

As optomechanics has emerged as a sub-discipline, new materials and techniques have come to the forefront.

New Solutions in Optomechanics

BY DANIEL VUKOBRATOVICH,
RAYTHEON CORP.



Optical engineers did not use the word optomechanics in 1980, when the first SPIE conference was held on this topic in San Diego, CA. Today, optomechanics has become a recognized part of optical engineering, with its own working group within the Society. The Tucson, AZ, division of my employer, Raytheon Corp., for example, devotes an entire 60-person department to the sub-discipline.

The growth of optomechanics was at least partially fostered by the publications, conferences, and short courses of SPIE. In particular, SPIE helped publicize and provide forums for discussing two important concepts in optomechanics: sub-cell lens mounting and the use of alternative materials such as silicon carbide. The technology associated with sub-cell mounting moved from idea to standard practice in high-performance aerospace applications in less than 15 years. Silicon carbide technology for mirror substrates is at the same

stage of development as sub-cell mounting was three decades ago. Designers are applying it in some systems, but it is not yet standard practice. As time passes, however, that should change.

New Methods in Mounting

Thirty years ago, G.E. Jones suggested a lens-mounting method that is now referred to as sub-cell mounting.¹ Six years later, Mete Bayer gave an analytical basis for most of the concepts used today in mounting lenses.² These two papers provide the foundation for the lens mounting methods used today in aerospace. Several optical engineers, including Paul Yoder, Jr., and me, have expanded on these ideas and spread them through SPIE short courses, conferences, and publications, helping optomechanical engineering grow.

The mounting methods introduced several decades ago dramatically improved both individual lens and optical system performance by reducing centering errors in assembly.

Sub-cell mounting takes advantage of the ability of modern manufacturing methods to make circular, cylindrical metal components. Much smaller tolerances of both absolute diameter and form are produced in metal cells than are possible in lenses; a roundness specification of 5 μm is not unusual in metal cell components, for example, while accomplishing the same tolerance for a glass lens is difficult and expensive. In sub-cell mounting, we center the lens within a cylindrical sub-cell, hold it in place with a compliant adhesive, and then press-fit the sub-cell into the lens barrel. This allows us to relax the centering tolerances on the lens while at the same time improving the centering accuracy of the lens optical axis with respect to that of the system. Centering accuracy in this type of assembly is usually comparable to the out-of-roundness errors in both the barrel and the sub-cell.

Jones pointed out that differences among the coefficients of thermal expansion (CTEs) of the lenses, sub-cells, and barrels introduced performance-degrading stresses in the optics. One of Bayer's contributions is the use of the relatively high-CTE adhesive around the lens as a compensator to reduce these thermal stresses. If properly designed, the radial thickness of the adhesive changes just enough to accommodate the change in the diameters of both the lens and the cell inner diameter as a result of temperature keeping the lens centered and in a zero-stress state.

Bayer gives an equation for the optimum radial adhesive thickness.² Controversy continues about the validity of this equation for the design of a zero-stress bond, centering around Poisson effects in the adhesive. Kirk Miller suggests that Poisson effects are not substantial due to the compliance of the adhesive, whereas Keith Doyle and his co-authors found that Bayer's original equation accurately predicts the required athermal radial bond thickness.^{3,4}

Regardless of the controversy, sub-cell mounting works and works well. It is now one of the most common methods used in the aerospace industry to mount lenses for high-performance applications. The technique is also used in mounting lenses for microlithography systems (see figure 1).

Despite success in high-end applications, sub-cell mounting is not applied in consumer applications such as digital cameras and cell phone cameras, primarily for reasons of cost and complexity. That situation may soon change. The centering tolerances required for digital imaging systems are reaching the limits of current manufacturing methods. Higher-speed lenses are needed to increase the range of acceptable illumination for digital photography. The tolerances required for such lenses cannot be achieved with current mounting methods, yet they are easily met with sub-cells. One challenge for the optomechanical engineering community is to find ways of moving the sub-cell mounting technology from high-cost, low-rate aerospace applications to low-cost, high-volume consumer products; there are, unfortunately, no SPIE publications on this...yet.

Beryllium Benefits

Another area of current interest in optomechanics is the development of new materials for lightweight mirrors. Many

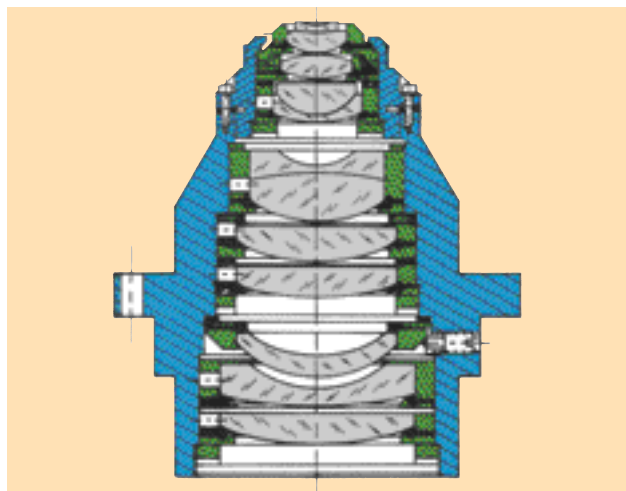


Figure 1 Mounting sub-cells (green) in the optical barrel (blue) enhances center-to-center alignment, as demonstrated in this UV laser scanner lens for a fluorescent microscope.

high-performance imaging systems used in mobile platforms ranging from ground vehicles to satellites incorporate mirrors. The primary mirror typically constitutes the largest mass in a reflective optical system, strongly influencing system weight. Weight is critical in many applications; for example, satellite launch costs are on the order of tens of thousands of dollars per kilogram delivered to orbit, so mirror weight is important in determining system cost.

The figure, ripple, and finish of a mirror determine optical performance. We associate figure under a variety of loading conditions with stiffness, which is a function of the weight of the mirror. Stiffness is related to the mechanical or natural frequency at which the mirror will ring when excited by a dynamic environment; this ringing affects shape and degrades optical performance. At a constant natural frequency, the weight of a solid mirror of diameter D made of any material varies as D^4 . Increasing the size of a mirror by just 10% increases the weight by a factor of almost 1.5, if natural frequency is kept the same.

Four design parameters influence mirror deflection (and therefore weight): support geometry, inverse specific stiffness, structural efficiency, and diameter. System optical requirements typically define size, so design usually concentrates on materials selection and lightweighting. Support geometry is often constrained by other aspects of the system and is difficult to change.

The inverse specific stiffness or ratio of density ρ to elastic modulus E of most common mirror materials is about the same; for example, the ρ/E value for aluminum and Pyrex are within 12% of each other (see figure 2). In other words, changing mirror material does not affect stiffness—with important exceptions.

One important exception is beryllium. The elastic modulus of beryllium is 1.5 times higher than that of steel, while the density of beryllium is comparable to that of magnesium. The inverse specific stiffness of beryllium is about 16% that of aluminum. Using beryllium as a mirror material therefore

provides phenomenal weight savings.

Unfortunately, there are problems with using beryllium in mirrors. The toxicity of beryllium is often perceived as a risk, although this hazard is minimal when appropriate industrial precautions are taken. The cost of beryllium is very high due to a complex manufacturing process and a limited number of suppliers.

These issues have fostered an interest in more economical alternatives. One of the strongest candidates is silicon carbide. Silicon carbide presents an inverse specific stiffness only slightly inferior to that of beryllium. In addition, it may be possible to make silicon-carbide mirrors in a shorter time, and at lower risk and cost than beryllium mirrors. There are, however, issues with the structural design, mounting, and current production cost of silicon-carbide mirrors.

The Silicon Carbide Alternative

A quick search of the SPIE publications database yielded 92 papers on silicon-carbide mirrors, which is a strong indication of current interest in the material. There are at least half a dozen companies in the United States alone working on silicon-carbide mirror technology, and strong interest exists within the U.S. government. One indication of progress with this technology is that some satellites are now operating with silicon-carbide components.

Today silicon-carbide mirrors often duplicate beryllium designs rather than exploiting the specific properties of the material. Fabrication for beryllium mirrors begins with a solid

beryllium in optical systems without increasing weight or lowering dynamic performance.

The mirrors must, of course, be mounted, which presents another challenge. Silicon carbide is a brittle ceramic that cannot suffer the stresses tolerated by metal mirrors. Surprisingly little work has been done on solving the mounting problem. This lack of development in mounting techniques suitable for dynamic or production environments increases risk in systems incorporating silicon-carbide optics.

Despite all of the interest, silicon-carbide mirrors remain the exception rather than the rule in production aerospace systems. The cost of the material is still surprisingly high. A 1990 study on mirror costs showed that silicon carbide was about twice as expensive as beryllium when used in mirrors, a situation that has not changed in the past 15 years.⁵ Lack of production orders, complex and labor-intensive manufacturing processes, and low yields are possible explanations for the continuing high cost. Despite the cost disparity, procurement times for silicon carbide are much shorter than those required for beryllium. Satellite systems require teams of expensive specialists; when mirror deliveries are late, these teams must still be kept together, increasing program costs. Shortening procurement times reduces program costs by minimizing the time needed for the specialist teams, so silicon-carbide optics may still be cost effective. More development of the systems aspects of silicon carbide, such as mounting interfaces, may reduce production cost, making this material attractive for a wider range of applications.

Thirty years ago, lenses were mounted by rule of thumb rather than by engineering design. Today, widely used methods such as sub-cell mounting greatly reduce risk while improving performance. Such advances have been fueled by the technical dialog enabled by conferences, publications, and short courses. This same dialog promises to enhance the development of silicon-carbide mirrors. The technology may or may not end up as standard practice, but the availability of an open forum to discuss it will greatly speed its development. As a side benefit, optical engineers will learn more—and just possibly get some enjoyment out of the process.

I know I have. **oe**

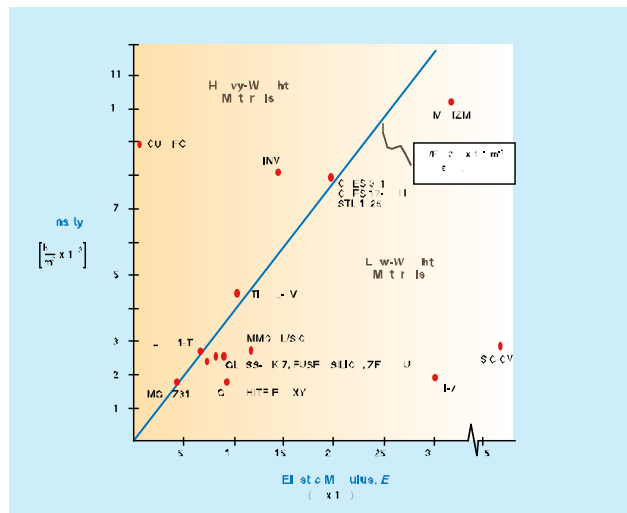


Figure 2 The inverse specific stiffness or ratio of density ρ to the elastic modulus E of most common mirror materials is roughly the same.

block of material, which is lightweighted by machining pockets in the back of the mirror. Although the resultant structure offers high stiffness at minimal weight, such open-back designs are relatively low in structural efficiency. The closed back or sandwich structures possible with silicon carbide yield much higher structural efficiencies, making it possible to obtain a natural frequency within about 5% of that of a beryllium mirror of identical weight. Thus, silicon carbide can replace

Daniel Vukobratovich is a senior professional engineer at Raytheon Missile Systems, in Tucson, AZ. Contact: 520-794-5746; 520-794-9531 (fax); dvukobratovich@comcast.net.



Author's Note

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