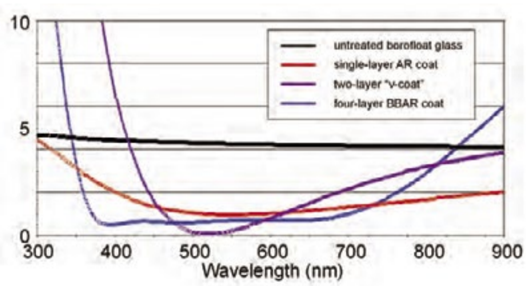

Figure 2 *Theoretical reflectance curves for untreated borosilicate float glass and borosilicate float glass with three different anti-reflective coatings.*

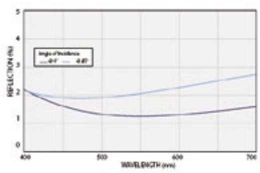

Figure 3 *Reflectance off borosilicate glass surface treated with a single layer of MgF2. The reflectance is not as low as a multi-layer BBAR coating, but it is lower than untreated glass at all wavelengths and incident angles.*

Most glasses used in the optical laboratory today have indices of refraction between 1.4 and 1.6. These values would suggest an optimal anti-reflective coating index of refraction between 1.20 and 1.30. Unfortunately, there are no known suitable compounds that have an appropriate index of refraction, are suitably durable, and can withstand the typical laboratory environment.

One compound that is commonly used for single layer anti-reflective coatings for visible spectrum elements is magnesium fluoride (MgF2). It has an index of refraction that is close to optimal (~1.38 at 500 nm) and is easily deposited onto glass. With carefully controlled process and substrate temperatures of 200° C to 250° C, a very robust coating can be applied, but otherwise care must be taken while cleaning magnesium fluoride-coated surfaces, as the coating can be rubbed off with vigorous cleaning. A theoretical reflectance curve for a single layer of MgF2 is shown in figure 2. The reflection gains at off-normal angles of incidence are relatively small for single-layer coatings, as shown in figure 3.

Single-layer anti-reflective coatings are especially popular when anti-reflection in the infrared is desired. Because many of the substrates used in infrared have higher indices of refraction (i.e., silicon, germanium, gallium arsenide, indium arsenide), there are many more choices for an optimal anti-reflective coating compound than for glasses. For example, the above-mentioned infrared substrates all have indices of refraction close to 4. A single layer of zinc sulfide can be used to anti-reflect all of these substrates quite effectively.[2]

V-Coating (Two-Layer Anti-Reflection)

If very low reflection is needed, but at only one specific wavelength, v-coating, a two-layer anti-reflective coating, is often the best solution. By using two layers with contrasting indices of refraction, it is possible to reduce the reflection at a specific wavelength to near zero. A drawback of this technique is that it actually increases reflection at wavelengths other than that for which the coating is optimized (evident on figure 2). If the actual goal is to minimize reflections at multiple wavelengths, v-coating will not produce the desired result.

Multilayer Coatings

For broadband anti-reflection of less than 1% in the visible wavelengths, multilayer coatings are required. Broadband anti-reflective (BBAR) coatings have an advantage of producing very low reflection over a controllable, broad range of wavelengths (figure 2). Beyond the region for which the coating is optimized, such as the v-coating, reflection off the optic is greater than reflection from untreated glass. BBAR coatings suffer slightly larger percentage reflection gains at off-normal angles of incidence when compared with single-layer anti-reflective coatings. Figure 4 illustrates these large reflectance gains at off-normal angles of incidence for multi-layer coatings.

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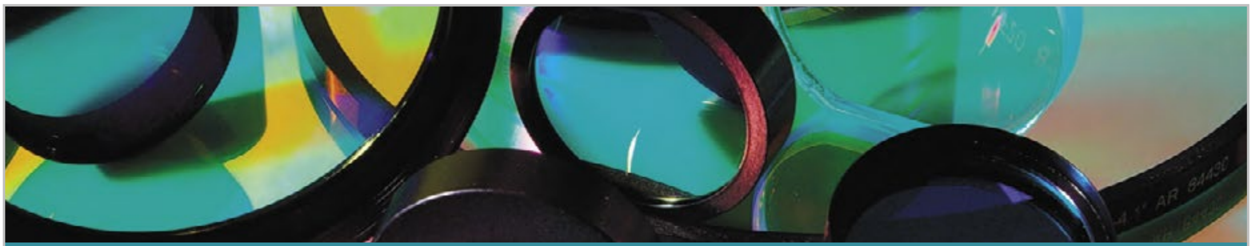

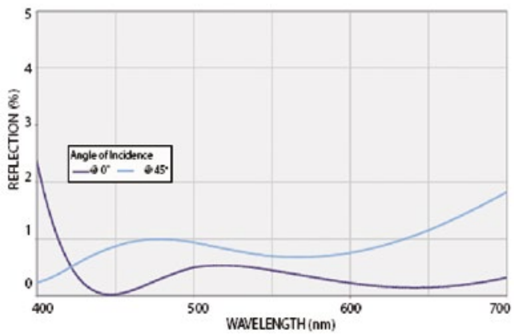

Figure 4 *Multi-layer broadband anti-reflective (BBAR) coatings can achieve reflections below 1% at a broad range of wavelengths, but at the expense of higher out-of-band reflectance and large percentage gains in reflectance at non-normal angles of incidence.*

Materials

Anti-reflection in the visible and near-IR wavelengths can be achieved with a variety of different deposited compounds. Silicon monoxide, yttrium fluoride, and magnesium fluoride are three popular low-index-of-refraction materials. Silicon monoxide is used primarily in the infrared wavelengths, while yttrium fluoride and magnesium fluoride are used most frequently in the visible region. The primary drawback of these compounds is their durability. While anti-reflective coatings utilizing either of these can be cleaned, care must be taken not to cause damage. Anti-reflective coatings also can be made using harder oxide compounds that are more durable, but they tend not to perform quite as well and require that the optic be subjected to high temperatures during deposition. In general, the more energetic (higher temperature) the process that is used to deposit the anti-reflective coating, the more durable the resultant coating is.

Moth-Eye and Random Microstructured Anti-Reflection

The physical structure of moths' eyes gives these insects a unique means of minimizing reflection. Reduced reflections off of moths' eyes can make the difference between their being eaten by a predator or remaining unseen. As a result of this environmental pressure, moths have evolved a regular repeating pattern of 3-D prominences on the surface of their eyes that effectively reduce reflection. With some effort, scientists have been able to duplicate the "moth-eye" pattern on glass to achieve a similar anti-reflection effect.

Initially, it seems non-intuitive that simply changing the surface structure of the glass should reduce reflections off that surface. By changing the initially smooth, flat surface of the glass to a surface that has a regular pattern of prominences that are hundreds of nanometers in size, the surface area has actually increased dramatically. Increased surface area would seem to suggest higher reflection rather than lower.

The reason for the reduced reflection off of a moth-eye surface is that the light no longer has a distinct boundary between the air and glass (or air and eye of the moth). Where there once was a very sharp boundary between air and glass, the transition now occurs over an appreciable fraction of a wavelength. Because reflections only can occur where there is a change in index of refraction and there is no longer a sharp boundary between materials, reflections are drastically reduced. In the visible range on fused silica, moth-eye anti-reflection treatment can achieve broadband reflection off each surface of 0.2% or better.

It is important to note that the size of the microstructures is very important. The structure on moths' eyes is a regular repeating pattern of hexagonal finger-like projections that are spaced roughly 300 nm from each other and rise about 200 nm from the eye's surface. This size of microstructure is optimized roughly for anti-reflection of the visible spectrum. If the structures are made slightly smaller or larger in size, the surface can be optimized to reflect shorter or longer wavelengths, respectively.

For example, arsenic triselenide is used in optics in the 5- to 15-micron range. A typical moth-eye structure for this window of wavelengths might have prominences that rise 3,500 nm from the substrate surface with an average spacing between prominences of about 2,400 nm.[3] Moth-eye structures of approximately this size can be seen in figure 5. Typical transmission improvement of the optic can be as much as 12% to 14% by treating just one side of the optic (figure 6).

One major advantage of microstructured antireflective glass is its ability to withstand high incident energies of nearly 60 J/cm.[4]

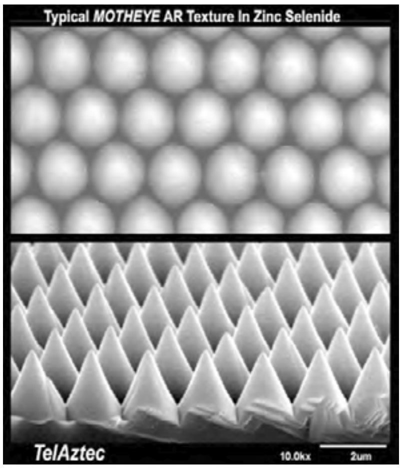

Figure 5 *SEM image of zinc selenide motheye microstructures. (Courtesy of TelAztec, Inc.)*

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APPLICATION NOTE Types of Anti-Reflective Treatments and When to Use Them

This is a sizeable improvement over the energy damage threshold of most thin-film anti-reflective coatings. Because the antireflective "coating" is made of the glass itself, it will have an energy damage threshold similar to that of the glass from which the optic is made.

To anti-reflect glass at visible wavelengths, an equally effective and more cost-effective anti-reflective coating can be created by etching the glass in a random pattern. An image of the resultant random spacing of the prominences is shown in figure 7. Treating a fused silica surface to create this random microstructure pattern can decrease broadband visible reflections by 80% to 90%.

Cleaning of microstructured anti-reflective surfaces poses a small problem. Physical cleaning of microstructured surfaces must be done carefully, if at all. The prominences that give the substrate its anti-reflective property can be easily broken off if the cleaning is too vigorous.

Absorptive Anti-Reflective Coatings

Another method for minimizing reflections off an optic is to make the substrate more absorptive. If the goal is to improve transmission through the optic, use of an absorptive optical coating generally will not help. However, absorptive coatings can very effectively absorb light that would otherwise be reflected.

Absorptive coatings are not usually the best solution for high-energy applications because, rather than transmitting the light that is being anti-reflected, that light now is being absorbed by molecules in the optical element, inevitably leading to heating and thermal damage.

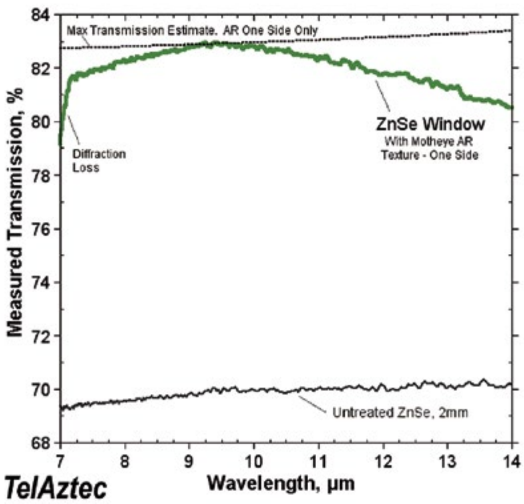

Figure 6 *Percent transmission for a ZnSe window untreated and treated with motheye AR texture on one side. (Courtesy of TelAztec, Inc.)*

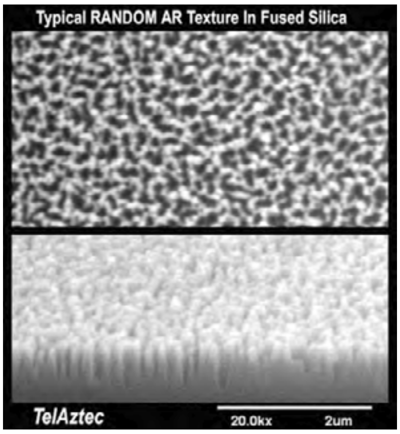

Figure 7 *SEM image of random AR microstructures in glass. (Courtesy of TelAztec, Inc.)*

Summary

There are a few different options available for building an anti-reflective optic. While no single solution fits all needs, by appropriately selecting the right anti-reflective technique, nearly any optic now can be anti-reflected to meet the needs of the user.

Dr. Michael Fink studied chemistry as an undergraduate at Bates College in Lewiston, ME, where he worked in the laboratory of Dr. Matthew Côté building a scanning tunneling microscope to determine the feasibility of using two color-distinguished oxidation states of tungsten oxide as a digital information storage medium. At the University of Oregon in Eugene, OR, Mike continued his studies, earning his doctorate in chemistry by improving the sensitivity of molecular Fourier imaging correlation spectroscopy in Dr. Andrew Marcus's lab at the Oregon Center for Optics.

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- 2. Hass G. 1955. Filmed surfaces for reflecting optics. J. Opt. Soc. Am. 45: 945-52.
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Filter Design Considerations and Your Light Source

Application Note

Overview

Available to system designers today are a wide array of excitation sources. Among the most frequently used are semiconductor lasers, LEDs (light emitting diodes), arc lamps, gas and solid state lasers, gas discharge lamps, and filament lamps. Each of these excitation sources have distinct physical and spectral characteristics which make it an optimum choice for a particular application. In practically all cases however, regardless of which excitation source is selected, the use of a properly designed excitation filter is required to enhance system performance and optimize signal-to-noise ratio.

While an excitation filters role is the same in every system, that is to deliver the desired excitation wavelengths while attenuating unwanted energy, the characteristics of the filter that achieve these goals are highly dependant on both the source characteristics and the overall system environment.

– by Mark Ziter, Senior Applications Engineer, Omega Optical

Filters for Gas and Solid State Lasers

Traditionally, gas lasers have been popular excitation sources. The most common, Argon ion and Krypton ion, provide lines at 488nm, 514nm, 568nm and 647nm. The laser emissions from these sources are precisely placed, exhibit narrow bandwidths, and are not subject to drift. While the output of such lasers are usually thought of as monochromatic, there are often lower energy transitions, spontaneous emissions, and plasma glow present in the output, all contributing to unwanted background. A filter to clean up the laser output and eliminate this noise will greatly enhance the system's signal to noise ratio.

Solid state lasers have properties similar to gas lasers. Along with the well behaved narrow primary laser emissions, these sources produce background noise from unwanted transitions and pump energy.

Excitation interference filters for both gas and solid state lasers share similar design considerations. The narrow bandwidth and wavelength predictability of these lasers means that filters designed for these sources can have very narrow passband widths. Deep out of band blocking to attenuate the background is required to ensure that no unwanted excitation source error energy reaches the detector and deteriorates the signal-to-noise figure

QuantaMAX™ Laser Line Filters (see page 57) are ideally suited to these applications. These filters, designated with an XLL prefix, have high transmission coupled with narrow pass bands, typically less than 0.4% of the laser wavelength. Manufactured with hard oxide surface coatings on monolithic high optical quality substrates, they exhibit exceptional thermal stability, shifting less than a few 1/100th of an Angstrom per deg C. The dense thin film coatings, deposited by energetic process, are unaffected by environmental humidity and their ability to withstand high power densities is unsurpassed in the marketplace.

Filters for Diode Lasers

The output of diode lasers is not as narrow or as precise as the output of gas and solid state lasers. These semiconductor devices have bandwidths in the 2nm to 5nm range. In addition, the actual output wavelength can vary a few nanometers from laser to laser. Compounding this lot to lot variation is the tendency these lasers have to drift with temperature and age. As a consequence, semiconductor lasers have an output wavelength uncertainty of up to +/- 5nm. Therefore, a diode laser designated as a 405nm device could have an output anywhere from 400nm to 410nm. Similarly, a 635nm diode laser may emit as blue as 630nm or as red as 640nm.

Optical interference filters designed for semiconductor lasers must be wide enough to accommodate this uncertainty in output wavelength. Additionally, since a given diode laser will drift with temperature, any ripple in the filter's spectral profile will result in an apparent variation in laser output intensity as the wavelength drifts across the filter passband.

Both of these considerations have been taken into account in the design of our XLD (Laser Diode Clean-Up) Filters. See page 54. Similar to all QuantaMAX™ filters, these are manufactured using ion beam sputtering to produce stable, dense surface coatings on high optical quality substrates. With wider passbands than our Laser Line Filters, the XLD filters will transmit a designated diode laser's output across its range of wavelength uncertainty. Their smooth transmission profiles, with less than +/- 1.5% transmission ripple across the passband, will not impart variation in laser intensity as the diode laser drifts with temperature. These filters' deep out of band blocking will eliminate the secondary emissions that are typical with semiconductor lasers.

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APPLICATION NOTE Filter Design Considerations and Your Light Source

Filters for LEDs

Light emitting diodes, or LEDs, are semiconductor devices that emit light as a result of electron-hole recombination across a p-n junction. Due to the absence of stimulated emission and laser oscillation, the spectral output of a LED is much broader than that of a diode laser, typically 30nm to 50nm at the half power points. In addition, the lot to lot wavelength variation of a given LED can be as large as 20nm. Spectral profiles of LEDs show long emission tails with substantial energy that usually extends well into the signal region. Often, the energy in these tails is the same order of magnitude as the signal to be detected.

Filters for LED excitation must attenuate the red tail. In order to allow signal collection as spectrally close as possible to the excitation, the filter needs a very steep blocking slope on its cut-off edge. Additionally, the filter needs to accommodate the wide LED bandwidth and output wavelength variability. Unless system requirements necessitate deep blocking at wavelengths blue of the LED output, there are few requirements on the blue cut-on edge. This edge can have a shallow blocking slope and does not need to be precisely placed. In fact, a short pass design is often the best choice to filter an LED excitation source. A steeply sloped short pass filter will eliminate the LED's red tail and the open ended transmission to the blue will pass the wide, variable LED output. The simplicity of design and high transmission offered by a short pass approach makes this an attractive alternative.

Filters for Hg Arc Lamps

Arc lamps produce light by passing an electric current through vaporized material within a fused quartz tube. The mercury arc lamp is a very popular excitation source for fluorescence microscopy because its spectral content has a number of very strong prominences at useful wavelengths throughout the UV and visible regions. The most commonly used are at 365nm, 405nm, 436nm, 546nm, and 579nm. Fluorescent dyes have been developed with absorption peaks that correspond with these emission lines. In order to take full advantage of these intense lines, we offer fluorescence microscopy sets with excitation filters designed specifically at these wavelengths. These include the XF408 (DAPI), the XF401 (CFP), and the XF406 (mCherry) sets.

Filters for Halogen Lamps

A halogen lamp is a tungsten filament incandescent lamp with the filament enclosed in an environment consisting of a mixture of inert gas and a halogen, such as iodine. The presence of the halogen causes evaporated tungsten to be redeposited back onto the filament, extending the life of the bulb and allowing it to be operated at a high temperature. The halogen lamp spectral output is continuous from the near UV out to the IR.

The continuous output spectrum of the halogen lamp removes all constraints on the wavelength placement and bandwidth of excitation filters designed to function with these sources. Where filters designed for all of the previously discussed sources need to be placed to take advantage of those sources spectral characteristics, no such considerations are required for filters designed to work with halogen lamps. The placement of cut-on and cut-off edges are determined solely by the absorption characteristics of the excited material and the spectral profile of the emission filter with which the excitation filter will function.

The characteristic of the halogen lamp which affords this excitation filter design latitude also increases the filter's blocking burden. The lack of prominences or bright lines means that the out of band energy levels to be blocked are of equal intensity to the desired wavelengths. Consequently, excitation filters for halogen lamps must block very deeply, especially red of the excitation band where the emission band is located. Also, since the Stokes shift of most fluorescence dyes dictates that the excitation and emission filter passbands be in close spectral proximity, a steep blocking slope on the red edge of the excitation pass band is required. A 5 decade slope of 1% or less is usually needed to prevent excitation energy from leaking into the emission range. For the same reason, the red edge spectral placement must be tightly toleranced.

Whatever your light source might be, we are always available to assist in the selection of the right interference filters for the best performance. Please contact us.

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Optical Interference Filters for Applications Using a LED Light Source

Application Note

Overview

Light Emitting Diodes, or LEDs, are high efficiency sources of electro-magnetic energy with a wide range of available wavelengths and very high brightness. These devices directly convert electrons to photons, rather than producing photons through blackbody radiation as a consequence of electron conversion to heat. As a result, there is little associated thermal pollution, or wasted energy.

LED Characteristics

although very effective at producing luminous power for scientific applications, LEDs have an assortment of limitations that must be considered. The primary limitation is that although they are very bright in lumens per unit area, they are quite limited in absolute power. A related limitation results from the fact that as current is increased across the light producing junction, the temperature also increases, causing a thermal shift of output wavelength. Whether caused by a change in the temperature of the environment, or by the residual heat of driving the junction to produce more photons, the consequence is that the output wavelength drifts.

Consistency limitations are exacerbated by the tendency of the output wavelength to vary from batch to batch. Minor variations in host impurities result in lot variations of Center Wavelength (CWL) of as much as 10nm, with occasional lots falling outside this range. Selection is a possible solution, but may result supply chain, inconsistencies.

At low levels of output, LEDs exhibit bandwidth (FWHM or HBW) which is typically 30 nm. At greater power outputs, they produce coherent emission which has a distinctive spectral power function. The characteristic of this emission is a region of intense spikes of energy superimposed on the continuum. These spikes have bandwidths which are typically 1 nm and can occur in groups of up to ten bands within a region of 5nm of a central peak.

Although much of the energy of LEDs is emitted in the specified region, there typically are secondary regions of light output. Usually these regions of secondary output are at significantly longer wavelengths, with infrared output at nominally twice the primary wavelength.

Without filtering, the secondary spectral output of LEDs can reduce their effectiveness in devices designed for low level photon conversion, such as fluorescence or Raman scattering. Even if the secondary output is six orders of magnitude less than the primary, it would contribute a critical error in these applications, made even more serious by the enhanced IR sensitivity of silicon based detectors.

Filter Recommendations

When considering filters or filter sets suitable for LED light source, it is important to verify that the LED peak band is transmitted by the excitation filters and reflected by the dichroic mirror. This can be accomplished by a quick check of the filter's spectral description to that of the LED's center wavelength.

For most commercial scientific grade LED sources it is probable that the standard filter sets used with a broad band lightsource, such as a Mercury burner, will suffice.

When using a custom LED, or LED array, a customized optical filter solution may be acquired.

Please contact us for assistance with filter selection.

▸ *See Light Source Reference Charts on page 109*

"CoolLED recommends that excitation filters are used with its LED excitation products. Although LEDs produce a narrowband of excitation, there can be a small "tail" of excitation to shorter and longer wavelengths which may be undesirable for some applications."

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Measuring Transmitted Wavefront Distortion

Application Note

Overview

What is Transmitted Wavefront Distortion? If you've ever looked through an old piece of window glass and noticed the image on the other side is distorted, then you are familiar with the effects of transmitted wavefront distortion (TWD) (Figure 1). Transmitted wavefront distortion refers to the deformation of a plane wave of light as it travels through an optical element (Figure 2).

Interference filters and dichroics for fluorescence and astronomy applications demand extraordinarily low levels of TWD. The acceptable TWD tolerance for these applications is often much tighter than can be perceived with the naked eye. When tight tolerances for TWD are required specialized instrument devices are necessary. This article focuses on one such device used by Omega Optical to measure TWD: the Shack-Hartmann wavefront sensor..

– Dr. Michael Fink, Project Scientist, Omega Optical

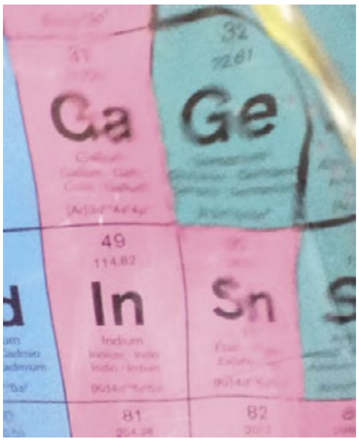

Figure 1

The effect of severe wavefront distortion is visible in this photo taken through a piece of cookware glass.

Methods for Quantifying Transmitted Wavefront Distortion

Interferometric Method

The primary alternative to the Shack-Hartmann detector is interferometry. An interferometric measurement of TWD works by interfering two plane waves. If the plane waves have traveled the same path length and are parallel, the resulting interferogram of the plane waves should be a field with uniform intensity. If we insert an imperfect optic into one of the two interferometer light paths, the optical path length is no longer constant for all parts of the wave. Some parts of the wave will be deflected or phase-shifted more than others due to imperfections of the optic. As a result, when light from the two light paths is recombined, the resulting pattern will no longer be uniform. Places where light destructively interferes will be dark and places where the light constructively interferes will appear bright. Some commonly resulting patterns can be seen below in figure 3.

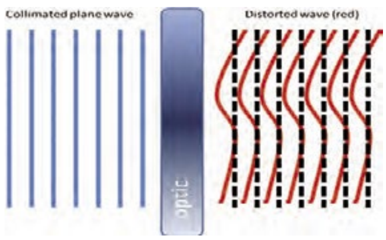

Figure 2

A plane wave travels through a slightly imperfect piece of glass. The resulting plane wave (red) deviates slightly from the original plane wave (black – shown as if it had not passed through any optic.)

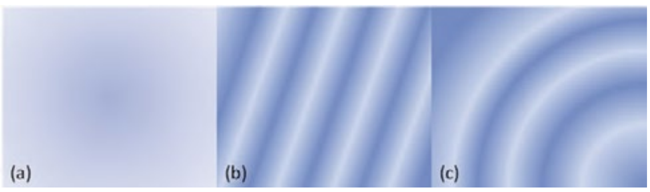

Figure 3

Depiction of interferograms a) Relatively uniformly intense field created by two parallel, plane waves, b) parallel fringes created by plane waves that are not parallel, c) curved fringes created by interfering a plane wave (reference leg of the interferometer) and a plane wave that has been distorted by an intervening optic. Specialized software is used to translate the fringe pattern into a quantitative value of TWD.

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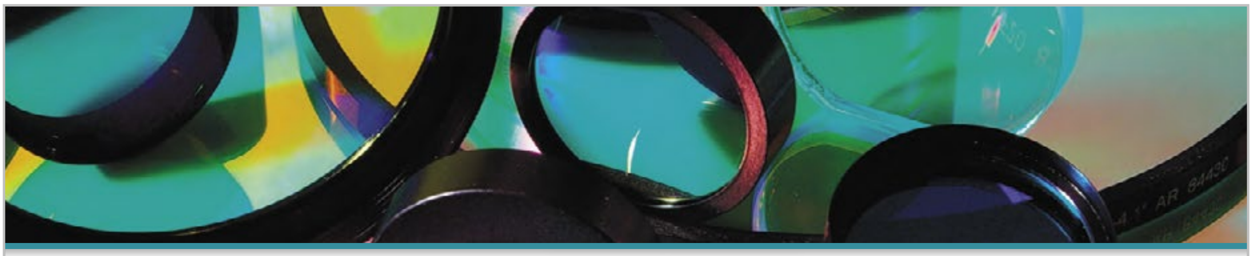

Shack-Hartmann Method

“Shack-Hartmann” derives from the names of two researchers who were responsible for advancing one of the primary components of the sensor, the lenslet array. The idea of creating an array of light points by spatial screening was first implemented by Johannes Hartmann in Germany in 1900 . Seventy-one years later, Roland Shack published a paper describing how the screen could be improved by replacing the apertures with tiny lenses . Shack’s lenslet array was implemented for the purpose of measuring TWD.

A Shack-Hartmann instrument employs a completely different method for measuring TWD. The following diagram displays a simple Shack-Hartmann setup.

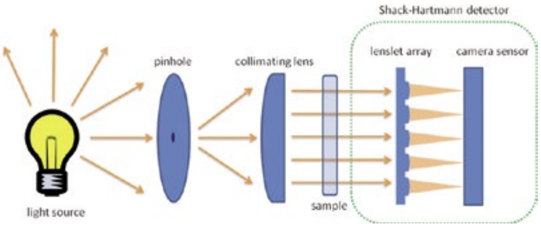

Figure 4 *Shack-Hartmann instrument*

To create a simple Shack-Hartmann based wavefront distortion detection instrument, only a few components are required. In Figure 4, a light source is passed through a pinhole to create a point source of light. That point source is collimated into a beam using a lens. It is in this collimated beam region that the sample will be placed. The light then passes into the Shack-Hartmann sensor.

There are two important components of the Shack-Hartmann sensor: a “lenslet” array (or a “microlens” array) and a camera sensor. The lenslet array is a regular, periodic distribution of tiny lenses. Usually, the lenslets are arranged into square or rectangular array. Behind this array sits the camera sensor. Often this sensor is a CCD array, but in principle, a Shack-Hartmann instrument could work with any camera – even a film camera.

Light focused on the camera sensor of a Shack-Hartmann detector will change position depending on the wavefront of the incoming light. In the top scenario, the light is a perfect plane wave and each microlens focuses the light to a point right in the center of its own region of the camera sensor. In the bottom scenario, the wavefront is distorted and the spots are no longer focused in the region directly behind the microlens. Instead, the spots have been displaced. By measuring the displacement of spots the wavefront distortion can be calculated. An actual spotfield from a Thor Labs Shack-Hartmann instrument is shown in Figure 6. A common useful visualization of the wavefront distortion is shown in Figure 7.

Figure 6

The actual “spotfield” from a Thor Labs Shack-Hartmann detector. Each spot is the light focused by an individual lenslet in a large array of lenslets.

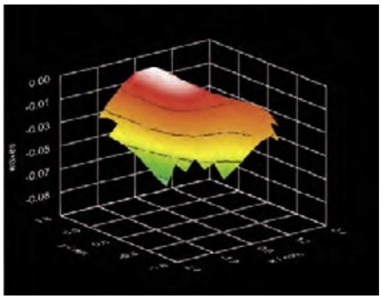

Figure 7

A depiction of TWD data taken from a Thor Labs Shack Hartmann sensor. The z-axis shows magnitude of TWD in waves at 633 nm. The axis of x and y demonstrates spatial position on the sensor.

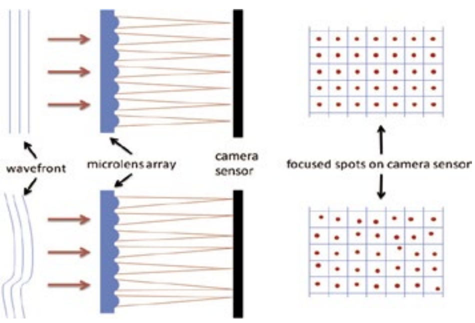

Figure 5

Light is focused onto a camera sensor inside the Shack-Hartmann detector. Each microlens focuses light to a point on the sensor, creating an array of points. In the top diagram, the incident light is a perfect plane wave. In the bottom diagram, the wavefront has been distorted.

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APPLICATION NOTE Measuring Transmitted Wavefront Distortion

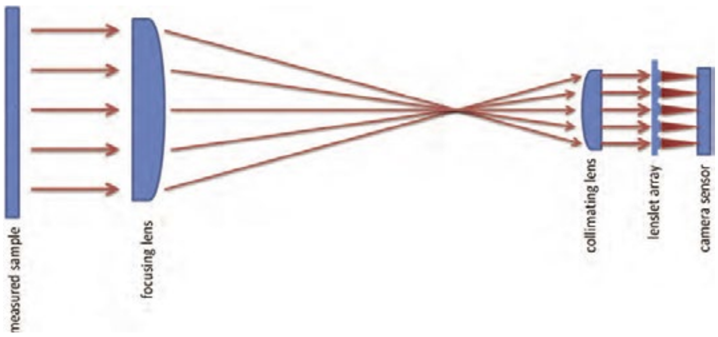

Figure 8

Adding a telescope allows the measured area to be much larger than the sensor.

In a commercial instrument, there are typically refinements made to a basic Shack-Hartmann design. One of the most common refinements is to add a telescope after the beam is collimated.

Adding a telescope (Figure 8) allows the measured area to be much larger than the size of the Shack-Hartmann sensor. Because the price of a sensor goes up very quickly with a larger size, it is much more economical to add a telescope than to buy a larger Shack-Hartmann sensor. Unfortunately, the addition of a telescope results in a loss in spatial resolution of data points. For example, if the collimated beam width at the measured sample is twice as large as the beam width at the sensor, then the data point density is only one-fourth its density without the larger collimated beam. However, with high quality optics even a moderate loss in data point density shouldn't result in severe data corruption problems such as aliasing.

Measuring TWD

The two most commonly recorded wavefront distortion statistics are peak-to-valley wavefront distortion and root-mean-square (RMS) wavefront distortion. Peak-to-valley distortion is the difference between the most positive and most negative values in the field of view. While peak-to-valley distortion only measures the difference between two data points, RMS distortion includes all data points in its calculation. If our data points are x1, x2, etc., this is computed as:

$$x_{rms} = \sqrt{\frac{1}{n} * (x_1^2 + x_2^2 + x_3^2 + \cdots + x_n^2)}$$

We currently employ two Shack Hartmann sensors with capability to measure peak-to-valley distortions as small as 1/15th of a 633 nm wave or RMS distortions as small as 1/50th of a 633 nm wave.

Another benefit of using a Shack-Hartmann sensor is its ability to separate distortion into unique "Zernike coefficients". Each Zernike coefficient corresponds with a specific type of aberration. For example, if the sample piece of glass is shaped slightly like a bi-concave lens it will exhibit a high value for the "defocus" coefficient ( ). The Shack-Hartmann software can distinguish aberration corresponding to different coefficients like astigmatism, coma, and tilt or spherical. Knowing the relative values of Zernike coefficients allows for specific correction of an optic by targeted polishing. For example, a common cause of "tilt" is glass that is wedge-shaped when viewed on edge. With additional polishing it is easy to remedy. Figure 9 shows a graphical depiction of the different Zernike coefficients.

Applications of the Shack-Hartmann Instrument

There two main applications of the Shack-Hartmann at Omega Optical; to validate finished product and provide verification that specifications have been met, and for performing in process manufacturing checks. A product can be measured at various points during production pinpointing steps that cause any additional wavefront distortion. Once these wavefront adding steps are discovered the material can be polished to correct for the introduced distortion.

TWD is one of the most critical interference filter specifications for anyone who is concerned with the integrity of the transmitted image. Biology and astronomy applications in particular are very concerned with image integrity. A TWD error that is imperceptible to the human eye in an interference filter could result in an inaccurate distance measurement between the moon and a planet or between organelles in a cell. With the help of a Shack-Hartmann we are certain of the quality of the images a filter will produce.

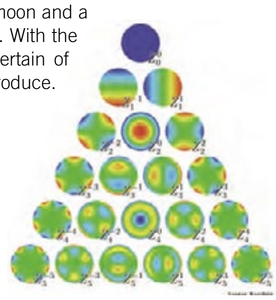

Figure 9

A graphical depiction of the Zernike coefficients. Applied to an optical piece; red indicates a region of positive wavefront distortion and blue indicates a region of negative wavefront distortion.

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GLOSSARY

A

- **Angle of Incidence (AOI):** The angle formed by an incident ray of light and an imaginary line perpendicular to the plane of the component's surface. When the ray is said to be "normal" to the surface, the angle is 0°.
- **Anti-Reflective Coating (AR):** An optical thin-film interference coating designed to minimize reflection that occurs when light travels from one medium into another, typically air and glass.

B

- **Bandpass:** The range (or band) of wavelengths passed by a wavelength-selective optic.
- **Bandpass Filter:** Transmits a band of color, the center of which is the center wavelength (CWL). The width of the band is indicated by the full width at half maximum transmission (FWHM), also known as the half band width (HBW). It attenuates the light of wavelengths both longer and shorter than the passband.
- **Bandwidth (HBW, FWHM):** Width of the passband: specifically, the difference between the two wavelengths at which the transmittance is half the peak value.
- **Blocking:** Attenuation of light, usually accomplished by reflection or absorption, outside the passband. Blocking requirements are specified by wavelength range and amount of attenuation.
- **Broadband AR Coating:** A coating designed to reduce reflectance over a very wide (broad) band of wavelengths.

C

- **Cavity:** Sometimes called "period". The basic component of a thin-film filter consists of two quarter-wave stack reflectors separated by a solid dielectric spacer. As the reflectivity of each of the quarter wave stack reflectors increases, the FWHM decreases; as the number of cavities increases, the depth of the blocking outside the passband increases and the shape of the passband becomes increasingly rectangular.
- **Center Wavelength (CWL):** The arithmetic center of the passband of a bandpass filter. It is not necessarily the same as the peak wavelength.
- **Clear Aperture (CA):** The central, useable area of a filter through which radiation can be transmitted.
- **Cut-on or Cut-off Slope:** A measure of the steepness of the transmittance curve x 100% where $\lambda_{80\%}$ and $\lambda_{5\%}$ correspond to 80% and 5% to absolute transmittance points.
- **Cut-on or Cut-off Wavelength (λ_c):** The cut-on is the wavelength of transition from attenuation to transmission, along a continuum of increasing wavelength. The cut-off is the wavelength of transition from transmission to reflection. The cut-on is the wavelength of transition from attenuation to transmission generally specified as the point at which the transition slope achieves 50% of peak transmission. The cut-off is the wavelength of transition from transmission to attenuation and again specified as the 50% point of peak transmission.

D

- **Dual Magnetron Reactive Sputtering:** A thin film coating method utilizing an energetic plasma in a controlled magnetic field and vacuum environment to precisely deposit alternating layers of high and low refractive index materials yielding a desired spectral response.

E

- **Evaporated Coating:** Precisely controlled thin layers of solid material(s) deposited on a substrate after vaporization under high-vacuum conditions.

F

- **Fabry-Perot Etalon:** A non-absorbing, multi reflecting device, similar in design to the Fabry-Perot interferometer, which serves as a multilayer, narrow bandpass filter.

H

- **Half Bandwidth (HBW):** The wavelength interval of the passband measured at the half power points (50% of peak transmittance). Expressed as half bandwidth (HBW), full width half maximum (FWHM) or half power bandwidth (HPBW).

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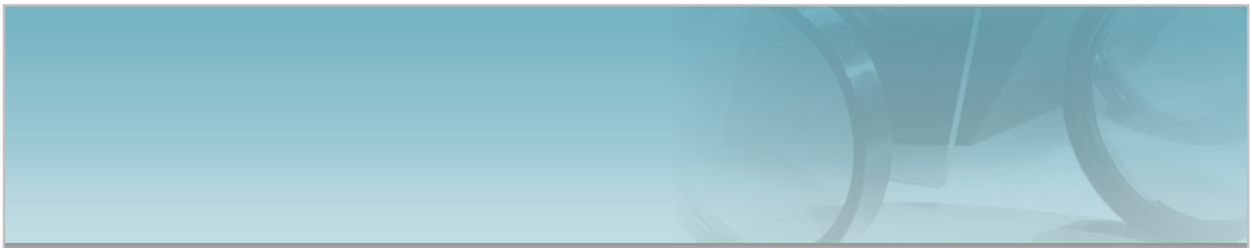

I

- **Intensity Crosstalk:** Intensity crosstalk occurs between channels and is a result of non-ideal optical filtering, where light from neighboring channels can leak through and be detected along with the filtered signal of interest. When the leakage level of a neighboring channel is higher than the noise floor that is associated with the channel of interest, it becomes the dominant noise factor in the SNR. As a rule of thumb, the intensity crosstalk of neighboring channels must be at least 20 dB below the target signal level. This type of crosstalk can be dealt with by using a high quality optical filter to eliminate all unwanted signals outside of the target channel bandwidth.
- **Interference Filter:** An optical filter consisting of multiple layers of evaporated coatings on a substrate, whose spectral properties are the result of wavelength interference rather than absorption.
- **Ion-assisted Deposition:** A technique for improving the structure density of thin-film coatings by bombarding the growing film with accelerated ions of oxygen and argon. The kinetic energy then dissipates in the film, causing the condensed molecules to rearrange at greater density.

O

- **Optical Density (OD):** Units measuring transmission usually in blocking regions. Conversion: $-\log^1 T = OD$. For example, 1% transmission is .01 absolute, so $-\log^1 (0.01) = OD\ 2.0$.
- **Optimized Blocking:** To conserve the most energy in the transmission band by controlling only the out-of-band region of detector sensitivity.

P

- **Peak Transmission (Tpk):** The maximum percentage transmission within the passband.
- **Polarization:** At non-normal AOI, an interference filter's spectral performance in p-polarized light will differ from its performance in s-polarized light.
- **Protected Coatings:** The process by which two or more substrates, coated with thin film depositions, are assembled together using an index-matching optical epoxy.

Q

- **QMAX or QuantaMAX™:** Surface coated single substrate designs with steep edges, very high transmission and no registration shift.

R

- **Reflection (R):** The return of light from a surface with no change in its wavelength(s).

S

- **Signal to Noise Ratio (S/N):** The system ratio of the integrated energy within the passband envelope to the energy outside this envelope and within the free spectral range.
- **Slope:** The rate of transition from attenuation (defined as 5% of peak transmission) to transmission (defined as 80% of peak transmission). Slope = (lambda 0.80 - lambda 0.05) divided by lambda 0.05.
- **SP:** Shortpass filters transmit wavelengths shorter than the cut-off and reflect a range of wavelengths longer the cut-off.
- **Surface Quality:** Allowable cosmetic flaws in an optical surface by comparison to reference standards of quality; usually made up of two types of standards defining long defects (such as scratches) and round defects (such as digs & pits).
- **System Speed:** When filtering a converging rather than collimated beam of light, the spectrum results from the integration of the rays at all of the angles within the cone. The peak wavelength shifts about one-half the value that it would shift in collimated light at the cone's most off angle.

T

- **Temperature Effects:** The performance of an interference filter shifts with temperature changes due to the expansion and contraction of the coating materials.
- **Thin Film:** A thick layer of a substance deposited on an insulating base in a vacuum by a microelectronic process. Thin films are most commonly used for antireflection, achromatic beamsplitters, color filters, narrow passband filters, semitransparent mirrors, heat control filters, high reflectivity mirrors, polarizer's and reflection filters.
- **Transmission:** The fraction of energy incident upon the filter at any particular wavelength that passes through the filter. Expressed as either percent (95%) or a fraction of 1 (0.85).
- **Transmittance (T):** The guaranteed minimum value of the peak transmittance of the filter (not necessarily occurring at the centre wavelength).

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FREQUENTLY ASKED QUESTIONS and ANSWERS

Q: What's a safe Angle of Incidence (AOI) range for an interference filter?

A: AOI is a critical parameter to consider when purchasing an interference filter. The primary effect of an increase in the AOI on an interference coating is a shift in spectral performance toward shorter wavelengths. That is, the principle wavelength of the filter decreases as the AOI increases. A typical interference filter will exhibit only minor changes in performance with a tilt of up to 10°. However, for certain narrowband filters and transition edges of dichroics, this slight shift may cause dramatic performance changes. For advice on how tilt affects performance please call one of our engineers.

Q: Would a dichroic have better reflection/transmission in S or P?

A: Simply put, reflection is better in S polarized light and transmission is better in P. This characteristic is most pronounced at the transition edge, where the dichroic is going from high reflection to high transmission.

Q: Why are blocking specs so critical?

A: Most people know where their signal of interest lies, but sometimes do not consider potential sources of "noise". This "noise" could be autofluorescence from the sample, or the signal from another fluorophore, or even energy from their light source. Blocking is the feature of a filter that attenuates this unwanted energy and permits the energy from the signal of interest to pass through. Using filters designed to block unwanted signals can improve signal-to-noise and robustness of the data.

Q: I want sharp edges, are the 3rd Millennium filters suitable?

A: 3RD Millenium filters are manufactured using Omega Optical's ALPHA technology , which produces very steep edges, capable of handling most application needs.

Standard 3RD Millenium filters utilize an ALPHA Gamma edge that has a 3% slope factor. This means that the filter's cut-on or cut-off edge will go from 50% peak height to OD 5 by the value: 50% peak height wavelength x (0.03).

3RD Millenium filters can also be manufactured with an ALPHA Epsilon edge. This filter has a 1% edge factor and thus will go from 50% peak height to OD 5 by the value: 50% peak height wavelength x (0.01).

Q: Do my excitation and emission filters need to transmit at the peaks of a fluorophore's absorption/emission probability curve?

A: Not necessarily. Although it is usually best to encompass as much of the probability peaks of a fluorophore as possible, sometimes other limiting factors preclude this solution. One example is a sample with multiple labels that have significant overlap of their emission peaks. In this case, moving the emission filter off the longer wavelength fluorophore's emission peak can improve signal discrimination.

Q: How do I clean my filters?

A: If dust and debris are the primary contaminants, filters can usually be sufficiently cleaned by using dry air (such as a puff from a pipet bulb) or compressed air (not canned air). If the filters have oily substances that cannot be easily removed, either acetone or isopropanol can be used with a soft, lint free applicator, such as a Q-Tip or soft lens paper.

Q: What does the arrow on the side of a filter indicate?

A: Omega Optical filters should be oriented with the arrow pointing in the direction of the light path. In other words, the arrow points away from the light source and towards the detector.

Q: Can I use an excitation filter as an emission filter and vice versa?

A: Though generally not recommended, Omega's QuantaMAX™ product line is manufactured on single glass substrates with extended blocking on both excitation and emission filters, thus allowing for an excitation filter to be used as an emission filter, and vice versa.

Note: QuantaMAX™ fluorescence filters are designed to function optimally as part of a filter set. Using a specific filter outside of the intended set may provide acceptable, though not optimal, performance.

Q: Can I use a dichroic from my microscope in a flow cytometer for the same dye?

A: Generally, no. Flow cytometers are designed to use dichroic beamsplitters which have different specifications than a fluorescence microscopy dichroic beamsplitter. When inquiring about a particular dichroic not sold as part of a filter set, you should always specify its desired application.

Q: I'm using a filter set to image Cy5®, but I don't see any image on the screen and I know I have enough dye loaded. Is the filter working properly?

A: Probably, yes. Cy5® is a fluorophore which emits at the far end of the visible spectrum (peak at 670nm), this can make viewing it through the eyepiece of the microscope very difficult and typically a B/W CCD camera or PMT is needed to detect it. Many CCD cameras come with IR blocking filters housed in front of the chip and attenuate light from 650 nm upwards. This effectively blocks signal from Cy5® and similar dyes from reaching the detector. Consult your camera's manual to see if the filter can be switched off line or removed.

Q: How thin can my filter be?

A: 1 mm (in limited cases 0.5 mm), and when reflection is not a requirement. Filter coatings can "bend" substrate materials, so the thinner the substrate, the greater the chance for bending, which will distort images.

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CLEANING OPTICAL INTERFERENCE FILTERS

Omega Optical interference filters are manufactured using state of the art technology for robustness and durability. As with all optical filters, care should be given to proper handling and cleaning.

Directions:

1. Avoid depositing oil from your hands onto filters by using finger cots. Hold filters from the edges only. For smaller filters use tweezers to help with handling.
2. Blow loose dirt and particles from the surface of the filter using a puffer. Do not blow air from your mouth. Food and drink particles can be deposited.
3. Apply isopropyl alcohol to a lint-free cotton swab and rub the filters surface in a circular motion, working from the center to edge. Gently apply pressure. Avoid rapid side-to-side motions.
4. Use a puffer to evaporate excess alcohol from filter surfaces.
5. Repeat steps 3 & 4 above using a clean, lint-free cotton swab with each cleaning until all surface contamination is removed.
6. To complete the cleaning process wipe filter surfaces using lens paper gently applying pressure.
7. Return your filter to the original plastic case or envelope provided.

Note: We do not recommend the use of water, detergents or any other non-optical cleaning materials for this process.

For an Omega Optical cleaning kit that includes the materials necessary to properly clean interference filters, please purchase from our website.

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INTRODUCTION

Founded in 1969 by Robert Johnson D. Sc., President and Technical Director, Omega Optical is a leader in photonics, exploring new areas with fresh ideas, an eager team, and the latest technology to produce the best in optical interference filters.

Our products encompass many markets including; Industrial, Commercial, Life Science, Clinical, Astronomy (amateur and professional), as well as Defense and Aerospace. We design and produce the most diverse offering of interference filters in the industry. With over 40 years of experience partnering with researchers and instrument designers to meet their requirements, we have the experience you need. Along with our experience, we bring a corporate commitment to cooperatively explore, understand and ultimately refine solutions. This support originates with our team of Scientists, Engineers, and Industry experts from various scientific fields. We want to be your partner on every project... challenging or simple. Our guiding philosophy has always been to find solutions. If you need us, call. We will be happy to assist. Toll free within the U.S. 866-488-1064 or +1-802-254-2690, sales@omegafilters.com

Our headquarters resides on the Delta Campus in Brattleboro Vermont USA. We encourage you to visit! Our location is in the heart of the New England business community, conveniently located off Interstate 91; a two-hour drive from Albany New York, Boston Massachusetts and Hartford Connecticut.

If you are currently a customer of Omega Optical, thank you!

If you are new to Omega Optical, we look forward to working with you.

This catalog is representative of only a small portion of products we have to offer. The filters within are **stock** (off-the-shelf) or **standard** (common specifications that are typical of industry standards). What's unique, and not represented in this catalog, is our ability to provide custom solutions in a reasonable time frame at typical catalog prices from our component inventory. Contact your sales representative, or use our online tool, buildafilter for your filter solution.

Original Equipment Developers and Manufacturers

Our expertise not only lies in the design and manufacturing of optical coatings, but in the support we can offer you in the development phase of your project. Based on your input, our engineering team will design a cost effective solution for the life cycle of your instrument. We urge you to contact us in the early development stage of your project. Our goal is to assist you in finding a solution that will achieve maximum system efficiency at the lowest cost. We will work closely with you through all steps, proof-of-concept, bread-boarding and prototyping to ensure the development of an optical solution that is consistent with your expectations.

We regard our relationship with you as a long-term partnership. Our support will continue into the production phase of your project.

Research Scientists and Engineers

Whether your lab or research project requires one or several interference filters we invite you to contact our technical sales team. We will assist in finding the right solution whether it is an off-the-shelf product, a semi-custom solution, or a filter custom manufactured to your requirements.

Stock interference filters are available off the shelf at competitive prices.

Semi-custom solutions from our extensive inventory of overstock filters or plate stock configured to your requirements can be processed and shipped to you in 5 business days.

Custom solutions are specifically produced to your requirements. Our sales team will work with you to develop the most cost effective solution for your application.

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ABOUT US

Collaboration

In any instrument development project, collaboration is key. Involving Omega early in the system design process results in optimized filter design before the system specifications become fixed. The result is reduced costs and improved performance. For these reasons, free flow of information is critical. To protect trade secrets, we ensure confidentiality throughout the life of the project. As the process unfolds, crucial performance features are identified, proof-of-concept filters are supplied for breadboarding needs, and beta parts are produced meeting the established requirements. With the completion of the development phase, we have demonstrated and provided a manufacturing plan that can be repeatedly executed for your specified production requirements.

System/Instrument Development

From many years of partnership experience with the world's leading OEMs, we have developed a comprehensive understanding of the needs of instrument developers and one of the largest ranges of capabilities and product lines in the thin-film industry. A collaborative engineering approach results in high signal-to-noise, application optimization, responsive prototyping, and rapid time-to-market cycles.

Throughout the design process our engineering and sales staff works with your development team to optimize total system performance within time and budgetary guidelines.

Following "proof-of-concept," breadboarding, and prototyping, a developed design is translated into an optimized manufacturing plan for production. An effective plan takes into account performance specifications, as well as yield maximization, product uniformity, and cost targets. Projections are then used to create delivery schedules to address critical inventory requirements. Review of manufacturing plans on a regular basis results in the integration of continuous improvements for your project.

Partnership

For more than 40 years we have been the filter supplier of choice to hundreds of system manufacturers. This stands as testament to our high technical standards, the ability to produce thousands of parts to identical specifications, and timely delivery. Throughout these long-term partnerships we build your confidence to become your sole supplier. A relationship is based on intimate knowledge of your instrument, and team that leads to increased efficiencies and instrument performance over time.

Custom Solutions

Standard catalog products can provide a high velocity filter solution with reasonable performance and, as a result, can be used for R&D, proof-of-concept, and breadboarding. For optimum system performance and significantly reduced cost we strongly recommend collaborative engineering and customized filter solutions for your specific instrument and application.

Custom Filters Overview

Custom filters are available in wavelengths from 185nm in the UV to 2500nm in the IR. There are a variety of filter types including bandpass, narrowband, wideband, longpass, shortpass, edge, rejection band, beamsplitters, mirrors, and absorption glass. Filters can be manufactured to almost any physical configuration up to 200mm round.

Omega has developed a number of programs to service the custom filter needs and requirements of OEM instrumentation customers and researchers.

Engineering Services Overview

Omega Optical's engineering services are founded on years of technical experience, proprietary software, and custom modified optical measurement instruments. Our engineers play a collaborative role in design teams, assembled to develop prototype instruments, and are experienced at optimizing system performance. For sub-assembly engineering and manufacturing, our design and manufacturing services include interference filters; optical components; and customized rings, holders, and mounting hardware. Further, the R&D group develops both new coatings, and novel applications of optical filters. These applications include biomedical scanning, pathogen detection, and photovoltaic stacks.

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ABOUT US

MARKETS & APPLICATIONS

Life Science

Omega Optical is a leading supplier worldwide of custom filters for research, clinical, and point-of-care fluorescence based instruments and applications. We service the world's leading system manufacturers and have developed one of the largest ranges of capabilities and product lines in the industry. Our filters are used extensively in research and clinical applications in the biomedical, biotech, and drug discovery markets, with filters being engineered into the next generation of life science instruments.

Representative Markets include:
- Microplate and MicroArray Readers and Scanners
- DNA Sequencers and Analyzers
- Lab-on-a-Chip and Gene Chip Readers
- Flow Cytometers and Cell Sorters
- Real-time PCR Analyzers
- Gel Documentation Readers
- Scanners and Imaging Systems
- High-Throughput and High-Content Systems
- Genomics and Proteomics Systems
- Fluorescence and Raman Spectroscopes
- Confocal and Multiphoton Microscopes

Fluorescence Microscopy

We have played a pioneering role in the developments of filter technology for fluorescence microscopy and are one of the world's leading suppliers in this market. We offer an extensive product line of dye-specific filter sets for single and multi-label fluorescence microscopy applications and work collaboratively with researchers, labs, and microscope manufacturers on the development of sets for new cutting-edge applications. Filter sets, individual filters, and holders are available for all major microscope manufacturers and models, including Leica, Nikon, Olympus, and Zeiss.

Representative Applications:
- Confocal
- Multiphoton
- Fluorescent Proteins
- Quantum Dots
- M-FISH
- FRET
- Ratio Imaging
- Caged Compounds

Astronomy/Aerospace

We are one of the most respected suppliers of optical filters in the world for space-based and observational astronomy and aerospace projects. We work in collaboration with NASA, JPL, AURA, ESO as well as a variety of international consortia, government agencies, and researchers. We have years of experience designing and manufacturing custom and standard prescription filters to the highest imaging quality standards. Our capabilities include solar observation, photometric sets encompassing Bessel, SDSS, Stromgren, and other filters.

Our filters have helped probe deep space as part of the Hubble Space Telescope's Widefield Planetary Camera and served as the eyes of the Mars Exploration Rovers. See pages 45-47.

Photolithography

Our i-line filters for semiconductor lithographic tools, such as LSI and LCD Steppers, surpass the performance of standard OEM filters. These high performance and environmentally stable bandpass filters resolve monochromatic wavelengths from the high power Metal Halide/Mercury lamps reaching the photomask substrate, so that optimum resolution is achievable. We also supply superior mask-aligner filters for the lithographic process. See page 64.

Color Imaging

Color imaging systems benefit from the use of precision optical filters which control the spectral properties of light and color separation to exacting tolerances. Image capture and reproduction are enhanced when the prime colors of light are precisely separated or trimmed on capture and then recombined before reaching the detector. Image quality and performance improves when system optics deliver precise color separation, high color signal-to-noise, and a wide dynamic range. Omega offers a variety of products to this market, including a patented color enhancement filter, as well as color separation, color correction, and color temperature filters. See pages 16-18. For detailed product specifications, please visit our website.

Raman Spectroscopy

Raman spectroscopy is employed in many applications, including mineralogy, pharmacology, corrosion studies, analysis of semiconductors and catalysts, in situ measurements on biological systems, and single molecule detection. While this technique provides positive material identification of unknown specimens to a degree that is unmatched by other spectroscopies, it also requires rigorous filter specifications for the detection and resolution of narrow bands of light with very low intensity and minimal frequency shift relative to the source. To meet these requirements Omega supplies a variety of products, including laser line filters for "cleaning up" laser signals and high performance edge filters that out-perform holographic notch filters.

Industrial Instrumentation

Industrial instrumentation requires precision filters for control, analysis, and detection. We provide a wide variety of filter solutions for various industrial applications that includes some of the following: Process Control and Monitoring; End Point Determination; Closed Loop and Real-time Instruments; Materials Analysis; and others.

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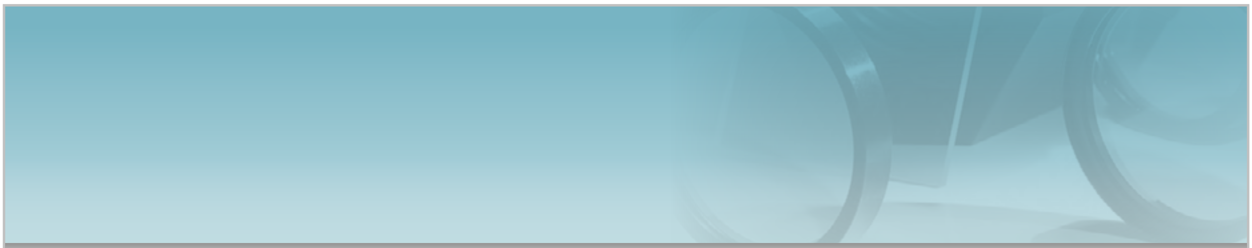

Capabilities

Design

- Thin Film DesignSoftware
- TF CALC
- Optilayer (Leybold)
- FilmStar
- The Essential Macleod
- Optical Raytrace Software
- Mechanical CAD Packages
- Instrumentation Interface Tools such as LabView and Python
- Chemical modeling with Hyperchem

Optical Testing

- Spectrally Resolved Measurements of Transmission, Reflectance, and Absorption:

- Multiple Spectrophotometers
- A Spectrophotometric Mapping System for large substrates
- Attachments for off-axis R&T Measurements including Polarization Effects

- Optical Density Measurements:

- Visible Laser Radiometers
- NIR Laser Radiometers

- Surface Quality (total wavelength distortion, flatness, wedge, roughness, and pinhole density):

- Broadband Achromatic Twyman-Green Interferometer
- Shack-Hartmann Wavefront Tester
- Autocollimator
- Integrating Sphere
- Angle Resolved Scatter Test Set
- Differential Interference Contrast (DIC) Microscopy

- Fiber Optic Testing at Visible and Near Infrared Wavelengths

- Fluorescence and Autofluorescence:

- Spectrofluorimeters
- Multispectral Fluorescence Imaging

- Environmental Testing:

- Low and High Temperature Testing
- Humidity Testing

- Photovoltaic Testing:

- IV/CV Profiles
- Kelvin Probe

Coating Systems

Of our numerous vacuum coating systems, we have the capability for coating a full range of dielectric metal and insulation materials. We achieve physical vapor deposition (PVD) (evaporated coatings) with or without ion assist (IAD) of refractory oxides, as well as thermal evaporation of metal salts and metal alloys. All of our coating systems have been designed to enhance our proprietary coating processes.

Optical Fabrication

- CNC Metal Machining
- Scribe & Break
- Laser Scribing, Welding, and Ablation

Our glass fabrication shop is equipped with a Speedfam grind and polish machine, along with diamond-tooled machines, including CNC drills, shapers, and saws.

Scribe and break

For the best competitive price and reduced lead times, our scribe and break capabilities make use of a unique diamond wheel cutting technology. Scribe and break is a clean process that does not require oils, blocking waxes, or exposure to heat. Additionally there is significantly less handling of the optical coated plate. Fundamentally, we scribe the exact shape of the finished product penetrating through the optical coating on the substrate material. Scribes may be generated with a depth up to 90% of the material thickness greatly reducing a required breaking force. This technology is useful over a wide range of substrate material thicknesses from .05 mm to upwards of 3 mm.

The end results of this capability include consistent outcome, higher yield, increased edge strength, rapid dicing, and a reduction of potential edge chipping and cracks. Cutting accuracy is very high enabling the production of very small finished product. Additionally, the ability to hold very tight tolerances as well as produce more unusual, irregular, or non-standard shapes becomes available.

Optical Assembly

Our fully equipped machine shop has the capability of producing jigs and fixtures along with a variety of custom filter rings, wheels, and holders.

Filter components are cleaned ultrasonically and assembled under laminar flow hoods.

Glass Substrates

We stock nearly all scientific glasses, fused silica, and specialty glass substrates.

04/22 / V01 / BG-IF / omega/application-notes-filters

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ABOUT US

Quality Assurance, Testing, and Certification

The Quality Management System of Omega Optical is modeled on the foundations of the ISO 9001:2000 quality management standards.

The overall company goal is to enhance product quality with standardized and systematic methods.

Filters are tested and evaluated at every stage of production. Spectrometers and optical measuring instruments are tested, controlled, calibrated, and maintained to meet the requirements of our quality system.

- Filter surface durability and quality is in accordance with MIL-C-48497A.
- Environmental durability, testing documentation and certification can be provided at the customer's request.
- When appropriate, we follow sampling procedures defined by MIL-STD-105E.
- REACH, PFOS and RoHS statements can be found on our website.

We have an in-house capability for making automated spatially-resolved spectral measurements of coated plates up to 200 mm in diameter. These high-resolution spatial-spectral measurements quantify in-spec regions of each plate; the result is fed directly to downstream part configuring operations. Plate regions that do not meet spec are inventoried for future sale requiring no additional spectral measurements. This one-stop measurement of the entire plate eliminates redundant measurement and drastically increases efficiency both in plate utilization to meet immediate orders and future data mining operations to locate surplus stock.

"Omega Optical will deliver quality product on time, which meets or exceeds customer expectations, through continual improvement and effective partnerships with suppliers and customers."

Personnel

A technical staff of engineers, industry specialists, scientists, PhDs, and technicians combine years of experience, a broad knowledge base, and a command of the craft involved in producing precision interference filters.

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INTELLECTUAL PROPERTY

3RD Millennium filters are available as high-performance commodity filters for OEM instrumentation or for research and lab applications. ▶ **Patent #6,918,673**

SpectraPlus™ for accurate hue, enhanced saturation, increased color signal-to-noise, and a resulting improved Modulation Transfer Function (MTF). SpectraPLUS coating technology is the deposition of multiple layers of thin film coatings on glass and acrylic lenses for the enhancement of viewing color images to address two primary areas. This technology benefits color imaging systems as well as applications where the eye is the detector. The coating allows transmission of the three bands of pure color—red, green, and blue—while blocking those intermediate wavelengths that distort the perception or recording of color. It also eliminates wavelengths in the ultraviolet and near infrared which are detrimental to an accurate color rendering and visual record. ▶ **Patent #5,646,781**

Multispectral stereographic display system ▶ Patent pending

Multispectral stereographic display system with additive and subtractive techniques ▶ Patent pending

ALPHA™ coating technology

Omega Optical's proprietary **ALPHA™ coating technology** for extremely steep slopes resulting in precise edge location, the ability to place transmission and rejection regions exceptionally close together, and high attenuation between the passband and the rejection band. ALPHA coating technology pushes the limits of fluorescence and Raman signal detection, producing extremely high signal-to-noise and brighter images for demanding imaging applications.

Multi-band Technology

Omega Optical holds the 1992 patent on all filters with multiple passband and rejection bands, including dual-band, triple-band, and quad-band filters. These filter types have usefulness in a variety of life science applications for visualizing multiple fluorophores simultaneously, as well as in a range of other applications. ▶ **Patent #5,173,808**

Multispectral Imaging

Omega Optical licenses and owns IP related to high speed systems for multispectral imaging of tissue. Our filters are used within a device, which has many applications in the biomedical optics field.

Organic Photovoltaics

Omega Optical owns IP related to organic photovoltaic devices. Our thin film expertise is leveraged to fabricate these devices, which have significant potential in the alternative energy field.

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