Designs and Materials for General and High Pulse Rate Laser Reflectors

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Coating Materials News

Introduction

Reflecting coatings are used to control optical paths integral to a variety of optical functions and instruments, including household mirrors, high performance reflectors used in space telescopes, short-pulse high-frequency high-energy laser applications with high damage resistance, and more. In this technical paper, we briefly discuss standard and advanced reflector designs, materials, and their applications.

General Reflector Designs

High reflector designs fall into two categories that are application dependent: protected metal and multilayer dielectric. Metallic reflectors cover the widest span of wavelengths and have low polarization properties. Highly reflecting metals are mechanically vulnerable to scratching and chemically corrosive environments and therefore, require abrasion and environmental protection. Commercial applications use Aluminum (Al), either as a second surface reflector or with a protective overcoating layer of Titanium Dioxide (TiO_2) or Silicon Monoxide (SiO).

SiO forms hard dense amorphous films that have low permeability to moisture. Because Silicon Dioxide (SiO_2) is the favored composition state of Si + O_2, careful consideration must be taken to manufacture SiO starting material and to deposit SiO as SiO. Thermal evaporation is typically used since the composition is easier to control than it is when using e-beam and sputtering deposition. SiO absorbs at wavelengths <450 nm and has a limited laser energy damage threshold. However, durability enhancement is a benefit for general purpose first-surface mirrors, including scientific and medical instruments. Similar coatings from the fully oxidized composition can be porous or require more complex stacks to achieve the same high performance and environmental durability as obtained with the monoxide.

Bare Aluminum reaches its maximum reflectance 88-90% and has the highest average Reflectance of any metal for wavelengths as short as ~200 nm at a thickness ~100 nm. To enhance the reflection to values ~95%, two stacks of high/low index dielectric layers can be added. Applications for enhanced reflection mirrors include scientific and medical instruments. The tradeoff is that spectral range for increasingly higher reflection is narrowed with added numbers of QW pairs as shown in Figure 1.

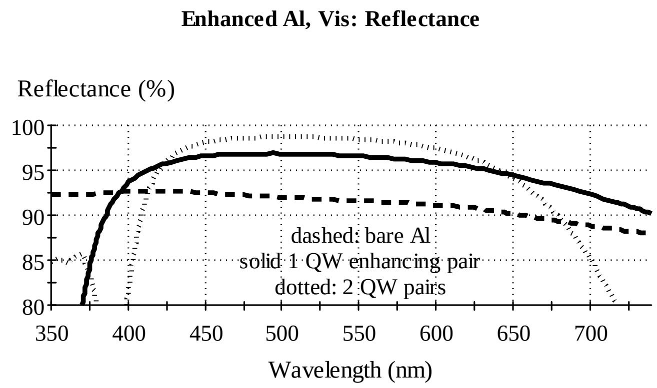

Figure 1. Al reflector protected by a single layer of SiO and enhanced by one and two QW pairs of TiO_2 and SiO_2. Dielectric layers increase reflectance but narrow the wavelength coverage.

Aluminum (Al) reflection decreases due to absorption centered at 810 nm and is problematical for some earth and climate research monitoring instruments that have responses in the absorption bands of water between 700 and 900 nm. Silver (Ag) is used when the Al absorption is an issue. However, Ag reflectance at wavelengths shorter than~450 nm is low. Silver is vulnerable to corrosion in air by gases containing sulfur and chlorine in the presence of moisture, and therefore, Ag mirrors require protection by additional dielectric coatings. We have discussed this in previous CMN issues [1].

An alloy of Silver and Copper was used to make mirrors during the 18th Egyptian Dynasty (c.1478-1390 B.C.). A thin layer of copper can be used to increase the lifetime of Ag mirrors by acting as a passivating inter-diffusing interface. Alloying with Palladium (Pd) or Platinum (Pt) can increase environmental durability at the expense of reflectance. Space telescopes used at visible through IR wavelengths typically use protected Ag to gain a few percent higher reflection over Al.

Dielectric coating combinations have been developed for several decades to protect Ag from atmospheric corrosion. Some protective coatings use Hafnium Oxide (HfO_2), Aluminum Oxide (Al_2O_3), Nickel-Chrome Nitride (NiCrN) and Silicon Nitride (Si_3N_4) components. In space, these coating combinations have proven to function for decades [2]. We have discussed protected Ag coatings previously.

Dielectric Reflectors Are Used in a Wide Range of Applications

Reflectors that are based on all dielectric layers are used in applications ranging from partial transmitters or beam-dividers, exposure to high energy densities, (i.e., with high Laser Induced Damage Thresholds, LIDT), phase delay control for high pulse-rate laser optics, phase equalization and retardance optics, etc. Often these applications are for operation at large Angle of Incidence (AOI). Figure 2 shows the reflectance at 45º AOI for a dielectric design using Tantalum(V) Oxide (Ta_2O_5) and SiO_2 computed with Essential Macleod software [3].

Dielectric mirrors used at non-zero AOI are sensitive to polarization interaction that intensifies with increasing AOI [4, 5]. The reflectance of the parallel polarization reflection plane, Rp, is narrower than that of the orthogonal plane, Rs. Reflectances at AOI >0 remain high however, polarization splitting is created, and the Rs and Rp components have different phases. This is important when polarized laser sources are involved. Phase difference is called retardance and will affect the state of polarization of the reflected and transmitted beams unless specifically controlled. Control can be obtained with the use of coatings on the total internal reflecting (TIR) surface.

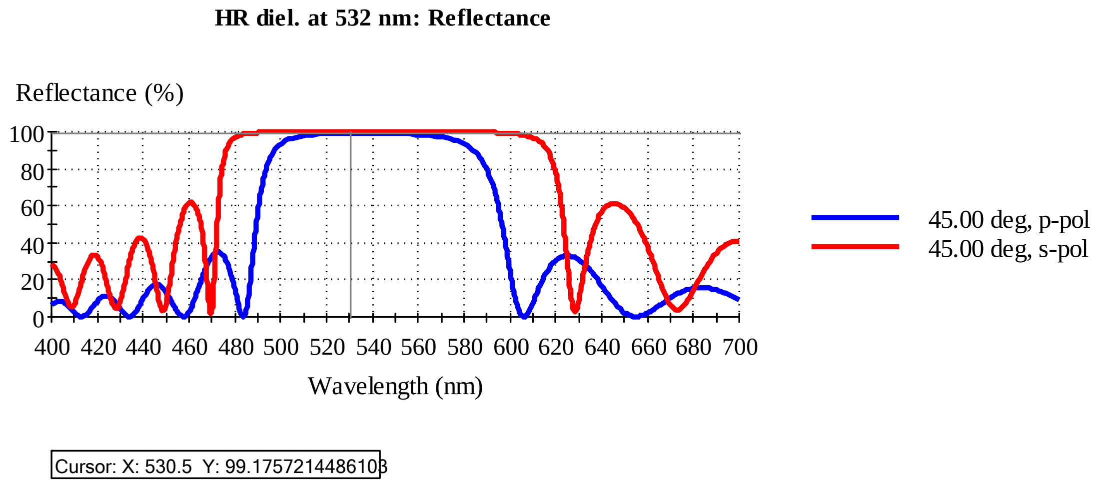

Figure 2. Reflectance at 45º AOI for the design $(HL)^{12}$.

Optical instruments that include TIR surfaces often need to control the retardance introduced by TIR. Example of these optical imaging instruments include binoculars, coherent beam combiners and polarimetric instruments. Below, Figure 3 depicts the TIR configuration with the phase-correcting coating on the reflecting hypotenuse. TIR occurs at the internal surface of a material (prism, for example) when the internal AOI exceeds $\Theta = \sin^{-1}(1/n_{glass})$ where *n* is the refractive index of the glass. For BK-7, ϴ = 41.1º; for n_{glass} = 1.8, ϴ = 33.7º. A 45º BK-7 glass prism is commonly used, as shown in Figure 3.

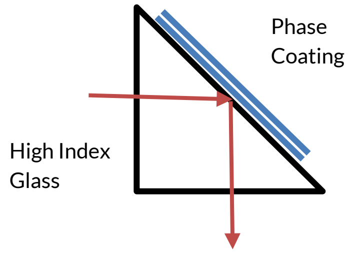

Figure 3. Configuration that produces controlled retardance at internal reflection.

TIR from the glass-air interface introduces a retardance of ~63º. Retardance can be changed by adding coatings to the hypotenuse. Figure 4 shows the change in internally reflectance retardance at the TIR surface from ~65º for the uncoated surface to ~90º with a retarder layer applied. The design uses a Quarter Wave (QW) of Ta_2O_5 on glass of index 1.78. Retardance is nearly achromatic over most of the visible wavelength region.

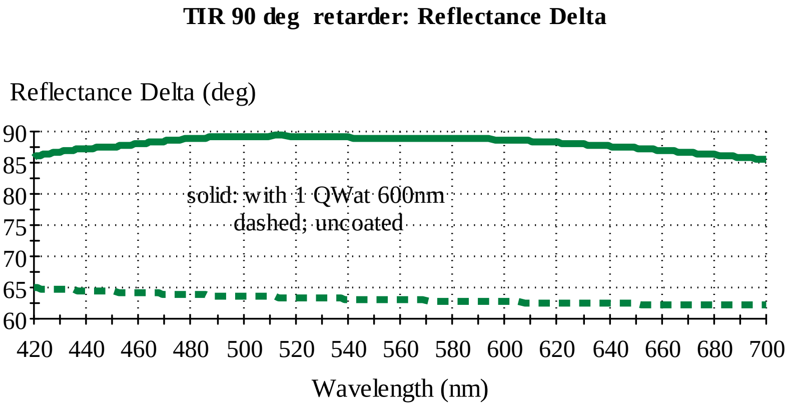

Figure 4. TIR retardances for a bare and a coated TIR surface. Retardance ~90º is achieved.

The retardance can be tailored to desired values by changing the design of the applied coatings. Figure 5 depicts the performance of a 45º retarder with Ta_2O_5 and SiO_2 layers (in nm) on high-index SF-56 glass: SF-56 /15 nm H/350 L/ 127H/8L/air.

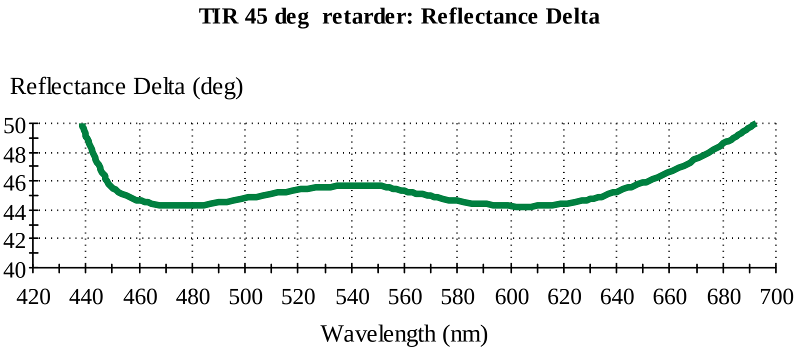

Figure 5. 45º retardance at a TIR surface in SF 56 glass.

The retardances from a series of reflections can be added to provide the total retardance required for a particular application.

Coatings for Short Pulse Laser Applications

Most reflector applications involve incoherent light, where the phases and frequencies of the irradiating in the light beam are not mutually related. Reflectors functioning in laser applications, where the energy is coherent, require control of the phase difference or the retardance that the reflection introduces [4]. Lasers with pulse widths in the femto- and atto-second (*fs* = 10^{-15} s; *as* = 10^{-18} s) ranges require special coating design considerations compared to typical laser coating applications.

Time and phase delays are negligible for incoherent light or pulses of longer duration but alter interference effects in optics that operate with fast pulses. At femto-second pulse frequencies, the round-trip transit time between when light it enters and travels through a coating and is reflected to interfere with incident light becomes a significant delay. In air, light travels 1 µm in 3.33 fs. The round-trip time in a dielectric path of a high reflector at 1064 nm having a thickness of 4.2 µm is ~20 fs for an effective coating index of ~1.7. If the return pulse is not in a predetermined fixed phase relationship with the incident pulse, optical behavior such as peak power will be adversely affected. Shorter wavelengths can be generated in non-linear materials by Q-switching and mode-locking. LIDT decreases with wavelength, therefore coating materials and their deposition processes become critical as the powers fall into the Giga Watt (GW) range. Irradiated spot size, total pulse count and repetition-rate are all factors to account for because they limit LIDT, and therefore influence time to failure.

Electric field strength distribution is affected by phase differences. To further complicate things, narrow pulses occupy a broad bandwidth and generate group delay dispersion (GDD) in materials. The resulting pulse spreading decreases the peak energy in each pulse. Coatings can be designed to compensate for dispersive effects, and by employing phase and group delay dispersion compensation, femtosecond lasers can generate multi-MW pulse powers. A 10 fs pulse with 10 milli Joule (mJ) energy can potentially deliver a peak power of 1000 GW (1 TW) when focused to a small spot if the GDD is near 0 fs^2. [6].

The reflector design in Figure 2 has near 0 fs^2 group delay dispersion and as shown in Figure 6, GDD increases away from the 532 nm design center because of the wavelength dependences of the material properties.

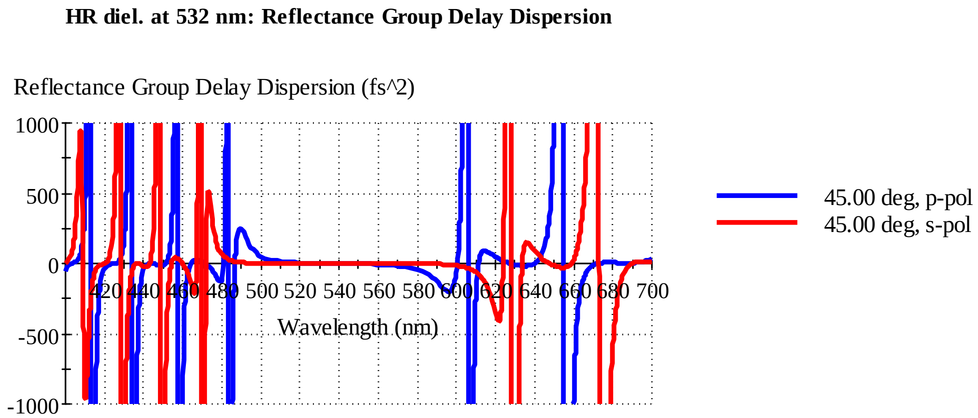

Figure 6. Group delay dispersion (GDD) changes rapidly away from the 532 nm center wavelength for the reflector of Figure 2.

Figure 7 shows that the retardance of the 1064 nm QW reflector is near 180º. This can be used to alter the incident polarization state from linear or circular polarization. Other retardance values can be produced through thin-film design.

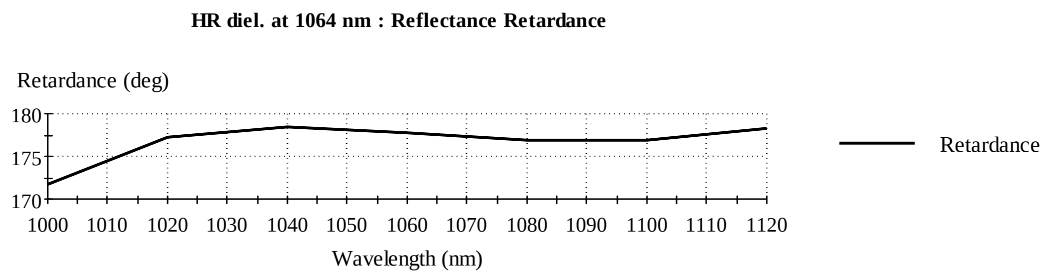

Figure 7. Retardance of a QW 1064 nm reflector with design $(HL)^{12}$.

Common applications for fs lasers include ophthalmic surgeries for cataracts and refraction correction, micro-machining and hole drilling in metals and ceramics, patterning of semiconductor surfaces, machining biomedical stents, and many more. An advantage of focused high power is that material is ablated rather than melted. Therefore, only a small area is affected by the laser beam. Sublimated removal avoids the damage through the heating of tissues and low-temperature materials such as polymers. Atto-sec lasers are used in the study of molecular dynamics.

LIDT Solutions for High Power Densities

Design configuration and deposition process and materials are critical for high-energy laser coatings. Past CMNs have discussed the relationships between defects, layer absorption, electric field strength distribution, and LIDT [4, 5]. As opposed to "slow" laser pulses and continuous irradiation that cause damage through heating, the damage mechanism for *fs* and *as* lasers is ablation and plasma generation by vaporization. LIDT is limited by the damage initiated by coating defects and impurity inclusions. Examples of coating defects are atomic displacements associated with compositional errors and structural growth morphology (non-amorphous nanostructure). Coating designs need to distribute electric field strength to be minimum in the high-index layers because those layers are more vulnerable to damage.

We have discussed the design and deposition processes that are used to produce reflectors that range from common mirrors to high pulse-rate laser applications. It is apparent that similar design and material deposition processes are relevant to fast coatings and to coatings with high LIDT.

References

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