Submitted to the Optical Society of America's Frontiers in Optics 2011.
16-20 October 2011, San Jose, California.

Gas-fusion Mirrors for Atmospheric Lidar

Shane D. Mayor [1,*], Anna Petrova-Mayor [1], Richard W. Wortley [2], Daniel S. Hofstadter [3], Scott M. Spuler [4], and Jim Ranson [4]

[1]Department of Physics, California State University Chico, Chico CA 95929
[2]Hextek Corp., 1665 E. 18th St., Suite 208 Tucson, AZ 85719
[3]Hofstadter Analytical Services, L.L.C., 10 N. Norton Ave., Suite #120 Tucson, AZ 85719
[4]National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307-3000
**Author e-mail address: sdmayor@csuchico.edu*

Abstract: Design analysis and test results of two 610 × 432 × 57 mm (24 × 17 × 2.25 in) light-weighted octagonal mirrors and a mounting system for a scanning 1.54-micron wavelength elastic backscatter lidar will be presented. The mirrors were designed to replace damaged gold-coated Zerodur mirrors and fit inside an existing mechanical scanner structure also known as a beam steering unit. Finite element analysis was performed to confirm that the design would meet the required flatness of 3 He:Ne (633 nm) laser wavelengths over the clear aperture. The mirrors were fabricated through a gas-fusion process for weight reduction and flexure stage mounts were designed to compensate for differences in the coefficient of thermal expansion of the borosilicate glass mirrors and aluminum enclosure. Enhanced aluminum coatings will be applied for high reflectivity at 1.54 microns wavelength and durability. Engineering design analysis results, including measurements of the polarization characteristics of the mirror coatings, will be described and field results from a whole system test of the lidar using the new mirrors will be presented.
OCIS codes: (120.4880) Optomechanics; (280.3640) Lidar; (230.4040) Mirrors; (310.5448) Polarization

1. Background

Spuler and Mayor [1] demonstrated a pair of flat lidar beam steering unit (BSU) mirrors that weigh 20% of a traditional solid-glass solution. The design was used in two field-transportable lidar systems [2, 3] and reproduced in several commercially available lidars [4]. The design used protected gold-coated substrates of 25.4 mm (1in) thick Zerodur that were bonded to 50.8 mm (2 in) thick aluminum honeycomb panels (Teklam A520C) with silicone adhesive (GE 167 RTV). Each aluminum honeycomb panel was fastened directly to the aluminum enclosure of the BSU in a 15 point grid. Although the design has been generally reliable in field operation, the fabrication process does not follow industry standard manufacturing practices. Specifically, the use of silicone adhesive as the sole mechanism for holding the mirror in place is undesirable because the mechanical properties of the adhesive required for analysis are not easily measured and can be difficult to obtain or unreliable. Use of silicone also makes removal of the mirrors for servicing a difficult and time-consuming process.

In the spring of 2010, the protected gold coatings of the pair of mirrors described by Spuler and Mayor and used in the National Science Foundation (NSF) Raman-shifted Eye-safe Aerosol Lidar (REAL) were damaged by the application of a commercially available spray-on/peel-off cleaning product. Rather than to sever the Zerodur substrates from the honeycomb panels, strip the damaged coatings, recoat, re-bond, and hope to meet the required flatness specification, it was decided to procure commercially available new mirrors that avoid the difficulties and uncertainties associated with the Spuler and Mayor solution. This paper describes some of the challenges associated with mounting such mirrors. Fabrication of the new mirrors is expected to begin soon after the time of this writing. Integration and field testing of the mirrors in the NSF REAL lidar system is expected to be conducted during the summer of 2011. In addition to engineering analysis results, we plan to investigate the polarizing effects of the mirror coatings due to the importance of polarization purity in some lidar experiments [2]. The final presentation will also show field results using the new mirrors.

2. Mirrors

The flatness requirement for the mirrors is 3 wavelengths (peak-to-valley at 633 nm wavelength) over the clear aperture. This was determined by Spuler and Mayor [1] by use of a ray-tracing model that included all optical components in the lidar receiver subsystem including a 200-micron photo-detector active area. A new pair of mirrors (see Fig. 1) and flexure mounting system (see Fig. 2) was designed by Hextek Corp. and Hofstadter Analytical Services, LLC. The new mirrors and mounting system were designed to match the dimensions and weights of the old mirror and mounting system (610 × 432 × 57 mm and 15.5 kg each) so that the mechanical structure of the BSU will not have to be modified significantly. The mirrors must meet the same 3-waves flatness requirement and be coated with a durable enhanced aluminum coating for high reflectivity at the lidar wavelength of 1.54 microns. The 3-waves flatness specification is not difficult to achieve, but the BSU enclosure that the mirrors will be installed in is constantly exposed to outdoor weather conditions and undergoes periodic accelerations during operation. Therefore, a finite element model was developed and an analysis was performed to evaluate the proposed mirror and mounting solution. Angular velocity data from operation of the BSU was used in the analysis. Fortunately, the mirrors are used for laser transmission and detection only during periods of constant angular velocity (in other words, during a scan but not during accelerations before and after each scan), so any front surface distortions caused by periods of strong accelerations between scans are not expected to present a problem.

3. Flexure stages

A primary challenge was to design a mounting system that minimizes the stress that would otherwise be imparted on the mirror when changes in temperature occur. As outdoor weather conditions change, the temperature of the aluminum BSU enclosure will change. The BSU enclosure is the mechanical support for the mirror mounts. Aluminum has a substantially larger coefficient of thermal expansion (CTE, 23.6 × 10^{-6} per ^{o}C) than that of borosilicate glass (3.5 x 10^{-6} per ^{o}C) which the gas-fusion mirrors will be made from. Therefore, the mounting system must allow for differential contraction and expansion while holding the mirrors securely.

To address this challenge, three 66 mm (2.6 in) diameter Invar or Kovar pucks will be bonded to the back of each mirror with Dow Corning Q3-6093 adhesive. The CTE of each puck will be matched as closely as possible to that of borosilicate glass. Each puck will have 6 tapped holes for mounting the 43.2 mm (1.7 in) long flexure stage. Each flexure stage resembles an I-beam and will be made from 303 stainless steel (CTE of 17.2 × 10^{-6} per ^{o}C). The height of a flexure stage will be 28.6 mm (1.125 inches) and the width 31.75 (1.25 inches). The three pucks and flexure stages will be attached to the back of the mirror with their softest axes facing the center of the mirror. The total thickness of the mirror, puck and flexure stage will exceed that of the 76.2 mm thickness of the Spuler and Mayor design by approximately 19 mm. Therefore, 66 mm diameter holes will be cut in the BSU enclosure and cups installed to accommodate the extra thickness of the new assembly in these regions.

4. Model Analysis Results

A review of BSU scan angle data shows some excitement of resonant enclosure modes, however all predicted mirror/flexure modes are well above 100 Hz. This is critical to avoid resonances and excitation of the mirrors. Finite element analysis shows as much as 0.5 mm of front surface displacement due to flexing of the enclosure. We have not carefully compared this to other factors that influence lidar pointing accuracy, but it is thought to be relatively small and unimportant as the lidar facility is on a trailer that is likely to tip and tilt more due to other factors such as wind load, soil compaction, and shifting internal loads (i.e. movement of personnel inside).

The most important result is the determination of the deformation of the mirror front surface caused by stress imparted by the mounting system and the weight of the mirror itself. The finite element analysis indicates that the largest deviations from a perfect plane are on the order of 1 micron or less and are within the flatness requirement of 3 waves (3 × 0.63 microns = 1.89 microns).

The largest uncertainty in our analysis is the result of using adhesive to bond the pucks to the back of the mirror. The finite element model neglected the compliant nature of adhesive and used a rigid connection between the puck and the glass. This resulted in localized mirror stresses approaching 5 MPa with a 10^{o}C temperature change and small puck area. Preliminary calculations indicate that compliance of the Q3-6093 adhesive will reduce this local stress significantly, and that peak stresses in the glass due to differential thermal expansion should remain below approximately 1 MPa. Therefore, temperature changes of 30^{o}C to 40^{o}C from the assembly temperature should be acceptable.

5. Polarization

We will also report on how the BSU mirrors, when used together in the BSU, change the state of polarization (SOP) of the laser beam. This will be done by constructing a miniature BSU in the lab from a cage system and pairs of rotary stages, right-angle mirror mounts, and 25.4 mm (1 in) diameter mirror witness samples. A linearly polarized CW beam at 1.54 microns wavelength from a fiber-coupled DFB laser and a polarimeter will be used to map the SOP for combinations of BSU azimuth and elevation angles.

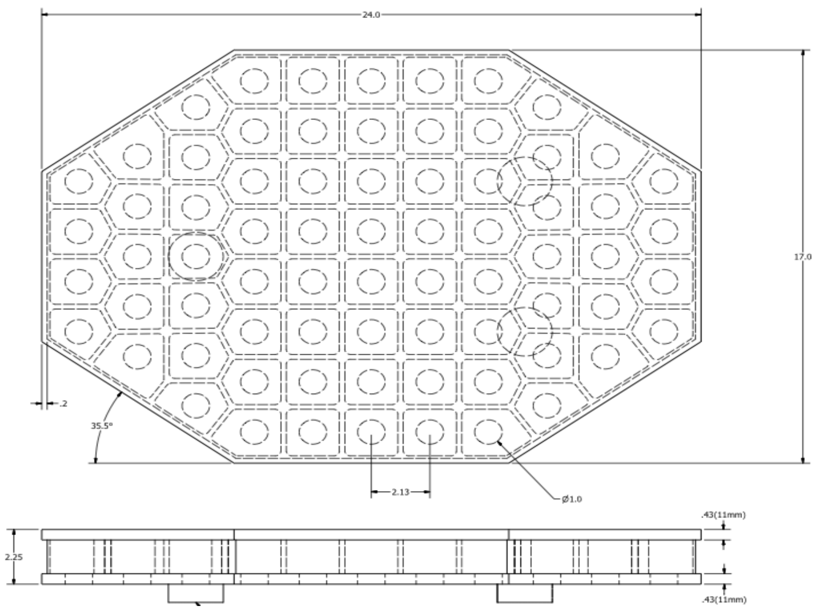

Fig. 1. Preliminary design of a light-weighted mirror that will be fabricated by a gas-fusion process at Hextek Corp. Final design will have tapered thickness on the left and right ends.

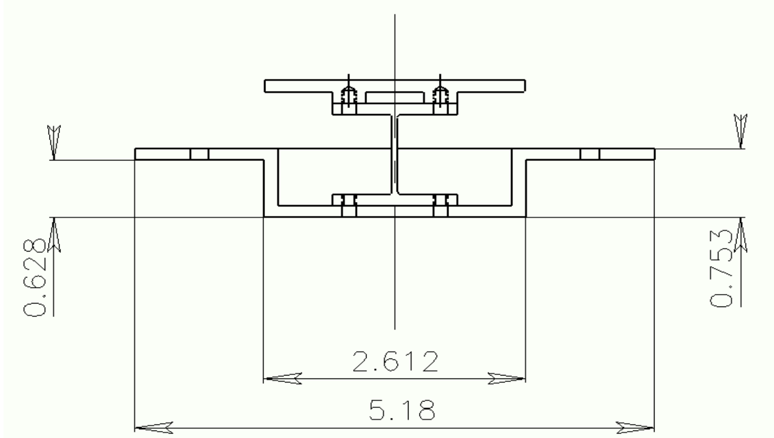

Fig. 2. Cross-section of a puck (top part), flexure stage (middle part that is shaped like an I-beam), and cup (bottom part) that will be used to hold the gas-fusion mirrors in place. Three such assemblies will be employed with the soft-axis of each directed at the center of the mirror.

6. Acknowledgments

This project was supported by NSF AGS RAPID-Award 1104342.

7. References

[1] Spuler, S. M. and S. D. Mayor, "Scanning Eye-safe Elastic Backscatter Lidar at 1.54 microns," J. Atmos. Ocean. Technol. **22**, 696-703 (2005)

[2] Mayor, S. D., S. M. Spuler, B. M. Morley, and E. Loew, "Polarization lidar at 1.54-microns and observations of plumes from aerosol generators," Opt. Eng. **46**, 096201, (2007)

[3] Radlach, M, A. Behrendt, and V. Wulfmeyer, "Scanning rotational Raman lidar at 355 nm for the measurement of tropospheric temperature fields," Atmos. Chem. Phys. **8**, 159-169, (2008)

[4] Mayor, S. D., P. Benda, C. Murata and R. J. Danzig, "Lidars: A key component of urban biodefense," Biosecur. Bioterror. **6**, 45-56, (2008)