Understanding Optical Coatings For Military Applications

By Trey Turner, Chief Technology Officer, REO

Virtually all optical components used in military applications, such as target designation, rangefinding and IR countermeasures, employ thin film coatings to somehow modify their transmission and reflection characteristics. Yet, despite their ubiquity, many military system designers are not familiar with the commonly encountered tradeoffs in thin film design, or with the characteristics of various coating deposition technologies. As a result, optical coatings are often specified in ways that drive up cost unnecessarily. This article reviews some of the most important design and deposition factors. It is intended to help those who specify optical coatings establish a realistic set of specifications that deliver the necessary performance in the most cost-effective manner.

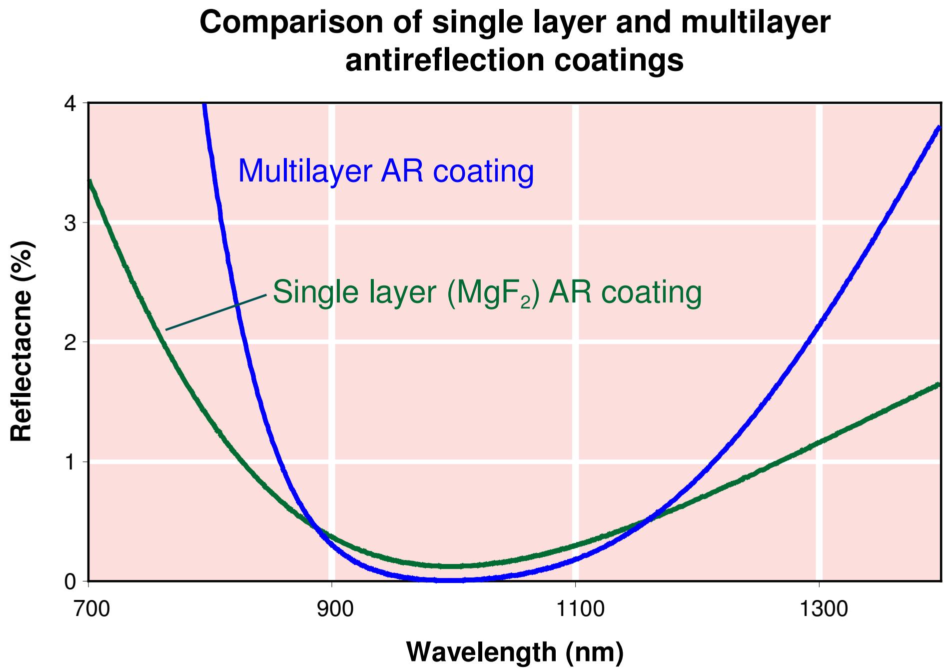
Practical Coating Design Tradeoffs

Thin film coatings consist of alternating layers of materials with high and low refractive index. They work by harnessing optical interference to enhance reflection at one or more wavelengths, or to preferentially reflect or transmit one polarization. Real-world coatings that accomplish these tasks can sometimes contain tens, or even hundreds, of individual layers, and are fabricated from numerous different available materials.

However, the range of materials available to the coating designer is not infinite, meaning that practical coatings must be constructed using a limited set of refractive indices. Furthermore, these materials cannot be deposited with absolutely perfect control of their thickness and refractive index. It is therefore important for the coating buyer to understand what level of performance specifications can be achieved in practice, and what specifications tend to drive cost, or result in other undesirable outcomes, such as decreased mechanical durability or reduced laser damage resistance. The most important considerations for specifying antireflection, high-reflection, beamsplitter and polarization-sensitive coatings are reviewed here.

Antireflection (AR) Coatings

Performance in an antireflection (AR) coating is typically specified by either the maximum allowable reflectance at a single wavelength or the average allowable reflectance over a particular wavelength range. For AR coatings intended for single wavelength, single angle of incidence use, very high performance can be obtained; less than 0.1% reflectance per surface at visible wavelengths on glass substrates is not at all uncommon.



Adding layers to an antireflection coating lowers the reflectance but reduces the coating bandwidth.

It becomes increasingly difficult to maintain high performance in an AR coating as either spectral bandwidth or angular range is increased. For this reason, it is important for the buyer to make it clear whether the specified performance must be held to its peak value or an average value over the entire operational wavelength or angle range. Otherwise, coating cost may be increased unnecessarily.

For AR coatings that operate at a nonzero angle of incidence, especially above 30°, the polarization state of the incoming light has a significant impact on coating design and performance. Therefore, it is critical that the state of the incident polarization be specified. Furthermore, the reflectance of a dielectric interface is higher for *s* polarization than for *p* polarization at all nonzero angles of incidence. Therefore, if low reflectivity from a tilted component is desired, it is advantageous to design the geometry of the optical system so that the optic encounters *p* polarized light.

The response of dielectric coatings shifts to shorter wavelengths as angle of incidence increases. In other words, an AR coating designed to produce minimum reflectance at normal incidence at 1064 nm will instead deliver minimum reflectance at a shorter wavelength when used at 45° incidence. This can become a consideration when applying AR coatings on highly curved substrates. For example, on a steep aspheric lens the angle of incidence at the center is 0°, while at the edge of the component it might be 70°. This means that, even when working with a single wavelength, the coating must have broad bandwidth so that it still performs well at the nominal wavelength even when its response is shifted. Furthermore, actually applying films on such steep surfaces may require special tooling in order to maintain uniformity. Thus, there may be a significant tradeoff in terms of film complexity and cost versus the reflectance.

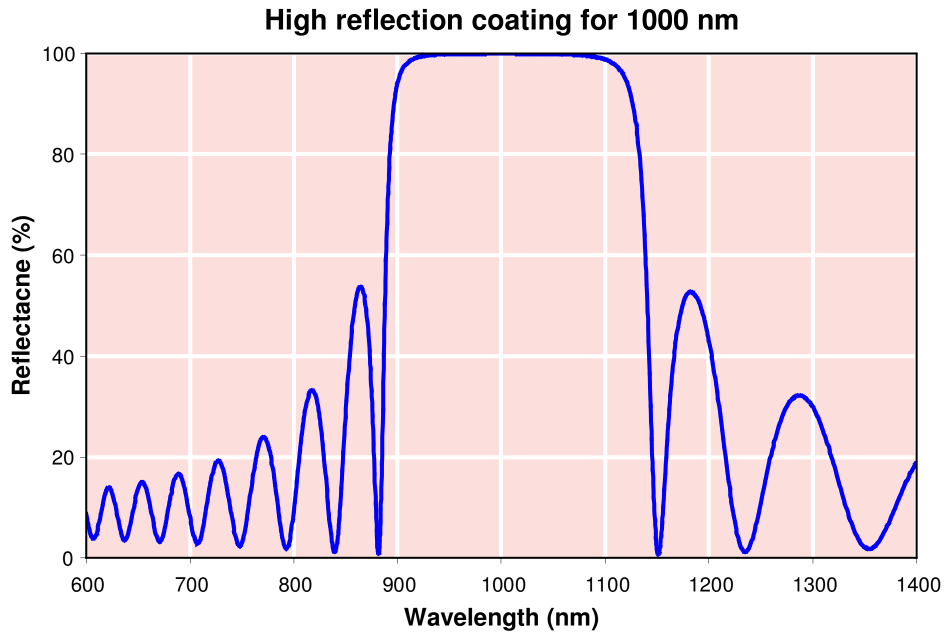
Antireflection coatings that work at two or more discrete wavelengths or spectral bands are common in military applications. In general, it's easier, and therefore more economical, to achieve high performance at a few individual wavelengths than it is to cover an entire band with the same performance level Additionally, specifying high performance at only one of the wavelengths, and relaxing specifications at the other(s), will also generally keep cost down.

Producing multi-wavelength AR coatings that operate in both the visible/near infrared and the mid-infrared or thermal infrared can also be challenging because of the limited number of materials that simultaneously transmit in these regions. Specifically, many materials that transmit in the visible don't work above about 5 µm, which makes it more difficult, and therefore costly, to produce coatings that work in both these spectral ranges.

High Reflector (Mirror) Coatings

For mirror coatings, probably the most important choice facing the consumer is whether to use a metal or metal/dielectric hybrid coating, versus an all dielectric design. The primary advantage of metal coatings is very broad spectral bandwidth. For example, aluminum, the most commonly used mirror coating, has a reflectance of over 85% from 400 nm to well past 10 µm. Gold delivers over 99% reflectance from 2 µm well into the far infrared. These levels of performance would be virtually impossible to achieve with all dielectric coatings. In addition, the difference in reflectance between the *s* and *p* polarizations is usually substantially smaller for metal coatings than for all dielectrics.

However, the peak reflectance of metal films does not equal that which can be obtained with dielectric coatings. Even gold, which offers 99.5% reflectance in the infrared, cannot compare with dielectric coatings that can routinely deliver 99.99% reflectance or higher, albeit at a single wavelength. The small amount of absorption in metal films which limits their reflectance also contributes to another significant limitation, namely, damage when exposed to high laser fluences.



Reflectance of a typical narrowband high reflector coating, in this case centered at 1000 nm.

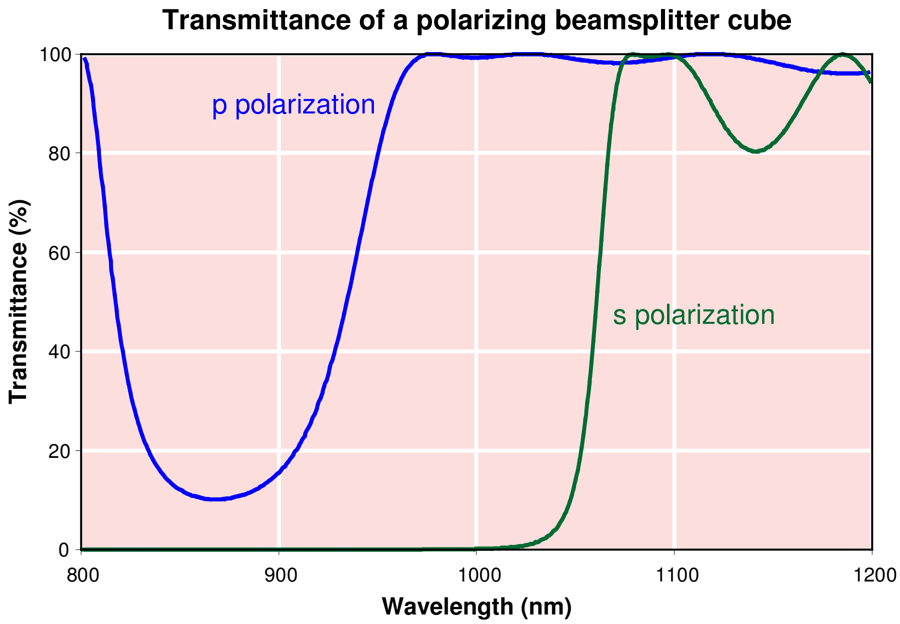
Metal films are also less physically durable than all dielectric coatings. Specifically, they have less resistance to abrasion, humidity, thermal cycling, and salt exposure than dielectrics. Silver in particular must always be covered with another material to prevent oxidization, which also significantly lowers its reflectance.

For all dielectric high reflectors, substrate quality is a consideration when specifying extremely high (≥99.995%) reflectivity because surface scatter becomes a performance limiting factor. Thus, the surface roughness of the underlying substrate must be specified, and the consumer should expect that specifying a very smooth surface will drive cost up because it necessitates the use of specialized polishing and testing techniques.

Partially Reflective (Beamsplitter) Coatings

The performance of beamsplitter coatings is highly dependent upon the configuration of the optic, namely cube or plate type. For non-polarizing beamsplitters, the cube format is advantageous because this arrangement is inherently less sensitive to input polarization than plate designs.

Conversely, polarizing beamsplitters can take advantage of the inherent difference in reflectance for *s* and *p* polarizations to achieve very high levels performance. Because of this, plate polarizers are virtually always configured to pass *p* polarization and reflect *s* polarization. They usually work best when configured for operation at Brewster's angle (at which the *p* polarization reflectance drops to zero), which is around 56° for visible wavelengths and glass substrates.



Polarizing coatings maximize the difference in reflectance between s and p polarizations to achieve high extinction ratios.

For polarizing beamsplitters of either plate or cube type, it is also important to understand that it is much easier to eliminate *s* polarized light from the transmitted beam than it is to keep *p* polarized light out of the reflected beam. Therefore, a transmission extinction ratio (T_p/T_s) of 10,000:1 is achievable for visible wavelengths, while a reflection extinction ratio of greater than 100:1 is difficult. Moreover, tightening the reflection extinction ratio (R_s/R_p) specification will rapidly drive up cost, so these performance characteristics should be kept in mind during system design.

Several factors can drive layer complexity, and hence cost, in beamsplitters. For example, as angle of incidence increases, the growing difference in reflectivity for *s* and *p* polarizations makes it progressively more difficult to deliver a partial reflector that performs equally well for both polarization states. Thus, it's advantageous to work with just a single polarization under these circumstances, if possible. However, if working with unpolarized light is inevitable, then it's better to design an optical system in which beamsplitters operate at lower angles of incidence so as to minimize the effects of this split. Bandwidth is also a major factor. Making a polarization insensitive coating that extends more than ±10% of the center wavelength (e.g. 550 nm ±50 nm) is a substantial challenge.

It's also important to be careful regarding how tolerances are specified. There is a big difference between a beamsplitter that must maintain its nominal performance over *the entire range* of 45°±5° incidence, versus one that must achieve nominal performance *somewhere* over that same range. In the first case, the performance specification must be met at all angles over the 40° to 50° incidence range. In the second case, the performance specification is only met somewhere in the 40° to 50° incidence range, and it is expected that the user will place the component in their system and tilt tune it to achieve the desired performance level. The first case demands a much more costly component than the second.

Another practical limitation of cube beamsplitters is that the prisms are typically attached with adhesive or by optical contact. This can compromise performance by introducing wavefront errors; furthermore, absorption in the adhesive can cause scatter and significantly reduce laser damage threshold.

Some leading manufacturers have overcome this problem with methods that eliminate adhesives by forming an actual chemical bond when the components are assembled. REO calls our embodiment of this technology Activated Covalent Bonding (ACB™). Tests at REO show that ACB yields a component that has the same mechanical strength and ruggedness as a monolithic cube, yet which avoids the absorption, scatter and damage limitations of adhesive bonding.

Military Coating Requirements

The particular functionality required for many military applications often necessitates overcoming some of the most difficult performance challenges already identified. For example, rangefinders/target designators typically utilize multispectral operation, functioning simultaneously in the visible, at 1064 nm, at the "eyesafe" wavelength of 1.54 µm, as well as in the mid-IR (3 – 5 µm). These coatings are also frequently specified to function over large angular ranges, and to exhibit a high degree of polarization insensitivity.

The drive to minimize system size and weight, especially in man portable and airborne systems, may motivate the optical designer to scale down component diameters. However, shrinking the diameter of a given power laser beam causes an increase in its power density. Therefore, laser damage threshold often becomes a concern.

The need to incorporate numerous layers in order to achieve advanced functionality can also result in relatively thick films which may exhibit high mechanical stress. That can be a problem when the optical system designer specifies components with a relatively high aspect (diameter to thickness) ratio to minimize weight. High coating stress can actually warp these thin components out of their original shape, thus increasing the wavefront distortion of the component and overall system.

Finally, military systems may experience wide swings in temperature and humidity, and are sometimes exposed to salt spray, smoke or other airborne contaminants. Some coating types absorb water, which, together with changes in temperature, can shift coating performance. Therefore, coating performance stability and mechanical durability (and the ability to be repeatedly cleaned) can be significant considerations.

Deposition Solutions

There are various different deposition technologies used to create thin film coatings. These can produce very different results in terms of resultant coating stability, durability, laser damage threshold and internal stress. It is therefore useful for the coating buyer to have a basic understanding of the characteristics, advantages and limitations of these methods. The table compares the most commonly employed coating methods for producing military coatings, namely thermal evaporation, ion assisted deposition (IAD) and ion beam sputtering (IBS).

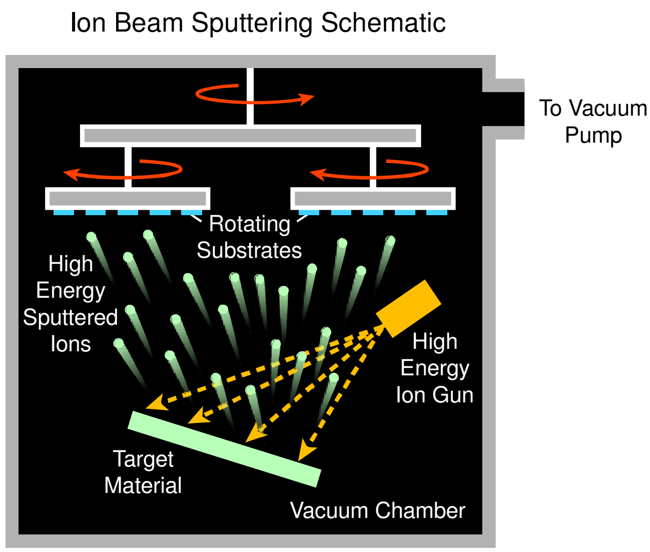
Table: Deposition Method Comparison Summary

	Coating Materials Selection		Mechanical & Environmental Durability	Laser Damage	Scatter & Absorption	Precision*	Cost
	400 nm – 3 µm	3 – 5 µm					
Evaporative	good	good	poor	good	poor	poor	good
IAD	good	good	fair	good	fair	fair	fair
IBS	good	fair	good	good	good	good	fair

*The ability to precisely control deposited layer characteristics and therefore reliably meet even difficult performance targets.

Thermal evaporation methods (either utilizing resistive heating or electron beams) are by far the most widely employed. Their advantage is that they work with a very wide range of materials, enabling coating optimization anywhere from the deep ultraviolet through the far infrared, and they are the lowest cost deposition methods. The big negative of thermal methods is that they produce porous coatings which can subsequently absorb moisture, thus changing the effective refractive index of the layers. This shifts the transmission/reflection response of the film, making it difficult to hold the desired multispectral or peak performance targets when exposed to changes in ambient temperature and humidity. Furthermore, porous coatings are prone to containing defects which lead to lower surface quality and can act as sites for laser damage. Evaporative coatings also exhibit the poorest mechanical durability of all deposition techniques.

IAD is a variant of evaporative deposition that uses energized ions as a “hammer” to pack down each layer as it is deposited. As a result, IAD delivers substantially more dense films, although some water absorption is still possible. Thus, it represents a step up in terms of coating stability and durability, while working with essentially the same material set. As a result, IAD often represents the best balance between durability and performance, particularly for coatings in the 3 – 5 µm range.



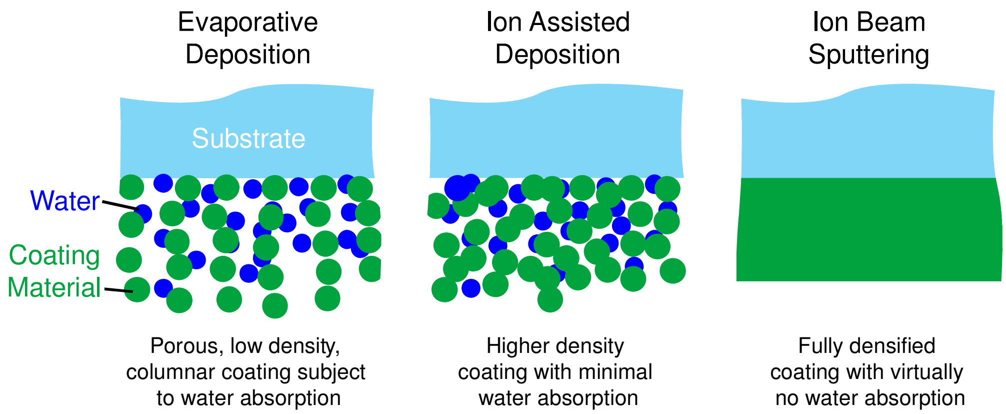
In IBS, a high energy ion beam is directed at a target causing atoms or molecules to sputter off with high energy, resulting in densely packed films.

In IBS, a high energy ion beam bombards a target, typically composed of a metal or oxide, causing target atoms or molecules to sputter off. These particles then stream away from the source and are then deposited on to the substrates. A low pressure of oxygen is usually present in the chamber to act as a reactant for the creation of oxides from metal targets, or to re-oxidize any free atoms dissociated by the sputtering process when using oxide targets.

IBS produces fully densified thin films, which are effectively completely impervious to water absorption, and thus, very stable in the presence of environmental changes. Another important feature of IBS deposition is that it deposits materials with highly reproducible refractive index characteristics. When coupled with the ability to accurately control layer thickness, this enables high coating precision. That is, the ability to consistently match the actual coating characteristics with the desired design specifications. This is particularly valuable in the production of multispectral coatings, as well as for meeting tight targets for broad angular range and specific polarization characteristics.

The biggest drawback of IBS is that it works with a more limited range of materials than evaporative methods. This isn't a problem in the visible and near infrared, but does become an issue in the 3 – 5 µm range because neither ZnS nor fluoride materials are compatible with IBS.

Another potential problem with all densified coatings is that they can contain stress which may negatively impact wavefront distortion. Manufacturers have developed various methods to control this. For example, post coating annealing processes can be utilized with some materials to reduce internal stress. An additional approach is prefiguring, where an optic is purposefully fabricated with a surface error which is then corrected back out by the coating induced stress. Also, a second coating is sometimes put on the back of a substrate to balance the stress of the frontside coating.



Evaporative deposition produces porous coatings which can absorb moisture, while IAD reduces this problem and IBS completely eliminates it.

Conclusion

Military applications often require high performance coatings that can withstand large environmental shifts, high laser power and exposure to contaminants. But, understanding the basics of coating design and deposition can help the buyer specify coatings in a way that meets these demanding performance targets in the most cost effective manner.

Author Bio

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Trey Turner is Chief Technology Officer at REO, where he has created a number of novel designs for thin film optical coatings. He holds a Bachelor of Science degree in Physics from Lawrence University and a Master of Science degree in Physics from the University of Texas at Austin.