

Losses in Optical Coatings

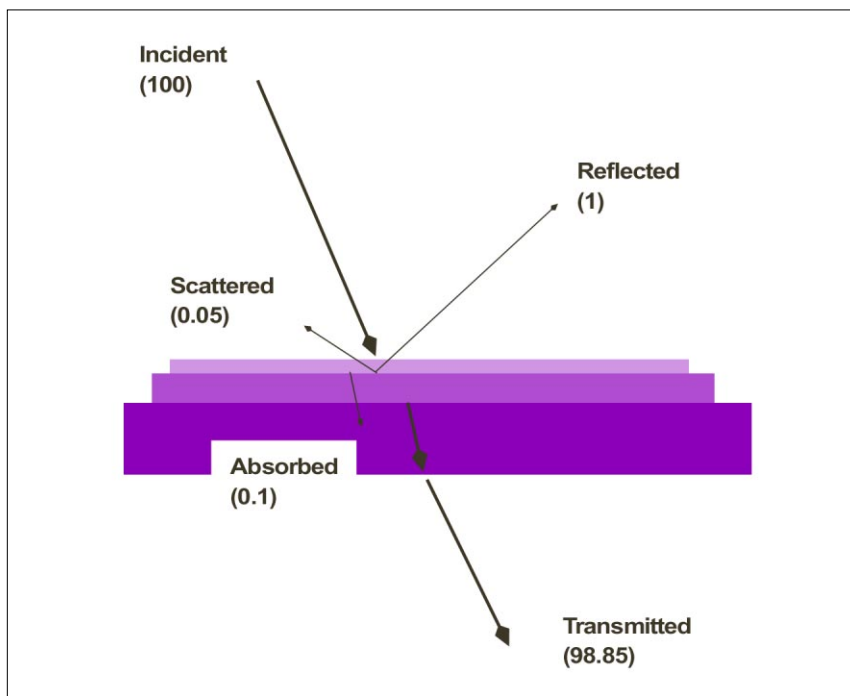
Light energy that is not transmitted or reflected by a system of thin film layers can be lost by absorption or scatter within the film, as illustrated in the figure, where some arbitrary values are indicated. The scattered, S, and absorbed, A, energies are generally very small compared with the T and R values, and for many applications these quantities can be ignored.

An example of an application where the value of A is important is in a high laser irradiation density environment. The generation of heat in the irradiated area results in a temperature rise because of poor thermal conductivity within the layers and can cause stress-related cracking or delamination, either of which will lower the laser damage threshold. Multi-layer constructions involving ten's of layers, such as with

bandpass filters and polarizing and dichroic beamsplitters, also require minimum absorption and scatter. In the case of the beamsplitters, optical contamination (crosstalk) can dilute the polarization separation or color isolation. The maximum achievable in-band transmittance for a bandpass filter is limited by the accumulated losses due to scatter and absorption in the perhaps 70 to 100 layers required to establish the bandpass and the out-of-band blocking. We have discussed in these Newsletters the fact that most thin-film layers possess an inhomogeneous, rather than an amorphous growth microstructure. Scatter can occur within the layer and at the discrete interfaces between the many layers, as well as at the surface. UV and Vis designs are composed of thin layers, and in that case, scatter at the high-to-low index

interfaces often dominates over bulk scatter. The deposition technique influences the microstructure and thus the layer bulk scatter characteristics. High-energy processes such as IAD and sputtering can be optimized to promote amorphous microstructure by breaking up the tendency for isolated column growth. As a result, narrow (~10 nm) bandpass filters based on oxide compounds can be very efficient and achieve in-band T_{avg} values in excess of 95%. UV coatings are constructed of either oxide- or fluoride compounds. Since scatter is inversely proportional to wavelength, smoother and amorphous microstructures are required for maximum efficiency at short wavelengths.

A significant loss of out-of-band rejection was detected in long-wave IR filters situated close to detectors where they subtend a large solid angle, and explained by the collection of scattered light within that large solid angle that normally is not sensed when the filter is widely spaced from the detector. This discovery and investigation by Dr. Stierwalt forced IR filter manufacturers to find ways to improve on the physical quality of the coatings. These improvements involved increasing the packing density, and thus reducing the discrete microscopic structure of the layers, as well as the spatter of microscopic particulates from the evaporation of the materials. Hence, ZnSe and ZnS materials that sublime rather than melt, are evaporated from resistance-heated baffled boxes to prevent the emission of particulates. The



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low-index component is a fluoride that is evaporated from a melt in an open source and therefore cannot emit particulates.

In critical optical systems, scatter from mirrors, both all-dielectric and metal, must be minimized. Assuming that the substrate is very smooth and itself non-scattering, scatter from metal mirrors can originate from large grain sizes in the metal layer or from the dielectric overcoat whose purpose is to protect the metal from abrasion and chemical reaction with the atmosphere. Aluminum is reflective to wavelengths near 200 nm. To minimize scatter losses at short wavelengths due to large grain size, aluminum must be deposited on cold substrates (<50° C) and to the minimum thickness that results in just becoming opaque. This thickness is ~700 nm. Higher temperatures and greater thicknesses will cause clumping growth cells of metal layers (aluminum, silver, etc) and high scatter. Dielectric materials require high energy to achieve high packing density, hardness, and adhesion. To prevent recrystallization of the reflector metal and the production of large grain sizes that scatter, the metal mirror cannot be heated to the optimum temperature required by the oxide or fluoride protector layer. IAD and sputtering are techniques that provide or exceed the benefits of high substrate temperature without imposing a high quantity of heat. Diffusion of atmospheric gases through dielectric overcoats that are not completely dense or that have pinholes due to microscopic particulates collected during evaporation or chamber turbulence is another cause of scatter that develops with time. Sulfur and chlorine gases in conjunction with water vapor permeate the overcoating and reach the metal; in the case of silver, the surface will obtain the appearance of white scatter centers that grow in size with time of exposure. More durable and corrosion-resistant silver coatings are in development that promise longer operational lifetimes.

Absorption losses in optical coatings have a different origin that can, however, have a relationship to film layer microstructure. Impurities incorporated in the film and possibly at interfaces can absorb energy and result in loss of efficiency or lower laser damage thresholds. The impurities in question are to be distinguished from contamination such as oil vapor that have external origins. The internal surfaces of the porous columnar microstructure of many oxides and fluorides can adsorb water from the atmosphere. We have discussed previously how the absorption of water will result in a higher refractive index, possibly a change in stress balance within the coating, and susceptibility to mechanical and chemical instabilities. If a water absorption band is close to a laser wavelength, the damage threshold will be lowered. Again, densification through high-energy deposition techniques reduces this external source of induced absorption. Selenide and sulfide compounds exhibit a smaller affinity for binding water, and therefore fewer problems are attributable to water adsorption in those materials.

While the addition of reactive ions and kinetic energy in IAD and sputtering processes leads to a more ideal microstructure in the sense that the packing density is near bulk values and the layers are homogeneous, absorption losses can also be attributed to errors in stoichiometry: the deposited layer does not have the proper composition because of incomplete recombination / reaction during evaporation or sputtering. Thus for example, instead of pure SiO_2 , the layer has a significant percentage of SiO_{x-2} in other words is a sub-oxide. It is well known that the lower energy process, e-beam evaporation, produces coatings with the highest laser damage thresholds. This is because more complete oxidation occurs. Additional absorption can also arise at the interface between two different oxides when one binds more oxygen than the other, leaving the interface partially reduced. Small oxidation differences can even occur at the substrate when oxide

compounds are deposited by e-beam vs. ion plating processes. The more reactive compound can deplete the less reactive species of oxygen. This has been observed between SiO_2 and TiO_2 layers, where the titania layers can partially reduce the silica interfaces [1]. Some of the added absorption observed with high energy deposition processes can be explained by postulating a gradual change in the binding energy created by the mixed interface of the high energy process (ion plating, for example). In that case, oxygen is shared between the two layers of materials, rather than distinctly belonging to either one. The shared binding energy can lead to absorption and lower damage threshold. We have encountered one of the paradoxes of thin film physics: graded interfaces between layers produce lower scatter than discrete interfaces, however they can produce higher absorption because of incomplete oxidation at the interface. This would suggest that coatings that exhibit high laser damage thresholds are composed of layers that possess physically and chemically (stoichiometrically) discrete interfaces, and that, conversely coatings that have graded layer interfaces exhibit the lowest scatter and might have lower damage thresholds. The issue is further complicated by the distribution of the electric field within and across the interfaces between layers. Therefore, each case must be considered individually.

Oxide compounds partially decompose during evaporation, and are preferably evaporated from reduced compositions to enable smooth evaporation. Reduced forms have the advantages of melting and because of this deliver a uniform evaporation rate without particulate ejection. Spitting and pressure bursts caused by the sudden evolution of oxygen or absorbed water are also avoided. Reactive oxygen species must be supplied during evaporation or sputtering to complete the oxidation.

Fluoride compounds generally melt, and do not decompose during evaporation unless high energy conditions such as

IAD (or sputtering) are imposed. Excess fluorine needs to be supplied with appropriate reaction energy to restore the correct composition. A problem associated with IAD deposition of films of fluoride compounds is the potential for replacement of some displaced fluorine with incidental oxygen. The new oxy-fluoride compound will be absorbing in the UV. When ZnSe and ZnS are evaporated, they decompose and, if conditions are correct at the substrate, recombine with accurate stoichiometry. In all these examples, layers composed of incomplete composition will be optically absorbing. With visible-region coatings, one can sometimes distinguish the type of absorption by the color of the coating. By placing the coating against a white paper, the appearance of yellow vs gray absorption colors reveals absorption due to small vs large oxidation error, respectively. In the most critical applications, for example, ring laser gyros where many interactions with the coated surfaces are made, absorption levels must be in the ppm range.

Optical absorption whose cause can be attributed to chemical impurity of the deposition source material has always been a subject for debate. The impurity can be intrinsic, where during the refinement of a compound, reduction of the concentration of chemically similar compounds or elements is difficult. An example is Ca in MgF_2 . Typical "impurity" Ca is ~1%. In this case, as in many similar cases, the undesired element or compound has the same optical and chemical properties, and therefore does not detrimentally affect the deposited film. We have discussed the benefits of the well established approach of deliberately introducing foreign materials in small quantities to "dope" the host material. Special mixtures of MgF_2 and other fluorides (CIROM-IRX™, CIROM-IRB™) are examples where the mixed materials exhibit superior mechanical and structural properties over the pure host material.

Very little data or analysis exists that permits us to define the upper limits of

acceptable impurity component in a coating material. The impact of the impurity is highly dependent on the chemical similarity to the host material, relative evaporation temperatures, and relative chemical reactivity. We know that the transition metals are highly absorbing in the UV and visible regions and highly oxygen reactive. Specifically, ions of vanadium, chromium, manganese, iron, cobalt, nickel and copper have high absorption coefficients, and consequently their trace quantities must be minimized, especially for UV applications. These trace elements must, obviously, be actually incorporated in the coating and not just be present in the source material to be optically significant. Since the evaporation process itself acts as a filter based on relative vapor pressures, impurities having the lower vapor pressure will be left behind and not transported to the deposited layer.

But just how pure does an oxide compound coating material need to be before it introduces intolerable absorption in the deposited film layer? The answer is somewhat application-dependent; again we site the extreme cases of ring laser gyros and high-power lasers. But for general applications, the answer can be surprising. We refer to a discussion by M. Friz and F. Waibel [2]. They estimate that for an impurity of 100 ppm of the transition metals mentioned, the absorbance will be 0.001% in a film of thickness 100 nm. This value is completely negligible for most applications. The bottom line is that for most coating applications, four 9's purity (99.99%) is entirely adequate, and that in some cases (low energy) three 9's is good enough, and that is assuming that these highly absorbing transition metal impurities are incorporated in the film layer.

We have discussed a variety of causes for losses in multi-layer optical coatings. Demonstration of the ability to control and minimize losses is the example of the pinnacle achievement in optical coating, DWDM filters, where losses of a fraction of a dB have been produced.

References

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2. Martin Friz and Friedrich Waibel, "Optical Interference Coatings", N. Kaiser and H. K. Pulker (Eds), Springer-Verlag Berlin Optical Sciences Series (2003).

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