Solar Technology
Efforts Refocused Following Financial Woes
Materials Evolving for Lighter, Stiffer Optics

Building better optical materials will impact applications in high-energy lasers, consumer devices and more.

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For optical materials, less can be more: Coatings that reflect less could lead to displays that are brighter and can be seen over a wider angle. Materials that expand or contract less as the temperature fluctuates could lead to better optics. Equally important could be lightweight materials that move less.

“One basically wants very stiff optical systems, but with as low a total mass as possible,” said Marc Tricard, managing director of precision optics for Zygo Corp. of Middlefield, Conn., which makes optical components and measurement instruments, and offers design and manufacturing services.

Light yet stiff optics are “particularly important for airborne and space applications, of course, but also semiconductor applications where lower mass translates into higher system accelerations and hence higher tool throughput,” Tricard said.

New materials would be beneficial in several other areas, he added. One is in materials with a low coefficient of thermal expansion. In response to demands from defense and semiconductor customers, the industry has pushed coefficients of thermal expansion from roughly 100 parts per billion per degree kelvin down to seven or better.

High-energy laser applications

Another area of focus is high-energy laser applications. The military is interested because high-energy lasers could...
replace conventional weapons. Also interested are those researching fusion power, since high-energy lasers are being used to ignite the reaction. For this scenario, Zygo has developed and qualified materials capable of withstanding as much as 8 J/cm², or nearly 60 times the intensity of sunlight. This is done for pulses of a few nanoseconds at a wavelength of 351 nm.

The need for relatively stiff yet lightweight materials is leading researchers to look again at single-crystal silicon. The stuff of chips and solar panels has the mechanical and thermal properties that make it an excellent compromise material, Tricard said.

Another well-known semiconductor, AlGaAs (aluminum gallium arsenide), is also promising, particularly for low-noise optical coatings, according to Dr. Garrett Cole, co-founder of Crystalline Mirror Solutions GmbH of Vienna. The startup manufactures high-quality single-crystal AlGaAs thin films on arbitrary bulk optics.

This is of commercial appeal because of the frontiers of science: As optical measurements become more precise, they demand higher optical and mechanical system quality. It’s the latter that now constrains performance. For instance, gravitational wave detectors are kilometer-long interferometers, but a small component sets the noise floor.

“There are two mirrors held 4 km apart, and the system is largely limited by the 6-µm-thick film making up the reflective element of those mirrors,” Cole said.

Because they are crystalline in nature, the thin films produced by Cole’s company have few defects and low mechanical loss. Just as importantly, the loss shrinks upon cooling, which is not true for all coatings. Therefore, as components are cooled and motion decreases, there’s an added bonus because the mechanical performance of the films increases.

One consequence of less mechanical loss is that devices can be made smaller, because unwanted motion as a percentage of the total cavity length is a critical constraint. If that must be below a given value, then a lower-loss material allows devices to be made smaller. That possibility is one reason why crystalline coatings have attracted the interest of defense researchers and contractors.

To produce the coating, Crystalline Mirror Solutions begins by growing an AlGaAs multilayer on a wafer via molecular beam epitaxy. The film is transferred in centimeter-sized swaths using a temporary flexible mount and then bonded to a final substrate, with care taken to eliminate voids. The resulting films are at least an order of magnitude better in terms of mechanical performance while offering optical characteristics competitive with those created by ion-beam sputtering, an alternative approach, Cole said.
Dr. Jun Ye, a fellow at NIST and the University of Colorado at Boulder’s JILA research lab, makes the world’s most stable laser, with a 30-mHz-wide spectral output. Partly due to this extreme stability, Ye’s group in January demonstrated an atomic clock that’s accurate to a second over 5 billion years.

In a quest for even better lasers, Ye was involved in testing the crystalline mirror coating developed by Cole and a team at the University of Vienna. He participated because the mechanical quality of an optical system determines its response to thermal noise. “That limits how stable a laser can be made or how precise an interferometer can be used to read out length information,” Ye said of what is known as mechanical Q.

For his part, he sees the potential for a big impact from these crystalline coatings. There’s a need for high-quality optical and mechanical components across a number of scientific disciplines, according to Ye.

**Consumer applications**

Another sector where high-performance optical materials are attracting interest is consumer devices. A case in point comes from JDSU, the Milpitas, Calif.-based optical technology company. Today, consumer needs drive innovation, noted Fred Van Milligen, vice president of research and development. For optical materials, an example of this can be seen in smartphones, which have ever-more-capable cameras, despite severe size and power constraints.

In general, the goal in consumer goods is to collect as much light over as wide a field of view as possible. Usually, this is done in a bandpass, with only the desired part of the spectrum getting through. Previously, this might have been for 2-D imaging in the visible, but now there’s increasing demand for 3-D and IR imaging.

Most of JDSU’s coatings involve sputtering of inorganic and organic materials onto substrates, with this often done directly on device-bearing semiconductor wafers. The coatings are carefully tailored to yield specific optical performance, and they can be complex.

“We tend to have a fair amount of layers in our coatings,” Van Milligen said. “We deliver some products with thousands of layers in them.”

Multilayer coatings are becoming more common, said Dr. E. Fred Schubert, a professor of electrical engineering at Rensselaer Polytechnic Institute in Troy, N.Y.; he co-authored an influential 2007 *Nature Photonics* paper on antireflection coatings.

In part, this interest in coatings is being driven by advances that allow the tailoring of a material’s optical properties by manipulating its physical characteristics, Schubert said. “We are able to control the refractive index by changing its porosity or nanoporosity.”

As a result, coatings can be designed based on calculations. Finding the sweet spot that optimizes a multilayer coating can be challenging. To do that, researchers and developers may make use of genetic algorithms, which evolve a coating’s properties from a starting point to arrive at the best solution.

**Metamaterials and more**

Finally, new optical materials have appeared on the horizon. For instance, Dr. Withawat Withayachumnankul, a post-doctoral researcher at the University of Adelaide in Australia, was part of a team that etched cavities into the surface of slightly conductive silicon, as described in a 2013 *Advanced Optical Materials* paper. The resulting metamaterial trapped and confined terahertz waves in ways that offered some significant advantages, one of which was improved imaging contrast.

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thanks to minimal cross-coupling between each pixel, Withayachumnankul said.

“Moreover, since each optimized cavity can absorb nearly 100 percent of the incident power, the imaging contrast is improved further,” he added.

The next step in the research will be to form a complete imaging system by integrating a thermal detector to read out the temperature change when terahertz waves strike the cavity array. The technique has attracted commercial interest, Withayachumnankul said.

Metamaterials in general allow the engineering of properties and so could enable new applications, he added. An example might be an optical tunable flat lens that actively responds to incoming light with polarization changes.

Another way to make new optical materials is to grow them. A research team from New York University, Harvard University and Dow Chemical Co. revealed in a 2012 *Nature* paper a self-assembly technique based on small particles suspended within a fluid. Such colloidal manufacturing could be very inexpensive and suitable for fabricating materials on plastics or other flexible substrates that can’t tolerate high temperatures.

Dr. Vinothan Manoharan, a chemical engineering and physics professor at Harvard who was a member of the research team, is investigating the technique as a way to produce photonic inks – materials inspired by bird feathers that generate color through interference. Since light isn’t absorbed, photonic inks might retain their hue longer than traditional pigments. Also, this structure-based approach relies on ambient light, making photonic inks potentially useful in low-energy-consuming electronic displays.

At present, the colloid-created photonic inks can change color in response to changes in their chemical environment, although Manoharan noted that doing so electronically would be best for displays. Being researched is how to make photonic inks mimic the appearance of traditional pigments. Red, in particular, has proved difficult to achieve. In addition, because these colors depend upon diffraction and interference, another area of improvement is being researched.

“You also have to get a color that doesn’t change as you change the viewing angle,” Manoharan said.

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An illustration of annular cavities etched into the surface of conductive silicon. Depending on their dimensions, the cavities trap terahertz waves at different frequencies and enhance imaging. These and other metamaterials form the basis for new optical materials.
largements of monolithic Galileo telescopes are relatively small as a result of the limitation in center thickness. However, as these are afocal beam expansion systems, they can be connected in series to successively enlarge the incoming beam one after the other in the beam course (Figure 4).

This opens up new opportunities. Just three of these elements can enlarge the beam by eight times; five elements, 32 times. If only individual elements with $M = 2$ are used, the increments of the possible enlargements are very approximate at $M = 2, 4, 8, 16, 32 ...$. This is an optimal solution if one requires strong enlargement with minimal space used and a high wavefront quality.

If, however, finer increments between the enlargement levels are desired, it is necessary to introduce other individual element enlargements, which also lie very close together. Two lower levels are offered here at $M = 1.5$ and $M = 1.75$, especially for the version in glass. Because of the afocal dimensioning of the individual elements, the meniscus lenses can be oriented in the course of the beam however one likes, as shown in Figure 4c. This means, when combined, there are not only three but actually six individual element enlargements available, which significantly increases the combinatorics level. If, for instance, one element is available for each basic enlargement, this produces 13 possibilities for the overall enlargement with just these three meniscus lenses. If we push these combinatorics further with additional elements, an above-average number of combination options are opened up by certain lens groupings.

What is common to all these groups is the presence of one element each with $M = 1.5$ and $M = 1.75$ and an increasing number of elements with $M = 2$. Figure 4b shows an example of an overall enlargement of $M = 21$ consisting of five individual elements. Using the specific group shown there $(1 \times M = 1.5; 1 \times M = 1.75; 3 \times M = 2)$, it is possible to realize 62 enlargement levels with the maximum at $M = 21$.

In practice, to implement such an aspherical cascade system for flexible beam expansion, very high surface qualities for the individual elements are required. To prevent restrictions on combinatorics for later use, each individual element must be significantly better over the whole free aperture than the “diffraction limited” requirement (i.e., wavefront error RMS $< \lambda/14$). For a Ti:sapphire laser wavelength at 780 nm, for instance, RMS $< 55$ nm; for $\lambda = 532$ nm, it is even just RMS $< 32$ nm. If the center thickness and the decentration of the surfaces are also produced very precisely for these requirements, this system is adjustment-free. This means that the attachment of additional monolithic elements to change the enlargement level also takes place completely adjustment-free and is thus quick and easy.

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