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Functional Aspects of Coatings in Optical Systems

Changing pace for this issue, we discuss coatings from the user's point of view. It is important for the most efficient engineering of an optical system that all parties – designer to coater to end user – be knowledgeable in the functions and limitations of optical coatings. We shall cover the bases for the appropriate application and limitations of typical coatings.

The most common optical coatings are anti-reflection (AR), thermal control windows, spectral and path separation, and reflectors. Coatings are also critical in the harsh environments of marine, battlefield, aircraft, and medical applications, and therefore deserve special considerations for the extraordinary durability that they must provide. The following is a set of guidelines ("old rules") useful to the designer of optical systems of which coated surfaces are an integral part.

AR Coatings

A. As incidence angle increases, all thin-film coatings become effectively thinner optically, and shift to shorter wavelengths. (see Figures 1 & 4).

B. Single-layer antireflection coatings are more effective on steeply curved surfaces (small radii of curvature) than multi-layer AR designs. The latter might produce reflection higher than the reflection of the uncoated substrate because of the wavelength shift. (see figure 2).

C. It is easier to achieve efficient AR on a high-n substrate than on low index because more index-value steps are available to smooth transition in impedance between the substrate and air. These steps can be provided by material changes, or more effectively in terms of process ease, by generating equivalent indices from a High- / Low-index pair.

D. Highly efficient AR on substrates with low index as fused silica and MgF_2 cannot be achieved over a large wavelength range. Single-surface reflectance can be reduced from 3.5% to <0.5% over ~70 nm bandwidth.

E. The bandwidth for an AR coating is typically from λ_2 to ½ $\lambda 2$, where $\lambda 2$ is the longest wavelength. To provide efficient AR from 900 nm to 400 nm requires many layers in a complex design in which layers are very thin, and the appearance of "humps" of higher reflection within that range.

F. AR on polymer surfaces requires special surface conditioning treatments, generally involving a reactive plasma. A chemical hardcoat is often applied that improves durability and smoothes the surface.

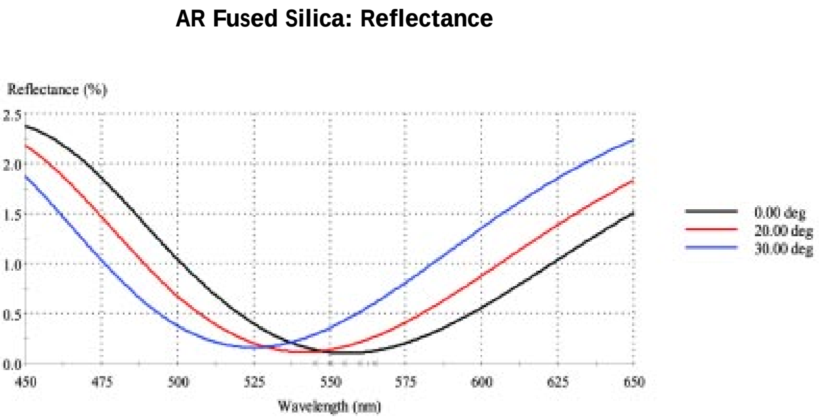

Figure 1. AR for fused silica showing shortward shift with incidence angles. The means of the polarizances created by non-perpendicular incidence are shown.

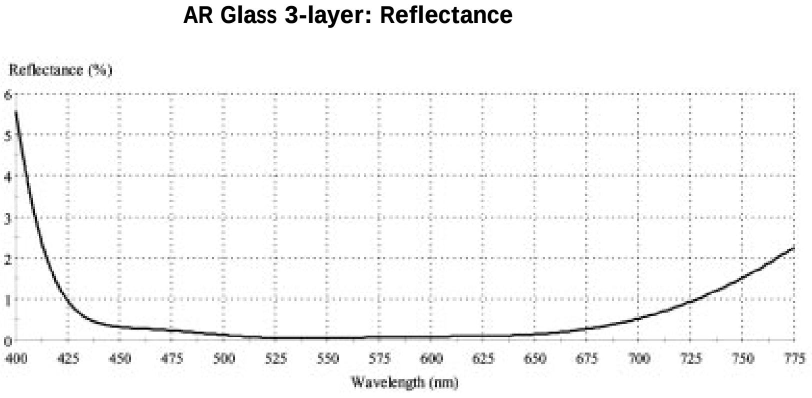

Figure 2. Three-layer AR on glass showing the fast increase in R exceeding the 4% value for a reflection from a uncoated glass surface.

High Reflectors

A. Reflection from dielectric surfaces an incidence angle >0° cause polarization of the Transmitted and Reflected beams. Polarization separation increases as incidence angle increases. The polarization created might interact with other polarization-sensitive surfaces in the optical system. Anti-reflection might reduce the effect.

B. Reflecting metals are deposited on cold substrates to minimize scatter. IAD can be used to compact and harden the metal layer. The highly reflecting (R~90%) metals, Aluminum, Gold, and Silver, require abrasion and chemical protective over coating with dielectrics because of their softness and vulnerability to scratching. Hard metals like Rhodium, Nickel, and Chromium do not require protection, but reflect <70%. Energy that is not reflected is absorbed and transformed to heat.

C. Reflection can approach 99% in narrow bands with quarter-wave stacks consisting of more than 20 layers (number depending on index ratio). Such reflectors exhibit very low absorption, and therefore are qualified for high-energy laser applications.

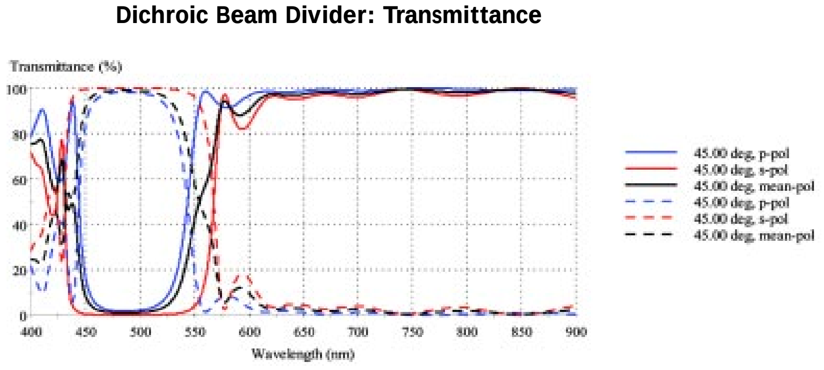

Figure 3. Dichroic beamsplitter at 45° incidence showing the polarization splitting in the transition zone between T and R.

Dichroic Beam Dividers and Polarization-Sensitive Coatings

A. At non-normal incidence it is easier to design and less expensive to make a coating that reflects the S-component and transmits P-component. A better match is obtained to the effective index that results from oblique incidence.

B. Polarization splitting increases as incidence angle increases. The transition between Reflection and Transmission is not steep or narrow in width. (see Figure 3).

C. Easier to reflect short wavelength regions and transmit long wavelengths than the reverse. This is because it is easier to reduce the amplitude of the ripple in the reflected band.

D. Polarizing beam splitters, PBSs, are effective only over small wavelength interval for 45° incidence. Dispersion in the effective indices, n_s and n_p, for the high- and low-index layers limits the bandwidth.

E. PBSs can provide a high extinction ratio only over a small acceptance angle, generally ~1°. This is again limited by the dispersion in the effective indices.

F. Neutral beam splitters containing metal operate over a wider bandwidth than all-dielectric B-S, but absorb 20-30%.

G Dielectric beamsplitters are neutral over limited spectral and angular regions.

Deposition Technology

A. Oxide coatings are harder and more environmentally stable than fluoride coatings.

B. Dielectric coating materials require a substrate temperature of 200° to 300° C or IAD to become mechanically durable and insensitive to environmental exposure such as humidity.

C. IAD of fluorides can partially deplete the fluorine concentration, causing absorption and lowering damage threshold in the UV, and therefore IAD is not used for high laser-energy coating applications; e-beam is better.

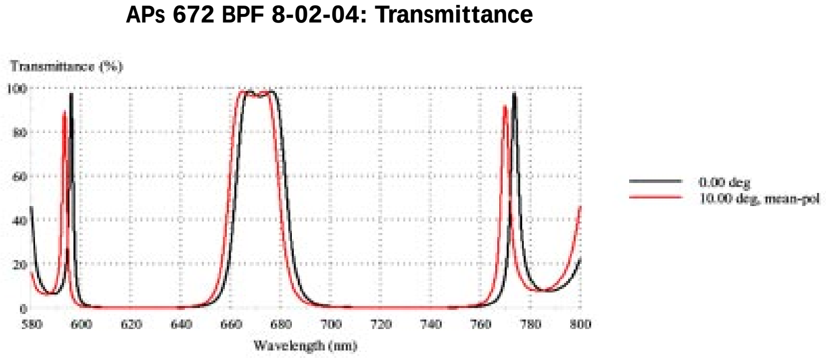

Figure 4. Angle sensitivity of a 10 nm FWHM bandwidth filter. The out-of-band transmission regions that require rejection are also evident.

D. The sequence of deposition processes yielding stable, harder and more adhesive coatings is as follows: IAD > Sputtering > E-beam > Resistance –Heated evaporation.

Spectrally Selective Coatings

A. All-dielectric bandpass filters can be designed and manufactured to isolate relative bandwidths (FWHM) from ~0.01% (DWDM) to >30%, BW is a function of available visible vs IR material indices. Energy that is not transmitted by the filter is reflected. Energy that is transmitted outside the bandpass must be removed by additional longwave pass or shortwave pass (edge) filters or with the aid of absorbing glasses (see Figure 4).

B. Reflection-type bandpass filter can be similarly made, but have fewer technological applications. They appear as decorative color coatings in the commercial and entertainment world. Simpler renditions can be made by selectively anti-reflecting metals; in this design fewer layers are required.

C. Filter bandpasses are very sensitive to incidence angle. In an optical system (camera, photometer, etc), the focal cone (F/no.) and the mean incidence angle of that cone must be small to prevent shifting the bandpass center wavelength to shorter wavelengths and distorting the bandpass profile. For the optical designer, this means that the filter must be placed where the rays will strike the filter at or nearly perpendicular. The narrower the bandwidth, the more tightly this condition must be met. For BW ~10 nm, the max incidence angle should be kept under 5° to avoid these problems. (see Figure 4).

D. Several transparent semi-conductors as thin-film layers provide high visible transmission and high infrared reflection. ITO is the most common example of a transparent conductive semi-conductor. ITO is used in thermal control and architectural glass and windshields for its wavelength selective ("green house") properties to admit light but prevent heat escape or transmission, depending on climate.

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A subsidiary of Williams Advanced Materials Inc.
P.O.Box 1178
Milwaukee, WI 53201-1178
Phone: 414-289-9800
FAX: 414-289-9805
web: www.cerac.com
e-mail: ceracinfo@beminc.com

Editor:
David Sanchez
Sr. Materials & Applications Scientist
CERAC, inc.

Principal Contributor:
Samuel Pellicori
Pellicori Optical Consulting
P.O. Box 60723
Santa Barbara, CA 93160
Phone/FAX: 805-682-1922
e-mail: pellopt@cox.net

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P.O.Box 1178
Milwaukee, WI 53201-1178
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Summary

The goal of making all parties that are involved in the production of optical systems aware of the limitations of optical coatings will result in smarter designs. Unnecessarily difficult challenges and demands will thereby not be imposed on the coating engineer and coating deposition technician. Often the thin-film coating requirements are considered an “afterthought”, rather than being included at the conceptual design stage, as a consequence of this lack of foresight, coatings are sometimes expected to solve some of the inherent optical system design. A common example is the sudden unexpected appearance of ghost images. Careful consideration of the placement of reflective surfaces, the placement of filters and beam splitters, the locations and curvatures of lenses, analysis of their spectrally-sensitive AR requirements and of all the potential multiple reflections of in-band as well as out-of-band energy will reduce or eliminate sources of undesired stray light and ghost images.