Types Of Anti-Reflective Treatments And When To Use Them

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

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).

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.

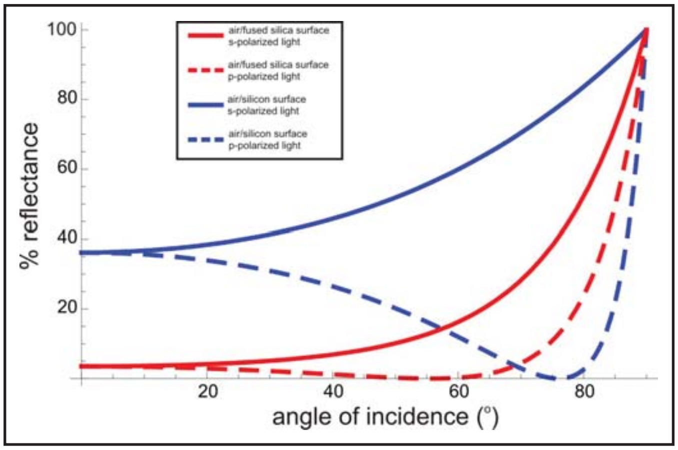

Figure 1: Percent reflectance of s- and p-polarized light off silicon and fused silica surfaces depending on angle of incidence (n_{Si} = 4.01, $n_{fused\ silica}$ = 1.46)

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 multielement 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%.

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. 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.

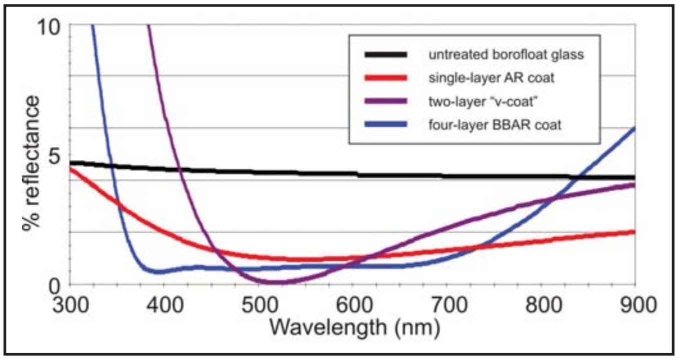

Figure 2: Theoretical reflectance curves for untreated borosilicate float glass and borosilicate float glass with three different anti-reflective coatings

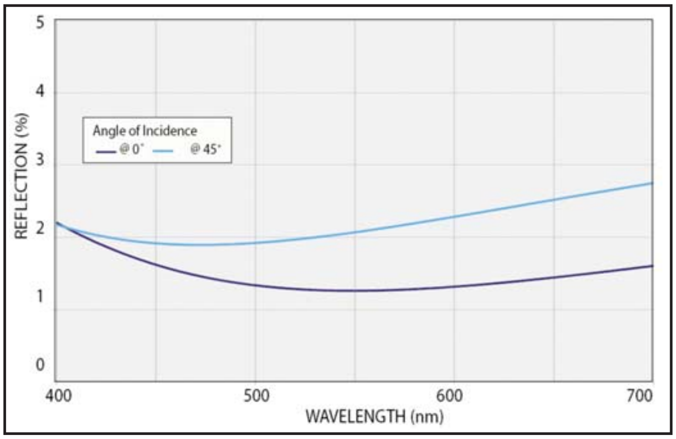

Figure 3: Reflectance off borosilicate glass surface treated with a single layer of MgF_2. The reflectance is not as low as a multilayer broadband anti-reflective (BBAR) coating, but it is lower than untreated glass at all wavelengths and incident angles.

One compound that is commonly used for single layer anti-reflective coatings for visible spectrum elements is magnesium fluoride (MgF_2). 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 MgF_2 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

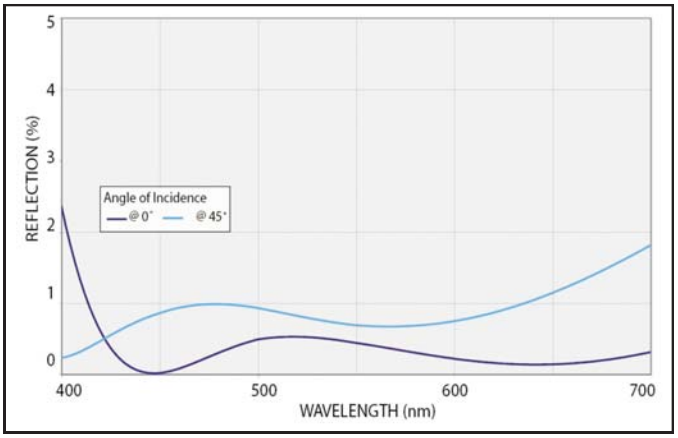

Figure 4: Multilayer broadband anti-reflective (BBAR) coatings can achieve reflections below 1% at a broad range of wavelengths but at the expense of higher out-of-band reflectance and large percentage gains in reflectance at non-normal angles of incidence.

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 multilayer coatings.

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*).

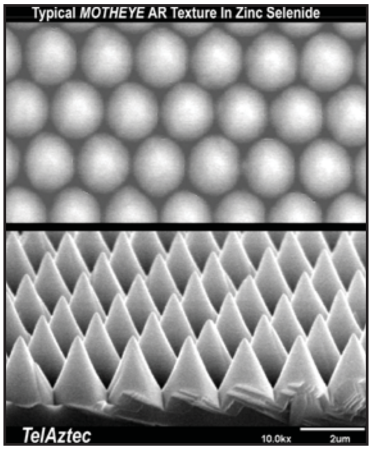

Figure 5: SEM image of zinc selenide moth-eye microstructures (courtesy of TelAztec, Inc.)

One major advantage of microstructured anti-reflective glass is its ability to withstand high incident energies of nearly 60 J/cm.[4] This is a sizeable improvement over the energy damage threshold of most thin-film anti-reflective coatings. Because the anti-reflective "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%.

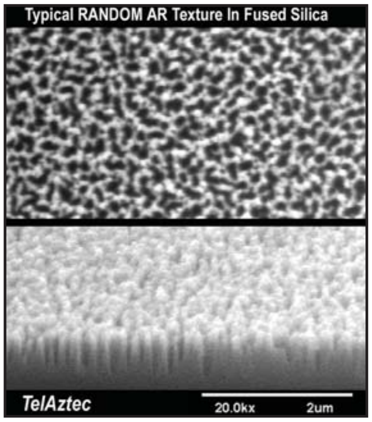

Figure 7: SEM image of random anti-reflective microstructures in glass (courtesy of TelAztec, Inc.)

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.

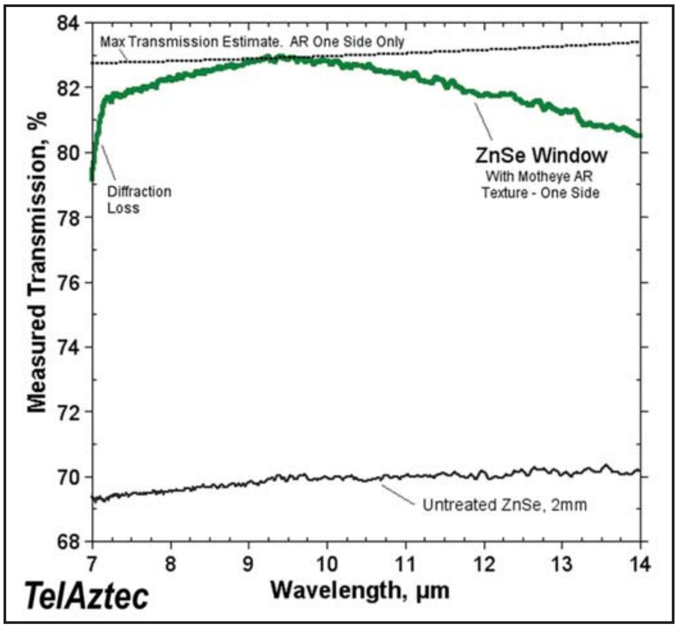

Figure 6: Percent transmission for a zinc selenide window untreated and treated with moth-eye anti-reflective texture on one side (courtesy of TelAztec, Inc.)

Summary

There are a few different options available to achieve the means of 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. ■

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4. Ibid.

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