High-Quality Microlenses and High-Performance Systems For Optical Microelectromechanical Systems

Richard S. Muller, Hyuck Choo, and Kishan Gupta
BSAC, Univ. of California, Berkeley

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A White Paper Detailing Opportunities

Abstract: Major opportunities exist for optical microelectromechanical systems (MEMS) and, despite recent economic setbacks for companies working in the field, concentrated research on optical MEMS is underway at many locations. Most of the research reported thus far has been focused on activated-mirror-micro-optical systems-- which have instantly recognizable applications in the display and fiber-optic-switching fields. Optical components other than activated mirrors must, however, be available for designers to produce micro-optical systems for other applications that are already of proven value in macro designs. Chief among the needed components are lenses with high optical quality that can be accurately formed and placed at specified locations in an optical system. Another need is for polarized-light beam splitters that can be fabricated using the materials and technologies that are generally available to MEMS designers. Research at the Berkeley Sensor & Actuator Center (BSAC) has led to important advances in producing both precise high-quality lenses and high-performance polarization-beam splitters for micro-optical MEMS [1], [2]. In this White Paper, we first make clear the need for precision microlenses and then describe an important new MEMS optical system that would be made possible by precision microlenses. We begin with a review of the significant progress that we have already made in building high-quality lenses as well as high-performance polarization-beam splitters at BSAC. We then describe some opportunity areas that have been opened through this progress. In a final section we present guidelines and milestones that will advance this work and lead to new optical-MEMS capabilities.

Microlenses in Optical MEMS

We are developing simple yet precise microlens-fabrication technology that is compatible with and exploitive of the technologies already developed at BSAC for surface micromachining. For example, we have developed means to fabricate precise microlenses and to mount them on mechanical structures such as the BSAC-invented “pop-up” supports, and to drive them with the interdigitated combdrive actuators also invented and heavily developed at BSAC. Our goal is to exploit the attributes of each technology (microlens fabrication and the technology for structural MEMS) in a complementary manner. Our success in this project will enable new, extremely useful, optical Microsystems. We have placed our initial focus on the development of a Shack-Hartmann (SH) system built with a unique MEMS-microlens array in which each individual lens image can be identified by means of its pre-assigned vibrational frequency. With this new design incorporating the new BSAC high-quality lenses, our SH system will advance the field by providing improved sensitivity and broader dynamic range than can be attained by present SH systems. In this White Paper, we describe the BSAC program after providing an introduction to SH systems and of the performance limitations of available SH systems. This discussion leads us to a review of ongoing research by groups active in the SH field after which we describe our

BSAC design approach and some of the encouraging results that we have achieved in this ongoing project.

Challenges and Limitations of Conventional Shack-Hartmann Systems

Conventional SH sensors are widely used in astronomical telescopes and ophthalmic-analysis systems as monitors for wavefront aberrations. They are fast, accurate and, in contrast to interferometers, generally insensitive to vibrations. When used in conjunction with adaptive mirrors, SH sensors are able to improve the image quality of astronomical telescopes by performing real-time corrections on the wavefront aberrations that are inherently generated as starlight traverses the earth's atmosphere. An SH system can also have important military applications as, for example, in a remote surveillance system for planes or satellites or in an optical-missile guidance system. A MEMS SH system with its inherent miniaturization and portability would be ideal for these defense applications.

1. Challenges involved in fabricating and characterizing microlens arrays for Shack-Hartmann Sensors

In SH systems, a microlens array dissects an incoming wavefront into a number of segments. Figure 1 shows a typical SH lens array positioned within an incoming light beam. As shown in Figure 2, each microlens in the array creates a focal spot within the assigned sub-aperture on CCD. A sub-aperture is typically made of forty CCD pixels. Because light travels in a straight path normal to the wavefront, the position of these focal spots is related to the average wavefront slope over each microlens aperture. Thus the pattern of spots at the focal plane contains information about the spatially-resolved wavefront slope that can be integrated to reconstruct the wavefront [3]. Three important requirements for microlenses used in high-performance SH systems are: an excellent uniformity of effective focal lengths over the entire array (ideally 0% variation in focal lengths); a small focal-point size-- preferably smaller than 5μm in diameter (roughly the pixel size of today's high-resolution CCD photosensors) in order to maximize the sensitivity and spatial resolution; and a high fill-factor (preferably close to 100%) in order to improve light-collecting efficiency. Due to these stringent requirements, fabrication of microlens arrays for high-performance SH systems is a demanding challenge. Manufacturers of commercial SH systems usually hold their lens-fabrication techniques as trade secrets [4].

A number of researchers have described methods for fabricating microlenses that may be suitable for SH systems. Some techniques that have been reported include: microprinting technology, a gray-scale mask/RIE etch followed by photoresist reflow and selective liquid-polymer deposition using hydrophobic effects [5-11]. The optical qualities of the lenses produced by these techniques have, in most cases, not been sufficiently characterized to evaluate them for SH-system use. Most likely, thorough optical characterization has not been presented because of severe challenges to measurements that are presented through the very tiny dimensions of the microlenses. Only two papers give numerical values for root-mean-square wavefront errors and peak-to-valley optical path difference [12], [13]. Ph. Nussbaum *et al* reported that microlenses formed by photoresist reflow/RIE etch show rms wavefront errors ranging from 1/5 to 1/4λ, where λ is 630nm [12]. Pulaski *et al* reported that microlenses fabricated by using a gray-scale mask/RIE etch have rms wavefront error on the order of λ/20 [13]. Although the fill-factor of gray-scale mask/RIE etch microlenses is very close to 100%, these microlenses can be expected to have rough surfaces due to the repeated use of complicated step-RIE processes, which will cause a high degree of optical scattering at the lens surface. This surface roughness causes the rms wavefront errors for these microlenses to be greater than λ/30.

Irrespective of the experimental challenges, optical characterization of the microlenses is essential. Without proper lens characterizations, there is no certainty that one can use the microlenses in more advanced optical designs such as SH systems. Hence, a set of characterization tools must be developed in order to monitor and to examine the optical properties of any fabricated microlenses. More specifically, we need to build optical testing setups to measure focal lengths, focal-spot sizes, wavefront aberrations, and other general properties of the microlenses.

Lastly, the performance of an SH sensor is determined by interplay between its microlens array and the paired CCD/CMOS imager. For cutting-edge optical detectors, pixel sizes of CCDs and CMOS imagers are being reduced below the 5μm-square size of today toward an eventual 1μm-square. The achievement of smaller pixel sizes for imagers should lead directly to improvements in the spatial resolution and sensitivity of SH sensors as illustrated in Figure 3, but to gain this improvement, we need to shrink the focal-spot size of the SH microlenses to the range of 1μm (Figure 4). Our SH-microlens array must have a diffraction-limited focal-spot size for visible light that is also 1μm. We have designed a system that fabricates microlenses to meet these needs. Light passing through the center region of our lenses shows rms wavefront errors lower than $\lambda/30$, a precision better than that reported by any previous researchers.

2. Limited dynamic range of Shack-Hartmann sensors: trade-offs among sensitivity, spatial resolution, and dynamic range

In addition to the fabrication- and characterization-challenges in making microlenses, the dynamic range (the range of measurable wavefront slope /curvature) of a conventional SH system has fundamental design limits that must be kept in mind; a SH system produces false results if the curvature of the wavefront being measured is too large. Figure 5 shows one of such cases in which a focal point of one microlens dislocates into an adjacent sub-aperture assigned to a focal point of another microlens.

Researchers have attempted to overcome this dynamic-range limitation of SH systems by employing a modified unwrapped algorithm, a SH array of microlenses with well-defined astigmatism, and a spatial-light modulator in front of the SH microlens array as a shutter (Figure 6-7) [14-16]. The researchers found that first two methods would have very limited practical use because they worked only with certain types of wavefronts. Also, using a spatial-light modulator is also impractical because it absorbs a great deal of light (at least 50% in the case of an LCD illuminated with unpolarized light); it increases the noise in the measurement; and it introduces additional aberrations to the wavefront being measured. In addition, a spatial light modulator is often polarization-dependent and is very expensive.

Up to the present, no practical solution has been demonstrated to improve the dynamic range of SH sensors. Wavefront imaging by SH sensors with high-spatial resolution, high sensitivity, and large dynamic range has continued to remain as an unresolved and demanding problem.

Solutions To The Problems: Our Accomplishments and Goals at BSAC

1. Microlens Fabrication

We have developed a technology to fabricate microlenses with excellent optical characteristics at BSAC. The lenses are formed precisely at desired locations on a wafer using a polymer-jet system in which hydrophobic effects define the lens diameter and surface tension creates a high-quality optical surface. To make the lenses, we first define hydrophilic circular regions at desired locations on a wafer using photolithography to pattern a 0.2-μm thick Teflon (hydrophobic) layer on a quartz substrate, as shown in Figures 8 and 9. Then, using a polymer-microjet printing system (Figure 10), we dispense an exact amount of UV-curable polymer within the hydrophilic circles and cure the deposited material to obtain microlenses having predesigned optical properties [17]. Figure 11 shows that adjusting the volume of the UV-curable optical epoxy within a hydrophilic circle of a given diameter changes the curvature of the microlens. The step resolution of the microlens volume is determined by the average droplet size (~25pL) of the polymer-jet print head. This hybrid method enables us to define the locations and diameters of microlenses with a ±1 μm precision as well as to control the curvatures of the microlenses with very high reliability and accuracy.

We know the optical characteristics of our lenses very accurately through measurements made on highly precise optical-characterization systems. Figures 12 and 13 are scanning-electron microscope pictures showing several of our microlenses. AFM measurements show surface roughnesses for our microlenses to be limited below 5nm. We use a WYKO NT3300 to measure the curvature and volume of the microlenses. The maximum deviation of the surface profile from an ideal circle is approximately 0.15μm for most cases (range ~0.05-0.23μm). The effective focal lengths measured are shown in Figure 14. The *f*-numbers range from 1.5-2.1, 2.0-5.5, 3.4-6.3, and 2.9-7.4 for 200 μm-, 400 μm-, 600 μm-, and 1 mm-diameter microlenses, respectively. The Seidel aberrations, root-mean-square wavefront errors (rms WFE), peak-to-valley optical-path differences (p-v OPD) of the microlenses are measured at λ = 635 nm using a commercial SH system with an accuracy of $\lambda/100$ [13], [18]. The rms WFE values of our microlenses are between $\lambda/5$ and $\lambda/80$, depending on the aperture size, diameter, and volume of the microlenses. The average p-v OPD values are 0.14, 0.25, 0.33, and 0.46 μm for 200 μm-, 400 μm-, 600 μm-, and 1mm-diameter microlenses, respectively. Decreasing the aperture size of the microlenses produces much smaller rms WFE and p-v OPD values, as shown in Figure 15. These values are sometimes as low as $\lambda/80$. The fabrication process has good repeatability as well; twenty 400-μm-diameter microlenses show ~1.43% variations in measured volumes and effective focal lengths. The feasible maximum fill factor is close to 90%.

The optical characterizations of our microlenses tell us that their performances are virtually diffraction-limited. Fabrication of the lenses is simple and compatible with MEMS processing technologies. Hence, our high-quality microlenses are suitable to be incorporated in an optical MEMS that may, for example, be used in a high-performance SH system.

We will continue to refine our microlens fabrication technology to obtain even better control over microlens properties. In one technique, we make use of the special excellence in the center region of our microlenses in which our measurements show that the rms wavefront error is appreciably less than $\lambda/30$. Hence, we can employ the center region of our microlenses as a master element for microlens replication, as shown in Figure 16.

2. Polarized Beam Splitter

In addition to our work on microlenses, we have also fabricated and characterized batch-processed polarization beam splitters (PBS) which are important optical components to separate the orthogonal TE and TM components of light. The value of PBS devices to optical MEMS is clear and, based upon our background in surface micromachining at BSAC, we have seen and exploited a method to produce them using thin-film, low-stress silicon nitride membranes. By stacking membranes, we have demonstrated a triple-layer PBS that produced extinction ratios of 21 and 16dB for reflected and transmitted light rays, respectively. A literature search led us to 1998 work by Pu, Zhu and Lo who investigated a MEMS-compatible surface-micromachined PBS made using thin-film polycrystalline silicon [19]. They achieved extinction ratios of 21 and 10dB for reflected and transmitted light with an insertion loss of ~50% at a 1.3μm laser beam. For visible as well as infrared light, this polysilicon PBS is excessively lossy, and clearly not suitable for a stacked PBS.

In order to obtain the optimal performance for a thin-film PBS, the film thickness must be accurately controlled. For 635-nm light and a thin-film membrane of silicon nitride (refractive index = 2.1), the thickness should be an integral multiple of 83.5 nm [20]. In order to obtain reasonable yield in our processing, we aim for a desired thickness of 417.5nm (five times the minimum thickness) trading off transmission through the film with membrane strength. A disadvantage of a thin-film PBS is that it shows a low extinction ratio for the transmitted TM mode since transmitted light still contains some TE mode. This disadvantage can be alleviated by employing multi-layer thin-film PBS to filter out more of the remaining TE mode in the transmitted light.

The fabrication steps we use to make the PBS are shown in Figure 17. Using low-pressure chemical-vapor deposition (LPCVD), we deposit a low-stress silicon nitride layer on *p*-type silicon wafers, aiming for a thickness slightly greater than the target value. Then, we reduce the nitride thickness down to the target value in a 160°C, phosphoric acid bath (Figure 17a). Next, we create etch windows by photolithographic-patterning and dry-etching the nitride layer on the backside of the wafers (Figure 17b) [21]. To open the window cavity (4.25mm square), we use 80°C KOH to etch through 530-μm (+/-5 μm) Si, leaving only the nitride membrane over the cavity (Figure 17c). Measurements using NANO Deep-UV System show that the final thickness of the membranes varies from 418.8 to 419.5 nm. Using a WYKO NT3300, we measure the radius-of-curvature of a typical nitride membrane to be 51 m; the membranes are virtually flat! Figure 18 shows several of the fabricated membranes: single-, double-, and triple-layer nitride membrane PBS. For a multi-layered PBS, membranes are stacked at an angle to clear the optical path for transmitted light.

Figure 19 indicates a possible design to integrate our thin-film PBS into an optical-MEMS by employing silicon nitride windows in pop-up structures. Such a system could be fabricated in an SOI process.

To test our silicon nitride membrane PBS, a 635-nm beam from a laser diode is directed at the surfaces of both single- and stacked-PBS devices at the film Brewster angle (64.5°). The transmitted and reflected rays from the test structures are then passed through two 15mm High-Efficiency Polarizing-Cube Beamsplitters (reflected-mode efficiency > 99.5%, transmitted-mode efficiency > 95%) using the system shown in Figure 20. The intensities of both TE and TM components were then measured using a photo detector. The insertion losses and extinction ratios derived from these measurements are listed in Table 1. Very good performance is demonstrated by the new MEMS PBS structures: extinction ratios (for reflected- and transmitted-light) of (21dB, 10dB), (21dB, 14dB), and (21dB, 16dB) for single-, double-, and triple-layer systems, respectively with corresponding insertion losses of 3, 10, and 13%. The stacked PBS devices clearly exhibit the expected improvements over single-layer splitters in the transmitted extinction ratios.

In the near future, we are going to fabricate our thin-film PBS using pop-up structures fabricated on SOI wafers. Again, the optical and physical properties of the PBS will be fully examined, and we will begin to integrate the thin-film PBS into our advanced optical MEMS systems.

3. Next Generation Shack-Hartmann Sensors with improved dynamic range and sensitivity

Using MEMS technologies available at BSAC, we can create densely packed active microlens arrays that are individually controlled to resonate at given frequencies. In other words, because the distances that the microlens and its focal point travel are equal, by energizing the microlens, we can make the focal point move similarly; thereby identifying the lens and its associated focal point. Figure 21 shows a schematic diagram of a microlens array and an enlarged view of an active MEMS microlens unit. Because, in our unique scheme, a lens focal point can be identified outside its associated sub-aperture, anywhere in the sensing array, the dynamic range of the SH sensor is dramatically improved. With this design, the SH dynamic range is not limited by the size of sub-apertures (usually 40 pixels) but, rather, by the size of the whole sensing array and by the numerical aperture of the microlens. Our new SH- system will be cost-effective because it will be batch-processed, and not demand any expensive components such as a spatial-light modulator. The design of our system is simple, and it is optically robust because the wavefront being measured passes through a very flat, thin silicon nitride membrane (whose thickness is controlled to minimize the reflection coefficient) and the low-aberration microlens.

Figure 22 shows the actual layout of our prototype SH-system, currently being fabricated in the Microlab at UC Berkeley. The outline of its fabrication process is shown in Figure 23. Microlenses are formed using the fabrication technology described in the previous section and are expected to have excellent optical properties. The diameter of the microlenses is 1mm, and each active microlens unit containing MEMS actuators is 1.5mm×1.5mm. We have designed the MEMS structures using a single pair of drive lines to control each MEMS microlens unit in the entire row. This greatly reduces the number of interconnect lines required to control a large array of microlenses. The resonant frequencies of the active MEMS microlens units will range from 0.7 to 7 kHz and their mechanical Q values will be between 8 and 80. The resonant amplitude is designed to be ±20μm from the initial position so that each focal point will move a distance of 40μm, easily detected on the photosensing array. If we assume that we serially identify focal points (i.e. one by one) in a 25×19 microlens array, it will take approximately 5.4sec (= 10msec per focal point × 25×19). In order to use this system in real-time applications, however, the total identification time needs to be smaller than 50msec. Hence, more optimized, efficient algorithms for operating and identifying a large active MEMS microlens array must be developed in parallel with the hardware implementation. Our preliminary work on this problem encourages us that a solution will be found.

We will demonstrate the hardware for the first prototype by mid-summer 2003 and expect to follow this with system refinements and optimizations in the balance of the summer. Refinement and optimization of the design will include minimization of the area occupied by the MEMS actuators and maximization of the area occupied by the microlens. We plan to demonstrate the hardware of more refined and optimized second prototype by the end of August 2003, and follow this with the development of custom software to produce a practical SH system.

4. Optical Characterization Tools for Microlenses and Optical MEMS

More microlens characterization tools will be built at Berkeley Sensor & Actuator Center (BSAC), UC Berkeley for complete microlens and micro-optics characterizations. Currently we have WYKO NT3300 (surface profiler), AFM, focal length measurement and focal spot size measurement setups available for microlens characterizations. We also plan to build setups for measuring point-spread function and diffraction efficiency in June and July 2003. For wavefront aberration measurements, we are setting up a shearing interferometer at BSAC (UC Berkeley) by the end of August 2003 and a SH system at Ginzton lab (Stanford University) in June. In addition to these two wavefront-analysis tools, a phase-shifting point-diffraction interferometer (PSPDI) may be considered and built in 2004. Having these characterization tools, we will be able to study and understand the optical properties of micro-optical components, especially the microlenses, and optical MEMS systems we develop at BSAC. This will in turn enable us to design and fabricate improved micro-optical components and optical MEMS systems. By the end of 2004, we expect to have at BSAC an unrivaled capability for the characterization of optical-MEMS hardware.

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