Design, fabrication, and testing of micro-optical sensors containing multiple aspheres

S. Rajic, C.M. Egert, B.M. Evans III, J.P. Cunningham, T.A. Marlar

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Oak Ridge National Laboratory
P.O. Box 2009, MS-8039
Oak Ridge, TN 37831

Prepared by the
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831
managed by
Martin Marietta Energy Systems, Inc.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400

ABSTRACT

The micro-sensor field is presently proliferating with designs and approaches. We have developed a micro-spectrometer for sensing application containing five precision surfaces, including two off-axis aspheres. The entire monolith is less than six cubic centimeters in volume. This particular design contains a bandwidth of about 1 micrometer which is centered at 980 nm. Once an appropriate starting substrate was produced, the entire system was diamond turned to maintain the required surface figure, inter-surface spacing, and surface tilts. Only three diamond turned fixtures were needed to produce the monolith. The results proved to be more than adequate for many sensing applications. Slightly altered designs could easily be produced containing different bandwidths and resolutions as needed by the customer. Due to the spectrum of interest and the fabrication method, PMMA was the material chosen for this sensor. Other designs configurations incorporating BK7 and sapphire are presently being studied.

1. INTRODUCTION

The design of the this sensor was very challenging due to the ambitious properties that were desired and the fabrication limitations that were available. The final design was a modified Czerny-Turner configuration containing five precision surfaces encapsulated in a monolithic structure. We were interested in exploring novel system designs, fabrication technologies, and examining numerous material systems, in the development of the micro-spectrometer. Our purpose at the early stages was to demonstrate the feasibility of the technology and not an attempt to address a specific sensing problem. Thus, we had great liberty to select the first prototype material, which is usually application specific. The first substrate material chosen was optical quality polymethyl methacrylate (PMMA). The principal names for this type of material are Acrylic and Plexiglass.

2. DESIGN

Many starting designs were initially examined for the demonstration of this micro-sensor.¹ The final system design decision was eventually narrowed down to two possible configurations containing five and six precision surfaces which are shown respectively in figures 1a and 1b. The design shown in figure 1a was chosen for development. This five surface design was chosen since it contained one less precision optical surface, yet included multiple off-axis aspheres. Although the alternate design had greater linear dispersion, due to a longer focal length, the difficulty of fabricating an additional surface could not be justified in this technology demonstrator. This is especially true since the six surface design contained a folded optical path such that scatter / optical homogeneity became much more important. Among the many and often conflicting design goals, the physical parameters were assigned particular importance. The overall volume was targeted at less than 6 cm³. This requirement was met with the extreme dimensions consisting of 2.4 cm X 1.9 cm X 1.2 cm. In this particular design, and material system, the mass was kept below 7 g. The wavelength range (bandpass) design goal was 1 μ m (0.6 μ m - 1.6 μ m). The PMMA is particularly transparent in this wavelength region and there are interesting effects to monitor within this band. The optical system was designed and optimized using the ZEMAX Optical Design software program to be entirely alignment free (self-aligning).²

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Figure 1. (a) Micro-spectrometer optical system layout for final design. (b) Alternate design with higher resolution but an additional optical surface.

The entrance aperture consists of an optical fiber input. This fiber is positioned directly on the entrance surface at a specific location on that plane relative to the other four precision surfaces. The numerical aperture (NA) of the input fiber must be large enough to fill the useful portion of the collimating surface (first off-axis parabola). In this design the NA of this 62.5 μm core diameter fiber was 0.275 ($\sim 16^\circ$ half angle). This core diameter represents the spectrometer entrance slit width and is not variable as in most laboratory sized instruments. The collimating surface redirects the light energy toward the grating with a focus at infinity. The light impinging on the grating arrives at a specific angle and with a collimated diameter of approximately 6mm. The grating in this design is a 300 lines / mm flat surface operating in the -1 order. The grating surface disperses the incident light toward the focusing surface (second off-axis parabola). The light at this point is diverging from the approximately 6mm diameter beam that impinged onto the grating. Thus the useful area of the focusing surface is the largest of the five precision surfaces at approximately a diameter of 10 mm. The focusing surface intercepts the diverging cone of light and focuses it onto the image surface. A linear detector array is then attached directly to this image surface.

The tolerances on the angles and spaces between these five precision surfaces were very challenging to maintain. However since a state-of-the-art diamond turning machine was used for the fabrication process, coordinates locations were achieved that met the required tolerances. The specification on surface figure was < 0.1 waves @ 632.8 nm. Although this requirement appears very stringent for an off-axis asphere, the full parent surfaces were generated in an uninterrupted single cut. The parent surfaces and useful clear apertures are shown in figure 2. The surface finish requirement was < 50 $\text{\AA}$ rms. The mechanical tolerances of intersurface tilt and despace were ± 0.3 mRad and ± 5 μm , respectively. This sensor was designed around readily available high power light sources. Since this was a prototype demonstration, the freedom to choose the wavelength range simplified that aspect of the optical design. The laser diodes chosen for calibration were 0.635 μm , 0.780 μm , 0.850 μm , 0.980 μm , 1.310 μm , and 1.550 μm . Miniature tungsten-halogen broadband, and mercury-argon calibration, sources were also used in the testing phase.

Figure 2. Optical layout with full parent surfaces included.

The bulk of the optical design effort centered on minimizing the focused spot size across the entire wavelength bandpass. Figure 3 illustrates the spot diagram for the final design for all six laser diode wavelengths.

Figure 3. Spot diagram for all six laser wavelengths.

Since the linear detector array lays along a vertical line connecting the spot diagrams for all six wavelengths, the horizontal spectral spreading is of no significance. A compromise focus was chosen for performance optimization across the detector array. This is evident from figure 4 which shows an expanded view of the individual spot diagram for the $0.980 \mu\text{m}$ laser. However, to maximize

performance across the spectrum this particular prescription was selected. Since typical detector arrays have pixel sizes ranging from $\sim 15 \mu\text{m}$ to $50 \mu\text{m}$ in length, we see that at most one to two pixels will be illuminated in this case. Thus achieving diffraction limited performance may not be required in all applications.

Figure 4. Spot diagram at $0.980 \mu\text{m}$ shows essentially single pixel illumination.

Once the optical prescription was finalized, a monolithic mechanical design was needed to encompass the internal light path. The design was optimized for minimum size. The relationship between the optical and mechanical designs is evident from figure 5. The five precision surfaces are labeled as in figure 1.

Figure 5. Micro-spectrometer mechanical design.

The mechanical design was accomplished using the Pro Engineer software package. This design tool was a great aid in linking the optical design to the fabrication process. This was particularly important since the diamond turning machine required global coordinates.

3. FABRICATION

The fabrication technique that was developed is particularly applicable to the manufacture of monolithic optical components and systems.³ The entire fabrication process including; fabrication engineering, rough machining, diamond turning, fixture fabrication, assembly, and coating, was performed at the Oak Ridge National Laboratory (ORNL).

The basis of the manufacturing process for this monolithic system consisted of a spherical surface, centered at the intersection of the major component optical axes and a wedge whose planes pass through the center of the sphere normal to the optical axes of the major optical surfaces. The use of the combination of a sphere and a wedge allowed the machining of an optical surface into the sphere. The substrate sphere was then tilted on its other wedge-shaped base. The part was again centered using the sphere as a reference. It was then possible to very precisely locate another optical surface with respect to the first surface since an effective tool centering technique had been used.⁴

This particular optical system consisted of two off-axis parabolic surfaces and three flat surfaces. However, this technique could be used to locate other combinations and numbers of surfaces. Ordinarily the manufacture of such a high quality optical device, absent the inclusion of multiple adjustments for each of the elements surfaces, would be extremely difficult without the use of the technique developed at ORNL.⁵

The first step of this process consisted of determining the intersection of the major optical axes and the selection of an appropriate spherical surface which contained these surfaces. A spherical surface was chosen which was slightly larger than the two parabolas that were designed. The center of the sphere occurred at the intersection of the axes of the two parabolas. In this instance, a cylindrical disc with a wedge machined into it was used as the starting substrate, Figure 7. The flat surfaces of the wedge were manufactured normal to the axes of the parabola and passed through the center of the sphere. The flat surfaces were used to mount the substrate on the diamond turning machine. The intersection of the axes of the two parabolas passed through the corner of the wedge, however the foci of the two parabolas were not necessarily at this point.

Figure 7. Cylinder with flycut wedge.

The next step of the process was to mount the cylinder on a high precision diamond turning machine with on-board metrology. Care was taken to ensure that the cylinder was mounted such that its axis coincided with the turning machine's center of rotation, and that the corner of the wedge passed through the center of rotation. In this process the diamond turning machine was used as a coordinate measuring

machine (CMM), and the cylinder was probed using a ruby-tipped, air-bearing, linear variable differential transformer (LVDT) while the cylinder was mounted on the machine. A cutting pass was made on the cylinder to bring the center of the wedge in line with the center of the cylinder to the accuracy of the diamond turning machine. The accuracy of the angle cut in the wedge was also verified during this step using the LVDT.

The next step of the process was the machining of the alignment sphere, the reference flat, cylinder, and the first parabola. These surfaces were all fabricated in the same machine setup, so that they would be positioned very accurately with respect to each other. The purpose of the flat and the cylinder was to provide reference surfaces for the machining of optical surfaces on the face of the substrate opposite the spherical surface and parabolas. The reference flat and cylinder provided an accurate reference for locating the center of the first optical surface and linear distances from this surface in subsequent steps. Figure 8 shows how the substrate appeared after this step.

Figure 8. Substrate after machining the sphere, reference flat, and optical surface 1

After the machining of the wedge, sphere and first optical surface (parabola), the second optical surface (parabola) was easily and precisely manufactured and located. The wedge was simply tilted on the vacuum mounting fixture and mounted on its other face. The previously manufactured sphere was used to align the center of the sphere/substrate with the center of rotation of the diamond turning machine via probing techniques which made use of circular sections of the sphere. Once the spherical substrate was mounted in position for cutting the second optical surface, the sphere was centered on the center of rotation of the machine. The second optical surface was manufactured with ease to the accuracy of the machine with very little error induced due to fixturing or setup changes, as shown in figure 9. It should be noted that only off-axis sections of the optical surfaces were needed. Thus it was desirable to have reference surfaces, associated with the optical surfaces, machined into the back of the substrate. These reference surfaces would often protrude through portions of other optical surfaces. However, this was designed to occur only through portions of the substrate not needed by the optical prescription.

Figure 9. Spherical substrate with two optical surfaces machined and two reference surfaces machined.

The next step of the manufacturing process involved removal of the substrate from the mounting fixture so that three additional optical surfaces could be machined on the opposite side. In order to have the remaining surfaces machined, cylindrical fixtures were used to mount the substrate using the reference flats and cylinders machined during the previous steps. The design next required that three flats be manufactured opposing the parabolas. The geometry subsequent to this step is shown in Figure 10.

Figure 10. Substrate with both parabolas and one flat machined.

The substrate was easily centered by first centering a cylindrical fixture, and then mounting the substrate's cylindrical surface inside this fixture. Distances relative to the previously machined optics were readily known using the flats and cylinders machined during the previous steps. The next required step was a flat surface offset a certain distance from the first machined parabola. This flat was perpendicular to the axis of its associated parabola and was accurately centered on the axis of the first parabola. The fixture used in this step is shown in Figure 11.

Figure 11. Substrate shown in fixture prepared for machining of additional optical surfaces.

An additional flat surface was required to be machined. It represented the entrance surface of the system. This surface was perpendicular to the axis of the second machined parabola, and it was offset a known distance. The same cylindrical fixture was used for this surface as was used for the previous optical surface. This feature is shown in Figure 12.

Figure 12. Substrate with two parabolic and flat surfaces precisely located with respect to each other.

The remaining step was an addition of a flat that was not perpendicular to any of the features previously machined. This optical surface was diamond turned in an off-axis tilted fixture. The back edge of the substrate consisted of a horizontal line which remained from the original wedge feature and was used as a reference to ensure that the substrate was in the proper angular orientation or "clocking". This edge was also probed and used to determine the proper depth of cut when this surface was machined. Figure 13 gives a view of the features present at that stage, and Figure 14 shows the fixturing configuration.

Figure 13. Substrate with five optical surfaces precisely located and aligned with respect to each other.

Figure 14. Substrate shown mounted in the tilted fixture for machining of the off-axis tilted surface.

4. TESTING

The testing phase of this project did not prove to be trivial. The micro-spectrometer was immediately subjected to qualitative tests after the initial fabrication process was complete. Light was injected into the entrance plane by means of an optical fiber. A visible wavelength was used to aid in the alignment process. However since this was a monolithic structure, with all optical surfaces predefined, only the input fiber and the detector array required alignment. A simple translucent white card was used to identify the image surface as the focal plane of the system. The different orders of the injected visible source were brought to a very sharp focus at the image surface as required. This quick test verified that the system contained no gross errors in either the design or fabrication phases. Thus the system was performing as a spectrometer although it had not yet been cut out of its surround.

Some of the system requirements were difficult to measure directly. For this reason system signal / noise was not specified explicitly. Since scattered light energy from all the internal surfaces contributes to the noise of the system the surface finish, which is directly related to scatter, was specified instead. This parameter, as well as surface figure, were readily accessible to physical measurement with both interferometer profilometers.⁵ Since all of the precision diamond turning was performed on the Nanoform 600 machine, the measured values of $\sim 50 \text{ \AA}$ rms met our specification as expected.⁶

Since this was a totally new spectrometric device, calibration was pursued soon after reasonable signals were detected. The calibration was accomplished with multiple laser diodes. The diodes were first analyzed through a more conventional spectrometer with greater resolution. Then the same signals were introduced into the micro-spectrometer and compared. Data was first taken before the device was separated from its fabrication surround. The results showed a higher than expected noise floor due to the presence of fabrication "dummy surfaces" that were not in the optical design. However, reasonable signals were achieved. After the device was separated from its surround the noise level was reduced substantially. Finally the device was blackened on all its rough machined non-optical surfaces and the desired results were achieved. The wavelengths used thus far for calibration, and shown below in figures 15 a,b and 16 a,b were; 635nm, 780nm, 850nm, and 980nm.

Figure 15 (a) 635 nm laser signal. (b) 780 nm laser signal.

Figure 16 (a) 850 nm laser signal. (b) 980 nm laser signal.

Evident from figure 15 are the second order spectra associated the 635 nm and 780 nm calibrating laser signals. This was due to the use of an oversized linear detector array containing 1024 pixels. Although for calibration purposes this can be advantageous, if more than a single wavelength is used the results can be confusing. The 850 nm laser in figure 16 also shows the beginnings of a second order signal. However the detector runs out of useful pixels before anything more than a small tail is seen. The 980 nm signal shows no signs of second order signals as expected.

5. CONCLUSIONS

It now appears clear that ultra-precision monolithic sensors, such as a micro-spectrometer, can be successfully fabricated. The prototype system that has been demonstrated can now serve as the basis for low cost production techniques involving mold fabrication. This would include both the Sol-Gel technique, which can produce silica systems, as well as traditional plastic injection molding. The system was designed for a linear dispersion of ~ 200 nm/mm. However a design has been shown that, with the addition of a single flat surface, will produce a system with linear dispersion between 75-100 nm/mm. This is typically sufficient for low / medium resolution sensor applications and would be tailored to the specific applications as required. The detailed analysis of the micro-spectrometer performance will be ongoing. The already identified applications include, emission mode laser warning receiver, transmission mode chemical / environmental detector, and a reflection mode corrosion monitor.

6. ACKNOWLEDGEMENTS

The authors would like to thank Brian Tiffany, Bill Lawrence, James Stiegler, Kathy Thomas and Roland Seals for their assistance and valuable discussions on this program. This work was sponsored by the laboratory directors research and development (LDRD) fund within the Oak Ridge National Laboratory (ORNL). ORNL is managed by Lockheed Martin Energy Systems for the U.S. Department of Energy under contract no. DE-AC05-84OR21400.

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