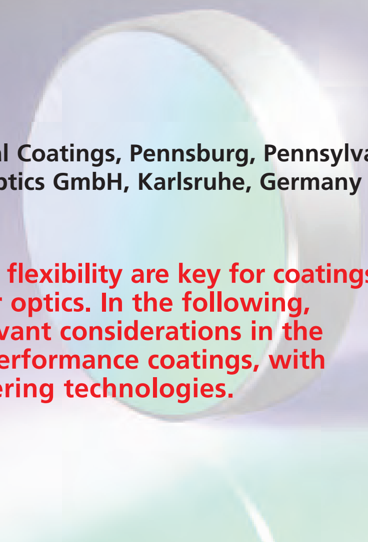
Improving laser optics coatings



Iain MacMillan, Penn Optical Coatings, Pennsburg, Pennsylvania, USA
Matthias Knobl, Edmund Optics GmbH, Karlsruhe, Germany

More process control and flexibility are key for coatings used with ultra-fast laser optics. In the following, we discuss the most relevant considerations in the manufacturing of high-performance coatings, with a special focus on sputtering technologies.

1 Introduction

Coatings used on UV, visible, near-IR and far-IR laser optics have evolved greatly over the last decade as new laser applications have grown creating a variety of challenges for the coating producer. Historically, laser coatings have been associated with a requirement to withstand and function in a high energy environment, with designs tailored to meet either high thermal loads or high electric field strength.

While the requirements of these high power laser coatings continue to increase, other laser applications have grown in popularity with a different set of design and process challenges. These emerging markets include femtosecond laser technology, where ultra-short pulses generate ever higher power densities.

One femtosecond is 1×10^{-15} s (or one millionth of a billionth of a second). Light can travel to the moon and back in less than 3 seconds, but it travels only a hair-width (30 µm) in 100 fs. Femtosecond lasers produce pulses typically in the range of 20–300 fs, repeating on the order of 50–500 MHz.

Another challenging laser-related application is Raman spectroscopy, where coatings are required to analyze and discriminate between laser-produced light and the wavelengths produced as a result of Raman scattering. These coatings require very high accuracy deposition of designs consisting of 200 layers or more. Coatings on mirrors, lenses, filters, and other components have become more sophisticated and diverse, and their designs and manufacturing processes allow for finer control.

New areas of diversification include ultra-fast laser coatings for medical, micromachining, and telecom industries, as well as precision Raman filters for the high growth life-science market. Different approaches to optical coatings are required, as coatings for ultra-fast lasers have a unique set of challenges. In some cases, coatings also must become even more specialized to meet the specifications.

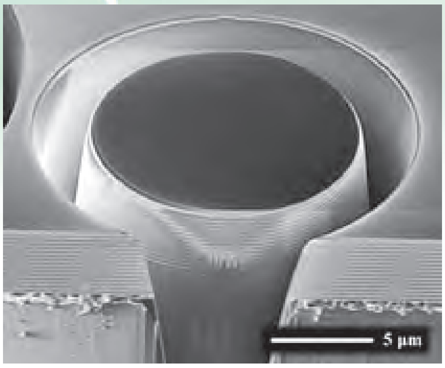


Figure 1: Micro-machining using femtosecond lasers can produce sharp, clean cuts with resolution at sub-micron level. Here a multilayer coating has been machined and clearly shows the individual layers in profile down to and including the substrate. Using this technique it is possible to machine filters down to 10 µm diameter with minimal damage to the coating

2 Who uses ultra-fast lasers

Biomedical applications are the fastest growing industry segment using femtosecond lasers, hence also driving the development of new coating technologies. This sector includes lasers in the biomedical field used for skin grafting, tattoo removal, treatment of hair loss, and diagnostic applications such as multiphoton tomography.

Ophthalmology is another area where the coatings used with shorter pulse lasers are seeing massive growth. Vision-correction surgeries such as LASIK and cataract removal are increasingly using femtosecond lasers. As the technology continues to improve, more surgical uses for lasers in the visible and IR spectra are being explored. Besides the biomedical sector, there are other areas such as lithography, where patterning with high definition requires fast UV lasers.

High-power short-pulse lasers are also in demand. Applications that work at extreme energy densities such as fusion reaction research involve challenges for the laser optic coatings as well.

One of the fastest growing areas for femtosecond lasers is in high-precision micromachining. The ultra-short pulse widths reduce the size of the heat-affected zone, significantly improving the quality of the cut and allowing machining at micron and sub-micron levels (**figure 1**). Pulse energies of 5 mJ are possible in some lasers, producing peak power densities of 50 GW/cm^2 for pulse widths in the order of 100 fs.

These high power densities and short pulse widths result in extremely clean cuts down to a sub-micron level. It is reported that any material can be cut by vaporization or be ablated using this technology [1]. Industrial scale lasers drive most of the demand for ultra-short pulse lasers in the far IR spectra. Used in many applications where heat sensing is important, optical coatings must meet different types of challenges with those lasers.

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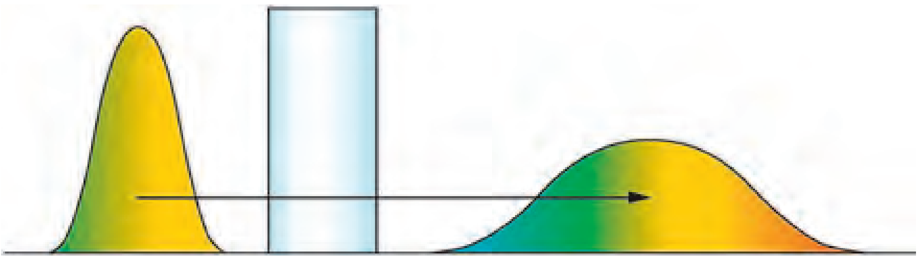


Figure 2: Broadening of a pulse as it travels through a dispersive optical material *(Source: Layertec GmbH)*

3 What matters in laser optics coatings

While some optical components are specifically designed for use with Continuous Wave (CW) operation and some for the pulsed modes, many optics are used in both modes, creating additional requirements for their coatings. In CW mode, an optical component's laser damage threshold (LDT) is determined by a thermal mechanism, which differs from the mechanism in pulsed mode. While the same processes are used to deposit coatings, the ideal materials are typically different for CW, nanosecond pulses, and ultra-fast pulses.

A decade ago the primary driver of laser coating performance was its Laser Damage Threshold (LDT). For CW and nanosecond pulsed applications the use of materials with intrinsically high LDT performance and the need for nearly defect- and contaminant-free optics and processes were critical to achieve these high performance coatings. Laser energy easily finds any defects and causes damage. Surface preparation, cleaning, polishing, and deposition processes were a real challenge, and process optimization became critical to obtain good performance. While these requirements are still as relevant as ever for these types of lasers, the newer breed of lasers and applications bring fresh challenges.

As lasers have gotten faster, coating designs have been forced to evolve. One of the most important goals for coatings on ultra-fast laser optics is that they improve performance while maintaining the profile of the pulse itself.

The beam from a very short pulse laser is Gaussian-shaped with both a defined temporal and spectral bandwidth. Importantly, the latter has a lower finite limit dependent on the temporal pulse width. The shorter the pulse, the larger the spectral bandwidth limit.

In a 100 fs pulse, centered at 1000 nm, the spectral bandwidth minimum is about 10 nm, but increases to about 100 nm for a 10 fs pulse. This spectral broadening for ultra-short pulses (**figure 2**) can result in loss of power through degeneration of the temporal properties of the pulse shape when transmitted through or reflected from media exhibiting chromatic dispersion.

As pulse broadens and the shape of the beam changes, the various spectral components within the pulse will travel through the media at different velocities. This pulse broadening is referred to as 'group velocity dispersion' (GVD).

An important feature of reflective optical coatings designed for femtosecond applications is that they deal well with GVD. Ideal reflective coatings shouldn't create broadening, but in practice it happens. One strategy that optical coating manufacturers use, is to create a coating that reverses the broadening effect, bringing the beam back to its original profile.

Chirped mirrors are correcting GVD in this manner. These coatings are designed in layers so that the reflecting path of the dispersive element in the beam compensates for the changes that occurred through earlier elements (**figure 3**). This property is sometimes referred to as negative GVD.

Beam splitters also have coatings that are designed to not change the properties of the beam. The coating must transmit and reflect in such a way as to minimize group velocity dispersion.

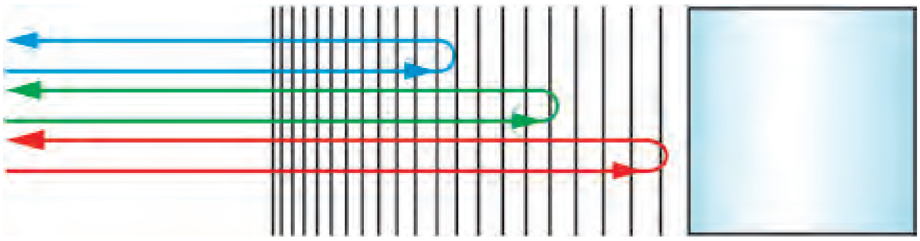


Figure 3: Negative GVD coatings correct optical path lengths of red, green and blue wavelengths *(Source: Layertec GmbH)*

4 Sputter processes pros and cons

Reactive sputtering (RSD) and ion beam sputtering (IBS) are two newer deposition technologies to meet the demands of ultra-fast laser coatings. Older, lower energy processes like evaporation create coatings with weaker bonds, growing at different speeds, being more porous and less homogeneous.

In contrast, sputtering features higher energy deposition processes, resulting in stronger bonds with both the substrate and other layers. The films become more like the bulk material of the coating source material, with similar density and optical properties. The coatings are very predictable and repeatable from run to run, and their optical properties are understood. Their thicknesses can be tightly controlled, they are very stable over time and in different environments, with accuracies and tolerances that allow designers to use them for femtosecond lasers.

The biggest challenge is producing films that perform as close to their theoretical design as possible. Designing and optimizing a sputter deposition process is labor intensive and non-trivial. Sometimes a coating design that works in theory may require several tests and design iterations to successfully complete. Of many initial design solutions found, it is likely that only one or two will be manufacturable and can be applied to production.

Less than 10% of the industry currently uses sputtering to create high performance optical coatings. Despite being more expensive, this newer technology is, however, a growing market as more applications using shorter pulses are benefitting from the superior properties.

5 Cost factors

There are several factors that add to the cost of coatings appropriate for ultra-fast lasers. Modern sputtering machines are costly to purchase and run, being engineering intensive equipment. Often, the designs are complex, take more time to set up, and require high levels of customization.

Also, in-house testing does not always advance at the same rate as technology. While most laser coating manufacturers are equipped to measure transmission of coated optics, very few of them have metrology equipment to measure pulse properties as GVD or LDT. Probably less than 5% of companies that perform testing can measure the pulse width properties of chirped mirrors, and it's expensive to set up and measure a small volume of work. Outsourcing these measurements may be a driver of costs, too.

LDT measurements are highly requested, and in some cases critical, adding significantly to the metrology expenses. Sometimes, optics buyers mistakenly over-specify their required LDT. They may not be sure what the average performance of their equipment is, so they estimate on the high side. This makes the coating more complex and difficult to produce, resulting in lower yields which drive up the price.

While there are many custom coatings available, manufacturers are making standard stock coatings now more than ever. These coatings fit the requirements of most applications. Using them keeps prices reasonable.

6 Other optical coating properties

Even though more users desire coatings that can withstand higher powers and power densities, they also need more control and the ability to fine-tune. New optical coating technologies that meet user-specific demands are becoming increasingly popular.

Hydrophobic optical coatings create surfaces that repel water and other liquids. Anti-static precision optical coatings dissipate the build-up of static electricity, preventing charge accumulation and not allowing dust or other particles to stick to the surface. New multi-spectral coatings work in both infrared and visible light, providing system designers with more flexibility while using fewer components.

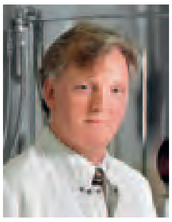
Given the recent rapid changes in laser coatings, it is reasonable to expect that more applications will emerge. As the demand increases to meet the needs of specific applications, the designs, deposition processes, and coatings will continue to evolve.

Literature:

[1] Brookhaven National Lab., *Femtosecond Laser Micromachining*, *www.inst.bnl.gov*

[2] R. Paschotta, *Femtosecond Lasers*, *www.rp-photonics.com/encyclopedia.html*

Author contacts:



Iain MacMillan
CEO
Penn Optical Coatings
1055 Mensch Dam Road
Pennsburg, Pennsylvania 18073, USA
Tel. +1/267-923-8798
Fax +1/267-923-8297
eMail: imacmillan@pennoc.com
Internet: www.pennoc.com

Matthias Knobl
Edmund Optics GmbH
Zur Gießerei 8
76227 Karlsruhe
Germany
Tel. +49/721/62737-30
Fax +49/721/62737-33
eMail: mknobl@edmundoptics.de
Internet: www.edmundoptics.de

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