Improving the performance of interference coatings for high-power laser optics

By C.K. Carniglia

Most optical surfaces within high-power laser systems require multilayer interference coatings. These are usually high-reflector (HR) coatings to provide a maximum reflectance at the laser wavelength or anti-reflection (AR) coatings to provide a minimum reflectance. Occasionally, polarizers or other types of beamsplitters are required. As the systems become more complicated, multiple wavelength requirements become more common, perhaps necessitating high reflectance at alignment laser wavelengths or high transparency for optical viewing through the system.

In addition to the spectral performance specifications, coatings for high-power laser optics must often meet several other performance requirements simultaneously. Among these are the following:

- *High laser damage threshold.* This applies especially to short pulsed lasers where the peak powers are highest.
- *Low absorption.* Significant levels of absorption are usually detrimental to all laser coatings. In addition, for long-pulsed or CW laser systems, heating of optical elements and the resulting distortion can be factors limiting the performance of the system.
- *Low scatter.* Scatter contributes to the losses within the system or it may introduce stray laser light that can pose other problems.
- *Environmental stability.* In gas lasers, reactive or corrosive gases are often present in the resonator cavity. Coatings that will not degrade in such an environment are often required.

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As the requirements become more stringent, coating technologists are forced to explore new areas to try to achieve the needed performance. This paper briefly reviews three areas that can lead to improved coating performance:

- The *coating process* used for depositing the coatings. These processes fall into several major classes. Within each process, there are refinements that can be made to optimize one or more of the coating performance characteristics.
- The *materials* incorporated into the coating. Often the choice is limited, but work on mixed materials may add some new options.
- The *design* of the coatings. Within the constraints of the required spectral performance, it is important to choose an optimum design. Occasionally, nonintuitive design techniques can lead to improved performance.

Coating process

The most fundamental factor affecting the characteristics of multi-layer coatings is the process by which the coatings are deposited. Some of the processes used for high-power laser coatings are:

Physical Vapor Deposition (PVD). This refers to evaporation of the coating materials onto the substrate, usually

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by heating them with an electron beam or a resistance heater. PVD is the most common method of making multilayer coatings. It is the most mature of the coating technologies and is useful for coating parts of almost any size.

The highest damage thresholds for multilayer coatings have been achieved using PVD.[1] However, not all materials can be deposited using PVD, and some materials fractionate when being deposited by this method. PVD films are often porous and frequently have defects arising from spatter or spitting from the evaporant sources. The use of lasers to evaporate the coating materials may provide improved control and higher material purity.

Ion-Assisted Deposition (IAD). This process is usually used in conjunction with PVD to alter the coating properties. It involves directing a stream of ions of moderate energy (100-1000 V) at the substrate while the coating is being deposited. IAD can affect the microstructure of the films, usually resulting in a denser coating. Coating stoichiometry can also be affected. IAD has the advantage that it can be retrofitted onto PVD systems that are in common usage.

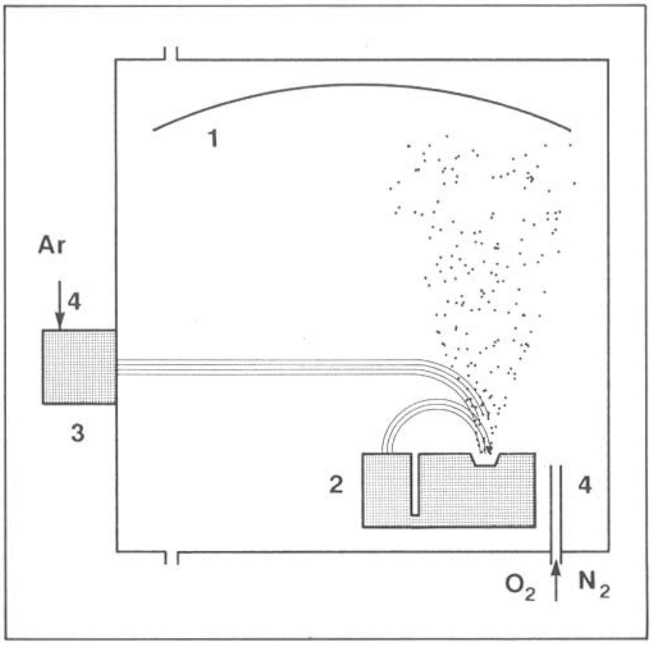

FIGURE 1. Schematic diagram of an ion plating system illustrating (1) dome-shaped substrate holder, (2) electron beam evaporative source, (3) plasma source, (4) gas inlet for Ar and O_2 or N_2. Balzers, used with permission.

Plasma Plating. In this process, the evaporated material is ionized and the ionized particles are accelerated toward the substrate. A schematic diagram of the arrangement of a coating chamber for plasma plating is shown in Fig. 1. The ionized particles condense on the substrate with higher energies than with conventional PVD. This has been shown to produce dense films with low scatter.[2] The process is still at an early stage of development and has not been used for high-power laser coatings.

Sputtering. This may be either DC or RF diode or magnetron sputtering. Diode sputtering requires a sputtering gas that is at a higher pressure (in the 10^{-3} torr range) than is commonly used for PVD. This requires short distances between the target and the substrate and makes coating large optics difficult. On the other hand, in magnetron sputtering, the pressures required are lower, making this process more applicable to optical coatings.

Due to the higher energies involved, sputtered films have higher densities and fewer impurities than evaporated coatings. The range of materials that can be deposited by sputtering is almost unlimited. The use of nitrides, which cannot be deposited by PVD, makes more environmentally resistant coatings possible.

Ion Beam Sputter Deposition (IBSD). This process involves directing a beam of ions of moderate energy (500-1500 V) onto a target of the desired coating material. The material from the target is sputtered by these ions onto the substrate. As with conventional sputtering, a wide range of materials may be deposited by IBSD. Coatings made using IBSD are extremely dense and have a minimal microstructure.[3] This results in coatings with reduced scatter.[4] IBSD has the disadvantages that it is slower than PVD and the films have a high degree of stress.[3]

Chemical Vapor Deposition (CVD). This process involves creating films by means of a chemical reaction between various gases. It is capable of producing extremely pure coatings by starting with pure gases. However, it often requires high coating temperatures that are not suitable for large optical components. On the other hand, components of unusual shapes can easily be coated.

Solution Coatings. These take many forms. They involve dipping the substrate into a solution and withdrawing it at a controlled rate to create a film of the desired thickness. In most cases, this requires baking after the coating is applied. Sol-gel coatings[5] have found a particular application to AR coatings for high-power laser systems because of their high damage threshold. However, sol-gel coatings are usually not as durable as some of the other types and the high damage threshold observed for AR coatings has not carried over into multilayer coatings.

Each of the above coating processes has its strengths and weaknesses. The greatest potential for improving the performance of interference coatings may lie in the discovery of some new coating processes. However, the development of a new process is a difficult task for two reasons. First, it is an expensive endeavor, usually requiring expensive equipment. High-power laser programs usually do not have sufficient funds to support the development costs involved. Often these processes are developed for a commercial market and then applied to high-power laser coatings. For example, the need for a low-loss coating for laser gyroscope mirrors led to intensive research in the area of IBSD,[4] which in turn led to improved coating properties that may find wider application in the area of high-power laser optics.

The second difficulty in developing a new process is that the results of using the new process must be compared with the performance of coatings made using more mature technologies. Early failures using new processes often discourage further development work. Because of the long time required to develop a new process (10–20 years is typical), an extended financial commitment is needed. Again, this is easier to justify if there is a commercial application for the coatings.

An excellent counter-example to the above arguments is the sol-gel coating developed at Lawrence Livermore National Laboratory.[5] The equipment necessary for the coating of small pieces was not expensive since the process does not require a vacuum system. Early experiments produced high damage thresholds, which encouraged funding sufficient to develop the process to the point that the AR coatings of the Nova laser system are made using the sol-gel process. This process has probably made the largest single contribution to improved damage threshold of high-power laser optics.

An alternative to developing a completely new process is the refining or modifying of an existing one. This usually involves experimenting with the various process parameters to find a region of improved coating performance. For example, the damage threshold of AR coatings made by PVD for pulsed 1.06 μm laser systems has been found to vary with coating temperature.[6] Also, the crystalline structure of coatings made by RF diode sputtering has been shown to be a function of process parameters.[7] This development of a process contributes to its maturity as a technology. It also has the possibility for making improvements in the performance of coatings for high-power laser optics.

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Coating materials

The choice of coating materials is often limited by the wavelength requirements of the laser system. For example, for visible laser systems, refractory oxides provide durable and transparent coatings. Materials like titania (TiO_2), tantala (Ta_2O_5), and zirconia (ZrO_2) are commonly combined with silica (SiO_2) to make coatings for this spectral region. These materials are also used for other coating applications and, thus, the coating techniques are well developed. As one moves to shorter wavelengths, titania and tantala are no longer useful because of the UV band edge, and other materials such as hafnia (HfO_2) and yttria (Y_2O_3) come into play.

The area of materials research is an important one to pursue for the development of improved laser coatings. Such development can take one of two paths: either new materials can be sought or mixtures of existing materials can be studied. In either case, the process often involves trial and error. The approach can be based on the identification of a particular class of materials for further study, such as the rare earth flourides, which are not commonly used.[8]

Some materials are not used because their optical properties are similar to less expensive or more common materials that perform better in conventional coatings. For example, niobia (Nb_2O_5) is a material that has an index and absorption edge between titania and tantala.[3] If one wants a high-index material, titania is the better choice. If one needs performance slightly farther into the UV, tantala may be preferable. However, niobia may be a promising material for visible and near-IR laser coatings.[9]

It is probably fair to say that most single components have been tried as coating materials. Further development of these materials probably lies in identifying promising materials that may have been considered marginal for some reason and eliminating or minimizing their shortcomings. For example, many fluoride materials are soft and hydroscopic when deposited by PVD, but may be more durable when used with IAD.[8] They may also be suitable for lasers operated in a dry or vacuum environment. The limited durability of sol-gel coatings has not prevented their use in large laser systems. Rather, extra care is taken in handling and cleaning these optics.

When all of the single component materials have been exhausted, the next step is to mix them together to form binary or ternary coating materials. Usually this mixing is done to achieve a particular result, such as affecting the microstructure of the film. In some cases, the second material can fill the voids that would have occurred in a single component film, leading to a denser coating than would otherwise have been achievable.[10] Mixtures might also help to stabilize a coating, preventing inhomogenities that might result from various crystalline phases being present within a single-layer film.

The difficulty with mixed materials is the control of the composition during the deposition of the films. In the cases of sputtering and IBSD, this is not as difficult because the composition of the coatings is usually similar to the composition of the sputtering targets. In the case of PVD, however, the materials can easily fractionate during coating. This problem can be solved by preprocessing the mixtures or by flash evaporation of small quantities of the materials to be mixed. Laser evaporation may be useful for this purpose.

Coating design

In some respects, developing new coating designs is the least expensive of the three approaches under consideration. With a mature coating process and well-developed coating materials, coatings of various designs can easily be made. The difficulty in making progress in this area results from the facts that the coating design is often dictated by the spectral performance requirements and that these requirements often lead to some fairly standard designs. Since most of these designs have been around for decades, innovations are difficult to come by.

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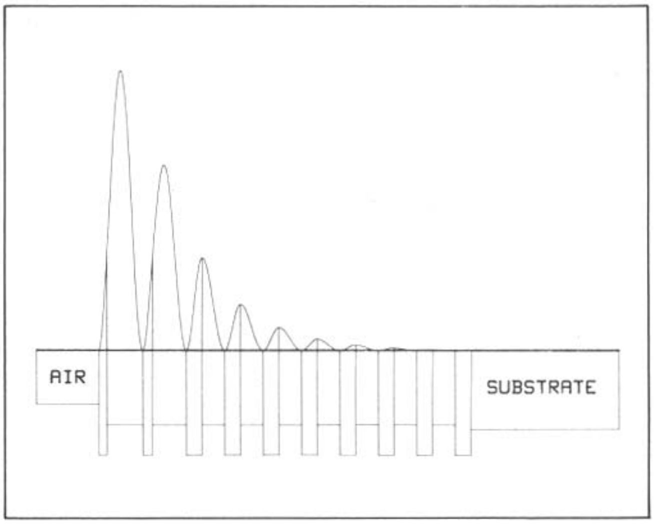

FIGURE 2. The electric field profile in a laser reflector. The coating design is indicated schematically below the axis and the electric field intensity is shown above the axis. The layer thicknesses have been adjusted to reduce the field in the high-index layers.

On the other hand, after one has gone to the trouble of optimizing a process and developing appropriate materials, it is important to use the best coating design available. Some important design principles are as follows:

- Place the materials with the highest absorption at positions of minimum electric field intensity.[11] The electric field profile for a laser reflector design with reduced electric fields in the high-index layers is illustrated in Fig. 2. This technique has led to damage threshold improvements in AR and HR coatings at a variety of wavelengths.
- For multiwavelength mirrors, place the laser reflector for the wavelength of highest laser power on the outside of the coating. If there are several high-intensity beams, place the reflector for the shortest wavelength on top. This procedure minimizes the standing wave patterns within coatings.
- Investigate the use of barrier layers with AR coatings and halfwave protective layers on HR coatings.[1] These techniques have proven successful in raising the damage thresholds of coatings for pulsed laser systems at several wavelengths.

The last of these three design techniques should probably not be referred to as a design principle. In fact, it has been called a design trick by some. However, it illustrates the fact that all of the factors relating to an optimum coating design are not yet fully understood and that improved design techniques still have the potential to lead to improved coating performance.

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