DEMONSTRATION OF A MONOLITHIC MICRO-SPECTROMETER SYSTEM

S. Rajic and C.M. Egert

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

-1139

INTRODUCTION

The starting design of our spectrometer was based on 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).

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 cm^3. 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 μm (0.6 μm - 1.6 μm). 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]

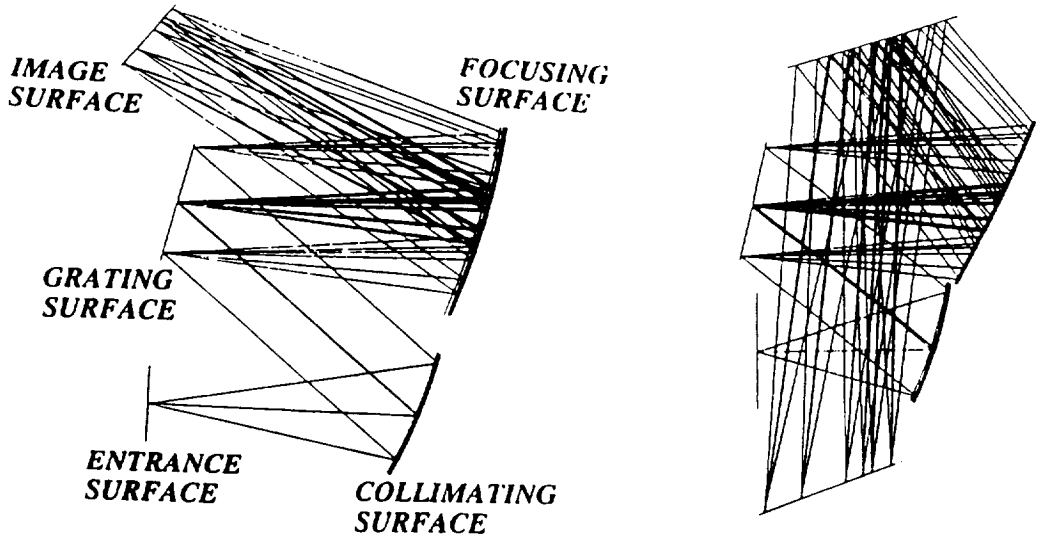

Figure 1. (a) Micro-spectrometer system layout of prototype. (b) Alternate design with higher resolution.

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 (~16^0 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 å 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.

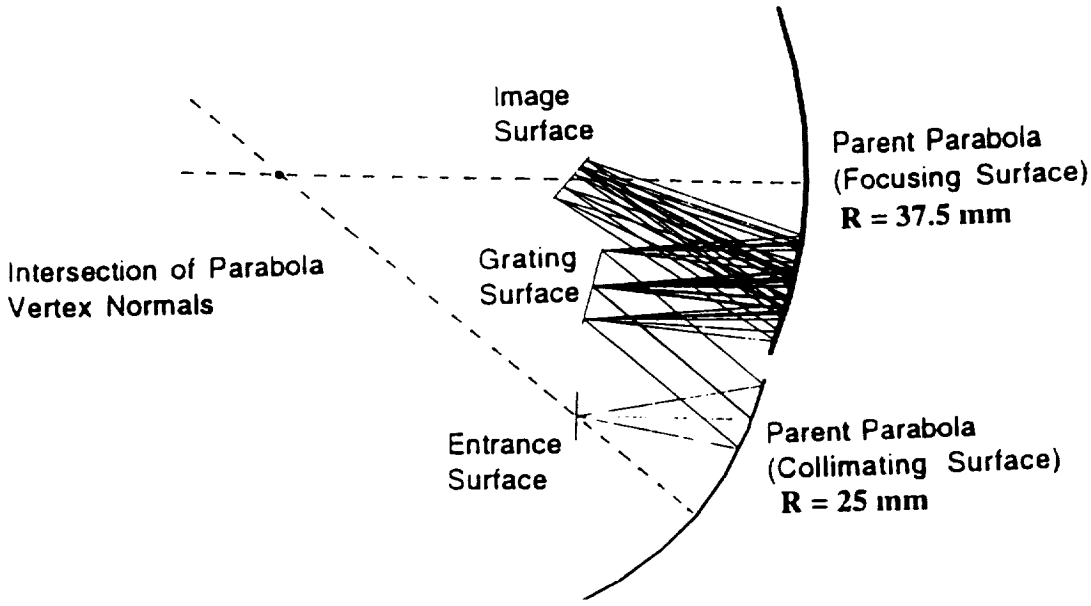

Figure 2. Optical layout with full parent surfaces included.

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.

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 μm laser. However, to maximize performance across the spectrum this particular prescription was selected. Since typical detector arrays have pixel sizes

ranging from ~ 15 μm to 50 um 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.

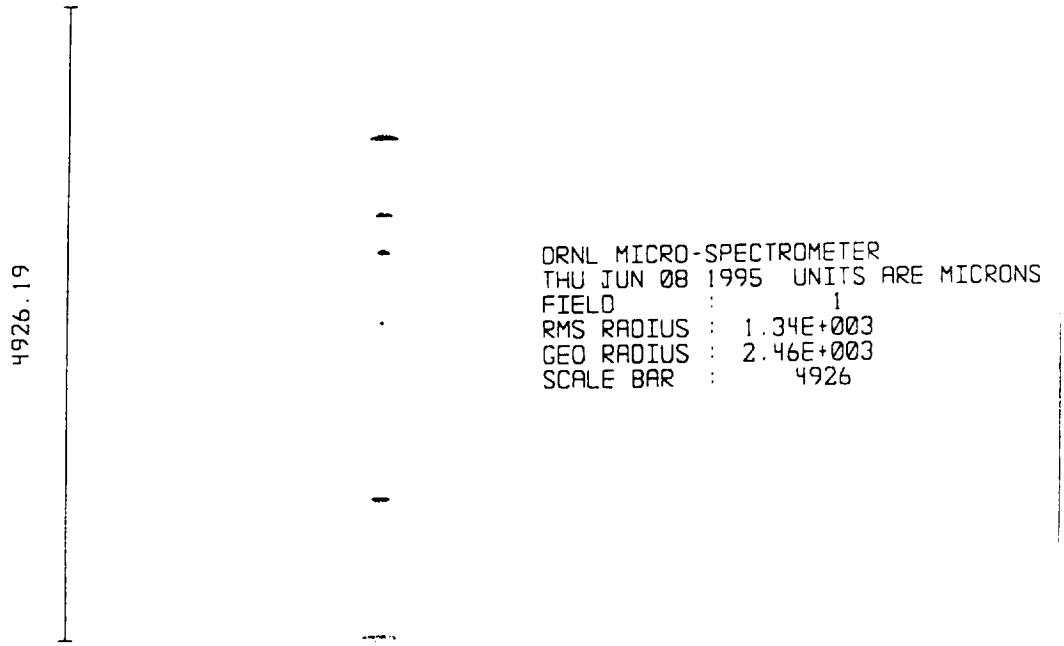

Figure 3. Spot diagram for all six laser wavelengths.

Figure 4. Spot diagram at 0.980 μm 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.

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.

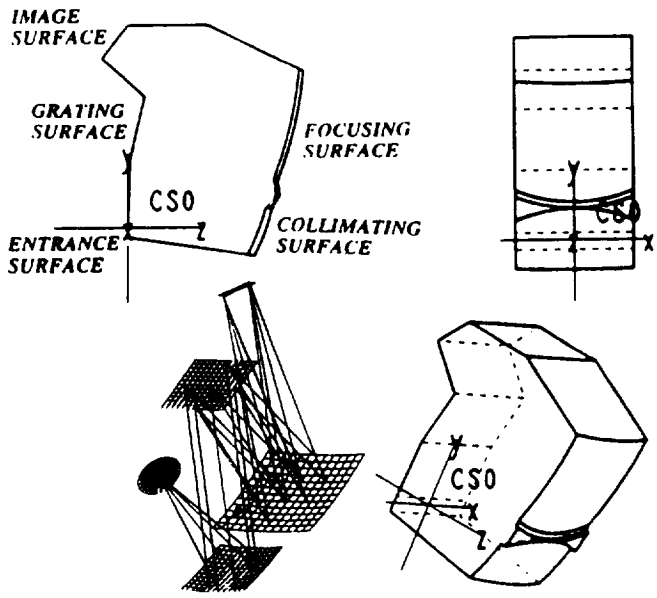

Figure 5. Micro-spectrometer mechanical design.

3. FABRICATION

The fabrication technique that was developed is particularly applicable to the manufacture of monolithic optical components and systems. 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). All of the diamond-turning was performed on the Nanoform 600 machine. The six major diamond-turning operations are shown in figure 6.

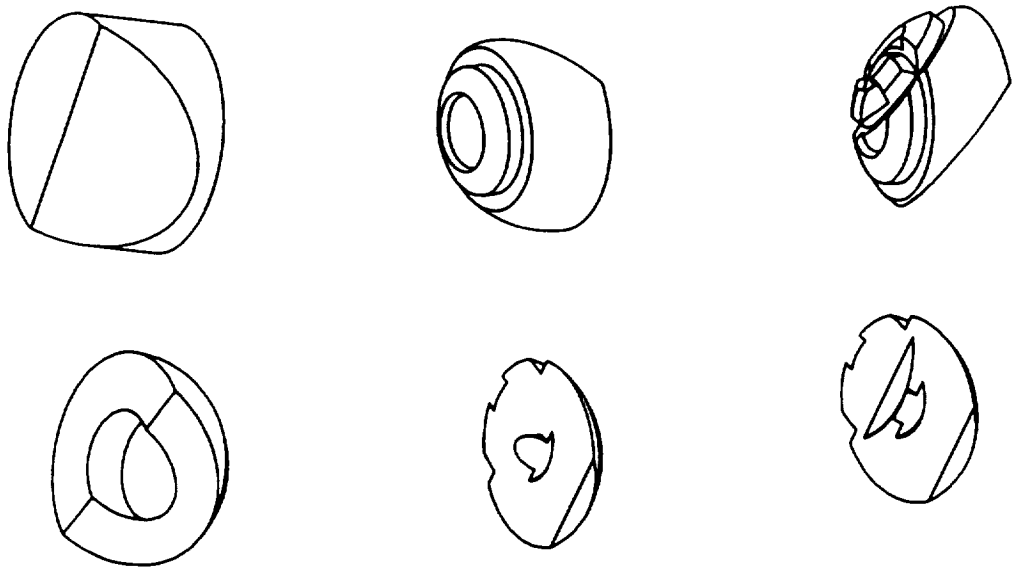

Figure 6. Fabrication steps.

TESTING

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 a 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 interferometers and profilometers.[3] Since all of the precision diamond turning was preformed on the Nanoform 600 machine, the measured values of ~ 50 å rms met our specification as expected.[4]

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 were; 635nm, 780nm, 850nm, and 980nm.

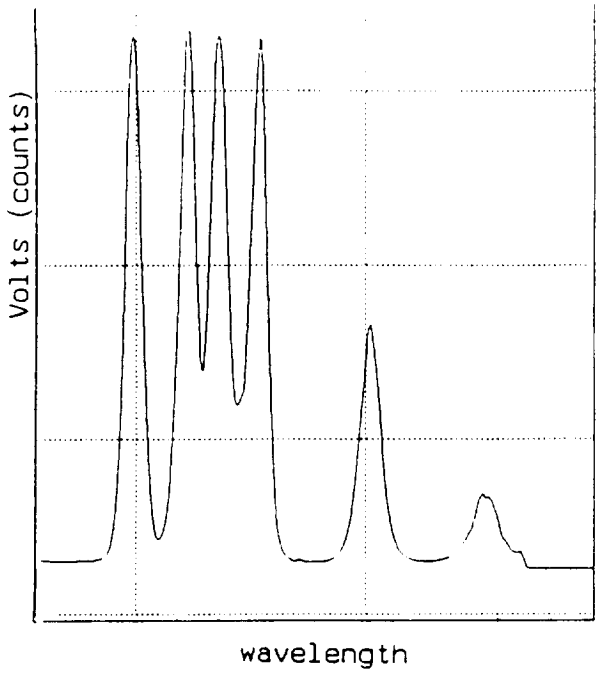

Figure 7. Calibration laser diodes 635nm to 980nm.

Evident from figure 7 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.

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.

ACKNOWLEDGEMENTS

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