Design and fabrication issues in the development of monolithic micro-optical systems

S. Rajic and C.M. Egert

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

"The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. DE-AC05-96OR22464. Accordingly, the U.S. Government retains a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes."

RECEIVED
OCT 27 1997
OSTI

19980219 098

ABSTRACT

The micro-sensor field is presently proliferating with various designs and approaches. We have recently been involved with several mini/micro optical systems which have pointed out several trends in design and fabrication that are somewhat more important to these smaller optical systems. These include: material choices, alignment strategies, fabrication methods, and freedom and complexity of the optical designs. Our recent experience indicates that since mini/micro optical systems are likely to be produced in much higher number, that traditional fabrication methods could prove exorbitantly expensive. Deterministic fabrication methods employing inherently self-aligning features are well worth investigating. This is particularly true for monolithic systems that fall into that "grey" area between mini and truly micro optical systems. This forum will allow the examination of three such recent systems with respect to design and fabrication.

Keywords: micro-optics, mini-optics, monolith, self-aligning, deterministic fabrication

1. INTRODUCTION

Micro systems that are of a size, and simplicity, to be completely fabricated by photolithographic techniques fall outside the scope of this paper. These systems are most likely already deterministically fabricated, inherently self-aligned and athermalized, particularly if they are not hybrid configurations. However they are typically limited in design freedom and restricted to mostly planar geometry. This paper will concentrate on electro-optical systems generally in the 0.5 to 15 cubic centimeter range. Three recent systems will be briefly described from which the "lessons learned" information was extracted regarding figure, finish, and intercomponent tip, tilt and despace requirements. These include: a laser threat protection system, a micro-spectrometer, and a laser warning receiver.

2. DESIGN EXAMPLE 1

The laser threat protection system was developed for protecting sensors and human eyes from battlefield laser threats¹. Although the practical laser power levels to date do not threaten the mechanical integrity of military equipment, they are sufficiently energetic to damage sensors and unprotected human eyes. While an elegant solution to the agile spectral threats may become available around the turn of the century, a practical near term solution was needed. A system employing a sacrificial mirror element can fulfill the requirements for both broadband spectral protection and near-term availability. The technique involves utilizing a reflective optical system containing a sacrificial component that can act quickly enough to defeat ultra-short pulse length lasers. However, below a certain damage threshold the system level transmission

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

can be quite high. Typically, a very stringent requirement for directed energy protection systems is a tightly focused spot size. This requirement typically requires precision manual alignment, which can be negated with the use of a self-aligning design.

It became obvious during early tests that precise and stable alignment was required to successfully protect against all threat levels. Low energy threats are the most difficult to attenuate since they lack sufficient energy to destroy the sacrificial element quickly and completely. Thus, alignment in this case was very crucial since the viewing and threat beam locations on the sacrificial element must be coincident if the element is not completely destroyed. In addition, since broadband protection was required, a refractive design was rejected in favor of an inherently achromatic system. The design chosen for the first prototype employed an all reflective, single point diamond turned (SPDT), self-aligning concept.

The system depicted in Figure 1 was designed so that incident energy above the protection design limit would be sufficient to damage and penetrate the mirror. Since this is not an instantaneous process, a delay is required before the energy is directed toward the observer. The incoming threat beam is focused by the parabolic surface onto the sacrificial mirror. Then the diverging energy is redirected toward the spherical surface. Since in this design the focus of the paraboloid and the center of curvature of the sphere are coincident, the energy would be retroreflected back toward the original focus after striking the sphere. By traveling the distance to and from the sphere, an effective delay loop is produced. The sacrificial mirror would, by that time, be completely penetrated even under marginally hazardous energy levels. If the initial energy were below the predetermined design threshold of the system, the input path would be retraced and the uninterrupted energy would be detected by the observer. Design and manufacturing of this self-aligning system were driven by the available SPDT technology^{2,3}. To aid in prealignment of the system, the paraboloid and the sphere were diamond turned from the same substrate.

Figure 1. Initial prototype laser protection system based on sacrificial mirror with sphere and parabola machined into single substrate with their respective center-of-curvature and focus coincident.

Figure 2. Miniature monolithic system design based on laboratory prototype.

Currently a miniature monolithic system approximately one cubic inch in volume is being designed and an early depiction is shown in figure 2. This system will burn through the back side of the penetrable mirror. However, since this system is based on the original design in figure 1, the following analysis conducted for the original system will still be instructive and applicable.

As shown in figure 3, two cases were investigated in our attempt to ascertain if this system could be fabricated in a completely alignment free configuration. The first case assumed that the focus of the parabola and the center of curvature of the sphere were perfectly coincident, but the metering structure that held the sacrificial mirror in place was displaced. The second case assumed that even though both surfaces were produced in a single SPDT operation, the focus of the parabola and the center of curvature of the sphere were displaced.

Figure 3. Two possible sources of misalignment error.

Figure 4 shows the numerical results of the two case analysis for displacement versus the optical path difference (OPD) in waves. The OPD for a wavelength of 632.8 nm was calculated for the two extreme rays A and B. Although this is not the appropriate forum for a discussion of threat laser energy density and the associated design burn-through threshold of the sacrificial mirror, it is obvious that for most envisioned applications the displacement tolerance from figure 3 in both cases is less than 3 μm . This corresponds to a total wavefront OPD of approximately four waves. The total wavefront OPD in the figure below is the sum of the absolute values of the OPD for the two extreme points A and B. This analysis only takes into account the two conditions stipulated earlier. Thus there is an assumption that the center of curvature and the focus, of the sphere and parabola respectively, are collinear along the direction of propagation.

Case #1			
Displacement	10 μm	5 μm	3 μm
OPD(λ)			
A	3.6593	1.8303	1.0982
B	-11.0978	-5.5526	-3.3322

Case #2			
Displacement	10 μm	5 μm	3 μm
OPD(λ)			
A	2.1388	1.0691	0.6414
B	-7.3130	-3.6569	-2.1942

Figure 4. OPD results of analysis for the two extreme rays A and B.

3. DESIGN EXAMPLE 2

We have developed a micro-spectrometer for sensing application containing five precision surfaces, including two off-axis aspheres⁴. The entire monolith is less than six cubic centimeters in volume (2.4 cm X 1.9 cm X 1.2 cm). 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 SPDT 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 customer⁵. We were interested in exploring novel system designs, fabrication technologies, and examining numerous material systems, in the development of the micro-spectrometer. Our purpose during the early stages was to demonstrate the feasibility of the completely alignment free technology and not an attempt to address a specific sensing problem. Thus, we had great liberty to select the performance and material composition of the first prototype, which is usually application specific. The first substrate material chosen for the system in figure 5 was optical quality polymethyl methacrylate.

Figure 5. Micro-spectrometer optical and mechanical design.

From spot diagrams it was evident that fabrication tolerances were going to be very tight if essentially single pixel illumination was to be maintained on our 1 X 1024 linear detector array. Six laser diodes ($0.635\ \mu\text{m}$, $0.780\ \mu\text{m}$, $0.850\ \mu\text{m}$, $0.980\ \mu\text{m}$, $1.310\ \mu\text{m}$, and $1.550\ \mu\text{m}$) were used as the calibration and design sources. Thus with a slit consisting of a $62.5\ \mu\text{m}$ diameter fiber core and a 300L/mm grating attached the extreme tolerances to meet the above criterion were; figure: < 0.1 waves @ $632.8\ \text{nm}$, finish: $< 50\ \text{\AA}$ rms, intersurface tip & tilt angles: $\pm 0.3\ \text{mRad}$, and intersurface despace: $\pm 5\ \mu\text{m}$. The use of SPDT for the fabrication of a single monolith structure aided by only three diamond turned fixtures ensured that the angle and despace requirements could be met. The figure requirement initially seems challenging, however since we were only using small off-axis segments of small parent surfaces, it was easily met.

The above described system was completely self aligned. Even the linear detector was simply pressed against the image surface depicted in figure 5. This type of fabrication can be very cost effective if the design allows off-axis machining, since multiple parts can be fabricated simultaneously. In addition, this process can be inverted to produce self-aligned molds which can further reduce manufacturing cost. Although this device is a technology demonstrator and not a commercial product, it could form the basis of a very cost competitive product. As an example, there are now several commercially available, albeit somewhat larger, mini-spectrometers on the market. The electro-optics head in one of these units uses five discrete classical surface components with five degrees of freedom each. These are then manually aligned with small positioning screws and finally anchored with a drop of epoxy. Although this will produce the ultimate results require, higher volumes will not significantly reduce the system cost. The above demonstrated technology could impact the cost of such systems by as much as an order-of-magnitude. The six major diamond turning steps are depicted in figure 6⁶.

Figure 6. Top, cross section, and angled views of the six major diamond turning operations are shown. Specifically depicted are the off-axis parabolas, flats, and fixture mounting rings.

4. DESIGN EXAMPLE 3

The final system example is a laser warning receiver (LWR). In recent years the enormous tactical advantage of employing technology such as laser based devices to dramatically increase hit probability (range finders, designators, etc.) has been demonstrated. Since this type of equipment is proliferating worldwide, a means to reduce the advantage that is provided an adversary would be highly desirable. Thus, what is ideally required in a LWR is the capability to: (1) identify a signal as a laser (coherent), (2) determine the nature of the threat (type of device being employed), (3) identify the direction of incidence.

Our approach utilizes the fact that spectrally pure electro-magnetic energy can propagate in a highly collimated manner. The degree of collimation and spectral purity can be directly measured. The basic system configuration contains two principal devices. The first is an imaging system consisting of a high resolution / fill factor CCD coupled with an objective commensurate with the CCD such that impinging laser energy would be focused onto only one pixel within the full field-of-view. The second device would be a low / medium resolution miniature spectrometer developed earlier at ORNL.

Each device has two functions. The imaging system establishes the presence of laser energy and determines the direction of incidence. The spectrometer helps confirm the presence of laser energy and determines the type of equipment being employed by the adversary.

We take advantage of the imaging systems direct mapping of object space into image space for quick and very accurate determination of direction of incidence. Depending on the degree of collimation of the incoming laser threat and the design of the imaging system, the angular resolution can be expected to be

well under 1 degree in both azimuth and elevation. Recent modeling suggests that even resolution between 1-5 minutes-of-angle is not unrealistic. The pixel size on applicable CCDs is typically between 10-50 μm . The technology developed at ORNL in both diffractive and aspheric optics could readily satisfy this requirement with a minimal number of optical elements as shown below.

Figure 7. High resolution imaging system maps object space into image space for detection and location of threat lasers.

With a requirement for single pixel illumination and a restrictive overall size limitation, the final design employed aspheric surfaces on all three air-spaced components. The optical design software constrained the aspheric departures to very mild aspheres for the purpose of simplifying testing. Since scattering may be an issue with such systems, some degree of polishing may be required to reduce the effects of the diamond turning lines. This small deviation from deterministic fabrication is acceptable since for small components the cost of attaining finish is off-set by the ease of achieving figure.

The spectrometric part of the LWR requires a linear dispersion of less than 100 nm/mm spread over a 10 mm linear detector array. Although this type of inexpensive sensor would not rival the performance of a large laboratory system, it would prove more than capable in the laser detection and specification roles. The system has been tested with both broadband and multiple laser sources. In addition to the spectral resolution capability, this device, unlike the two dimensional CCD of the imaging system, can update fast enough to be used for pulse repetition rate measurement which will identify the nature of the threat. The electro-optic sensor module is depicted in figure 8.

The system could use both of the above mentioned devices in tandem to reduce falsing for a field-of-view (FOV) of about 40 degrees. Multiple systems would then be used with overlapping FOV to further reduce the falsing rate. It is important to note that neither of these devices is spectrally limited to predetermined wavelengths. The system will work with Ruby, Ti:sapphire, Alexandrite, Nd:YAG, and emerging high power diode arrays, as well as other frequency agile lasers. The system performance could be enhanced

further by filtering out energy below $\sim 690\text{nm}$ (ruby) to greatly improve S/N since potential laser signals would not be attenuated, but the majority of the solar background would be eliminated.

Figure 8. Several views of the EO sensor, spectrometer and imaging system.

5. CONCLUSIONS

It has been our experience that deterministic fabrication techniques are particularly applicable to miniature systems. Ordinarily challenging figure tolerances can be routinely met by either diamond turning, ion beam milling or ductile grinding⁷. Inter-surface/component distances are also very challenging for the traditional iterative fabrication community. However, if the fabrication is performed on a SPDT machine with resolution comparable to coordinate measuring machines, these distances can be fabricated and known on the order of a micrometer. This assumes that the fixturing used in the process is also SPDT. For many applications the finish that is produced by deterministic fabrication will satisfy system requirements. If this is not the case, then a minimal post polishing effort will be required as reported by Parks⁸. He indicates that in many cases most of the surface roughness reduction is achieved in the first 2-10 minutes. Thus the surface figure for particularly aspheric surfaces would most likely not be degraded substantially in this time frame. It is also our recommendation that monolith systems be designed when ever the optical path is short enough, and the associated absorption of the material low enough, to allow its introduction. This is because even if virtually perfect components can be fabricated, they still need to be assembled, even if self-aligning techniques are employed. Finally, material choices become very important in monolithic designs since some materials are much friendlier than others to deterministic fabrications methods. With the wide range of materials presently available it should not be impossible to use either direct precision machining or precision mold making to address most miniature monolithic system needs.

6. ACKNOWLEDGEMENTS

This work was funded by the US Army TACOM, and the Oak Ridge National Laboratory (ORNL). ORNL is managed by Lockheed Martin Energy Research Corp. for the U.S. Department of Energy under contract no. DE-AC05-96OR22464.

7. REFERENCES

1. S. Rajic, "Snap-Together Directed Energy Threat Protection System", OSA, Optical Fabrication & Testing Workshop 92', Boston.
2. Pneumo Precision Inc., A Designers Guide to Diamond Machined Optics, Keene, NH, 1983.
3. M.C. Gerchman, "Specifications and Manufacturing Considerations of Diamond-Turned Optical Components", SPIE, O-E Lase, 1986.
4. S. Rajic, et al, "Design, Fabrication, and Testing of Mirco-Optical Sensors Containing Multiple Aspheres", SPIE, Annual Meeting 95', San Diego.
5. Instruments SA, JOBIN YVON/SPEX Division, Guide for Spectroscopy, Edison NJ, 1994.
6. B.M. Evans III, et al, " Manufacturing Method for a Monolithic Spectrometer Containing Five Self-Aligned Optical Surfaces", ASPE Spring Topical Meeting '95, Tucson.
7. T.W. Drueding, et al, "Ion Beam Figuring of Small Optical Components", Optical Engineering, Vol. 34, No.12, p 3565.
8. R.E. Parks, "A Method for Polishing SPDT Aspheric Surfaces", OSA, Optical Fabrication and Testing Workshop 92', Boston.

M98000579

Report Number (14) ORNL/CP--94501
CONF-960163--

Publ. Date (11) 199512
Sponsor Code (18) ~~GSA~~ DOE, XF
UC Category (19) UC-900, DOE/ER

DOE