A Concept for Zero-Alignment Micro Optical Systems

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ABSTRACT

We are developing a method of constructing compact, three-dimensional photonics systems consisting of optical elements, e.g., lenses and mirrors, photo-detectors, and light sources, e.g., VCSELs or circular-grating lasers. These optical components, both active and passive, are mounted on a lithographically prepared silicon substrate. We refer to the substrate as a micro-optical table (MOT) in analogy with the macroscopic version routinely used in optics laboratories. The MOT is a zero-alignment, microscopic optical-system concept. The position of each optical element relative to other optical elements on the MOT is determined in the layout of the MOT photomask. Each optical element fits into a slot etched in the silicon MOT. The slots are etched using a high-aspect-ratio silicon etching (HARSE) process. Additional positioning features in each slot's cross-section and complementary features on each optical element permit accurate placement of that element's aperture relative to the MOT substrate.

In this paper we present the results of the first fabrication and micro-assembly experiments of a silicon-wafer based MOT. Based on these experiments, estimates of position accuracy are reported. We also report on progress in fabrication of lens elements in a hybrid sol-gel material (HSGM). Diffractive optical elements have been patterned in a 13-micron thick HSGM layer on a 150-micron thick soda-lime glass substrate. The measured *rms* surface roughness was 20 nm. Finally, we describe modeling of MOT systems using non-sequential ray tracing (NSRT).

Keywords: micro-optical systems, hybrid sol-gel material, systems with diffractive optics

1. INTRODUCTION

An optical table allows the two-dimensional assembly of optical elements of different functionality. We are proposing to miniaturize the optical table and to develop fabrication and micro-assembly techniques that preserve the versatility of an optical table while at the same time allowing for highly accurate, passive alignment of a wide variety of passive and active optical elements. The result is the micro-optical table (MOT) concept and the associated idea of a photonics cube.

Extensive work in the development of micro-optical systems has been performed by Wu, *et al.*¹ That research is based on the fabrication of optical elements on micro-hinges using surface micro-machining techniques. The optical elements are raised from the prone position to form an optical bench. Tilt of the elements is controlled by the use side latches. An attractive feature of the free-space micro-optical bench (FS-MOB) technology is the capability to integrate micropositioners and microactuators into the optical bench using the same surface-micromachining techniques as those used to fabricate the optical elements. A difference between the FS-MOB technology and the MOT/photonics-cube approach has to do with the type of micromachining that is employed in each case. FS/MOB systems are fabricated using surface micromachining whereas MOT/photonics-cube systems are fabricated using bulk micromachining of a substrate material such as silicon. The required silicon bulk-micromachining processes are a recent development.²

Optical benches have also been fabricated using the LIGA process.[‡] One example has been reported by Müller, *et al.*³ This LIGA bench contains two ball lenses and a spectral filter. The micro-optical LIGA bench allows passive alignment of two 900- μ m-diameter ball lenses, a filter plate, and an optical fiber. The mounting slot for the filter plate is rectangular in cross-section. The mounting slot in this LIGA bench does not include any optomechanical features to tighten the alignment of optical elements.

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1.1. PHOTONICS CUBE

The concept of stacked optical systems was described by Iga in 1982.⁴ Stacked planar optics are essentially 1D or 2D arrays of optical benches. Each optical bench is an in-line collection of optical elements. Optical elements can include spectral filters, polarizers, waveplates, active optical elements, and arrays of large numerical-aperture (NA) lenses. On the other hand, the photonics cube described here is a stack of micro-optical tables (MOTs).

More recently, Singer and Brenner have described a method of stacking optical systems using mechanical grooves produced in silicon by means of wet etching.⁵ The mechanical grooves protruding from the alignment-block substrate have a triangular cross-section. The triangular cross-section of the protrusions in the alignment block is matched by triangular intrusions in the building blocks of a stacked optical system. The building blocks can be arrays of lenslets, beamsplitters, sources, and photodetectors.

The MOT-based photonics cube concept admits opto-electronic systems with higher complexity than stacked planar optics. Optical elements and electronics can be combined on the same silicon substrate without conflicts such as obscuration. Three-dimensional beam folding inside the photonics cube can result in a very long optical path, a property useful in chemical and biological detection.⁶

In summary, we are developing a new methodology for designing micro-optical systems. This methodology offers passive alignment of passive and active optical elements, modularity, and simplicity in fabrication.

Figure 1. MOT concept. Part (a): Schematic depiction of the micro-optical table (MOT) concept. Part (b): Optical elements mounted in a test MOT. See text for details.

2. CONCEPT DESCRIPTION

Zero-alignment micro-optical systems are built by mounting optical elements, both active and passive, on a specially prepared substrate [see Figure 1(a)].

We refer to the substrate as a micro-optical table (MOT) in analogy with the macroscopic version routinely used in optics laboratories. The position of each optical element relative to other optical elements on the MOT is determined in the highly accurate layout of the MOT photomask. Additional optomechanical positioning features on each optical element permit accurate placement of that element's aperture relative to the MOT substrate. By expanding the same mounting idea further, we envision an assembly of multiple MOT's that can be mounted on a "motherboard," in analogy to boards mounted in a personal-computer chassis. The result is a photonics cube, illustrated schematically in Figure 2.

Figure 2. Photonics-cube concept. Multiple MOTs are embedded in a support backplane to form a 3D micro-optical system. Light can be coupled between adjacent MOTs by use of blazed gratings or off-axis lens sections. Photonics cubes measure millimeters on a side.

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In Figure 3(a) and Figure 3(b), we show details of a MOT mounting-slot design and the etched version a MOT mounting slot. Control over the position of each optical component is achieved by the MOT mounting-slot guide protrusions or intrusions that match complementary structures in the optical elements to be placed within the slot (see Figure 4). An optical element can fit only one way into the slot and the depth to which it is inserted is defined by the complementary structures patterned into the front surface of the optical-element substrate [see Figure 4(b)]. The major positioning errors are axial-position errors and errors in pitch and yaw rotation of the optical element.

Figure 3. Example mounting slot cross-section. Part (a): Photomask detail. Part (b): Fabricated mounting slot etched through wafer.

The fabrication of MOT systems requires several unique and novel fabrication technologies: (1) use of grayscale photomasks for patterning of optical elements, (2) bulk-micromachining capability for high-aspect-ratio etching of silicon, and (3) hybrid sol-gel material (HSGM) to serve as the patterned medium.⁷ The use of a grayscale photomask allows the fabrication of more sophisticated optomechanical alignment features that can result in a better fit between the optical element and the MOT. The same grayscale photomask also permits the fabrication of higher-diffraction-efficiency diffractive optical elements or the patterning of refractive surfaces. The use of hybrid sol-gel materials helps to simplify the fabrication process of the MOT optical elements since such materials require only UV exposure, development, and baking steps. No etching is required.

Our first goal was to demonstrate the fabrication of a simple rectangular slot and a corresponding optical element. The demonstration would be completed by mounting the optical element in the slot.

Figure 4. Optical element fabricated in a hybrid sol-gel material. Part (a) shows the topography of the fabricated surface measured with a non-contact optical profilometer. Part (b) shows top view of the element. Note the on-axis Fresnel zone plate and two rectangular mounting structures beneath the zone plate.

3. MICRO-ASSEMBLY EXPERIMENTAL RESULTS

The prototype silicon MOT was etched at Sandia National Laboratories using the high aspect-ratio silicon etching process (HARSE). Mounting slots were etched through the entire thickness of a silicon wafer, i.e., 440 μm . The prototype micro-optical elements were fabricated using a hybrid sol-gel material (HSGM) coated on 150- μm

thick soda lime glass substrates. The thickness of the HSGM coating was 4 μm in these prototypes. In more recent work, we have achieved an HSGM coating thickness of 13 μm and an *rms* surface roughness of 20 nm. An *rms* surface roughness of 20 nm corresponds to a total integrated scatter (TIS) of 0.16 at 632.8 nm and normal incidence.⁸ The *rms* surface roughness was measured over a 60 μm by 45 μm area within the center zone of the aperture shown in Figure 4(b).

The fabricated optical elements were mounted in slots such as the one shown in Figure 3(b) using a micro-assembly workstation at Sandia National Laboratories. The micro-assembly workstation includes a computer controlled pair of LIGA-made tweezers that are mounted on a stage which can be translated in 1- μm steps, a video-camera-equipped microscope and a side camera. The lenslet optical elements were first sawed from the soda-lime glass substrates. Second, a lenslet was placed in the MOT mounting slot [Figure 3(b)] using the computer-controlled tweezers (see Figure 5). Finally, the lenslet was cemented in place by using UV-curing optical adhesive (Norland P/N 6101).

Figure 5. Top view of the alignment of the optical element to the MOT mounting-slot (MS) location.

We repeated the optical-element mounting procedure twice. The results of these two experiments are shown in Figure 6 labeled in chronological order "A" and "B."

Figure 6. Two optical elements mounted and cemented in a MOT. See text for details. Image courtesy of T. Carter, SNL.

Position	Position Error
Roll rotation (z axis)	Not estimated
Yaw rotation (y axis)	8 ± 1 mrad
Pitch rotation (x axis) [§]	31 ± 6 mrad
Axial position (z axis) ^{**}	-3 ± 1 μm
Vertical position (y axis)	Not estimated
Lateral position (x axis) ^{††}	2 μm

Table 1. Optical-element positioning errors based on optical element "B" (see Figure 6).

[§] The pitch rotation of the optical element is primarily due to a widening of the mounting-slot width with increasing etch depth.

^{**} Axial position is estimated at the top of the wafer. Negative value indicates that element is separated from the mounting-slot wall.

^{††} Our current estimate is based on the resolution of the translation stage which moves the computer-controlled tweezers (Newport PM500-C).

Analysis of SEM micrographs of a mounted optical element (element "B," see Figure 6) led to estimates of positioning errors (see Table 1). The pitch rotation of the optical element is primarily due to a widening of the mounting-slot width with increasing etch depth. The mounting slot is narrower at the top of the wafer than it is at the bottom of the wafer. For example, a typical mounting slot width at the top of the wafer is $212 \pm 5 \mu\text{m}$ and $240 \pm 5 \mu\text{m}$ at the bottom of the wafer. As a result, an optical element mounted in the slot can assume a pitch tilt. We anticipate that this problem can be corrected by variations in the HARSE process.

The axial position is estimated at the top of the wafer. The negative value for the axial-position error indicates that the optical element is separated from the mounting-slot wall. Our current estimate for the lateral position is based on the resolution of the translation stage which moves the computer-controlled tweezers (Newport PM500-C). The yaw-rotation position error was estimated from the thickness of the optical adhesive between the front surface of the optical element and the wall of the mounting slot that contains the guide protrusions.

4. MODELING AND ANALYSIS OF MICRO-OPTICAL SYSTEMS

The performance of an optical system can be estimated most completely by means of non-sequential ray tracing (NSRT). We are using NSRT to model micro-optical systems currently in development (for an example of a very simple micro-optical system, see Figure 7). Non-sequential ray tracing is used to model general optical systems in which there is not a determined sequence of surfaces that a ray will intercept. Instead, all surfaces are defined in a global coordinate system. Sources and receiver planes, e.g., photodetectors, are also defined in the same global coordinate system. Each ray is assigned a starting position and direction. Rays are then traced and each defined surface is examined to determine if it is the next intersecting surface. When a ray encounters a surface, the ray is reflected, refracted, or scattered. One or more of these options may be selected depending on the description of the encountered surface. For example, in the case of a beamsplitter, a single ray may give rise to a transmitted ray and a reflected ray, both of which are subsequently traced through the optical system.⁹ The trace of a ray is terminated when it intersects the defined receiver plane.

Parameter	Parameter Value
Lenslet focal length	3.6 mm
Lenslet aperture diameter	1.2 mm
Point-source/Lenslet separation	3.6 mm
Lenslet/Lenslet separation	7.2 mm
Lenslet/Receiver-plane separation	3.6 mm

Table 2. Specifications of the example two-element optical system used in the non-sequential ray-tracing analysis.

Stray-light analysis can be carried out using any one of several commercial packages, e.g., *LightTools* or *ASAP*.^{10,11} The value of NSRT analysis applied to MOT-based optical systems and photonics cubes is that NSRT analysis can support the design of micro-optical systems in which light is controlled more efficiently. A specific example is the determination of the need for and locations of micro-optical baffles. Such baffles can be used to minimize stray-light cross-talk in a complex photonics cube that features multiple sources and multiple photodetectors. A limitation of NSRT analysis is that interference of light cannot be directly modeled. This is a result of the underlying ray trace approach.

Figure 7. Model of 2-element MOT-based optical system in *LightTools*. The configuration shown corresponds to $m_{L1} = -1$ and

$$m_{L2} = 0.$$

As an example of NSRT analysis, we consider the 2-element optical system shown in Figure 7, consisting of two F/3 diffractive lenslets with a focal length of $f = 3.6$ mm. It is a 4- f system (see Table 2 for model details). We approximate each lenslet as a superposition of three refractive lenses: a refractive lens of $f_{-1} = -3.6$ mm (-1^{st} diffraction order), a plane-parallel plate (0^{th} diffraction order), and a refractive lens of $f_1 = 3.6$ mm ($+1^{\text{st}}$ diffraction order). The light source is modeled as a point source with numerical aperture $NA = 0.13$ (see Figure 7) and intensity of 0.40 mW/sr. Rays are traced through each of nine possible combinations of the lenslets' diffraction orders. In each case, the spatial irradiance distribution at a receiver plane located at the paraxial focal plane of Lenslet 2 is calculated. The total-irradiance distribution in the receiver plane is the result of adding the individual irradiance distributions in Figure 8(a)-(i), i.e.,

$$E_{\text{tot}}(x, y) = \sum_{m_{L1}=-1}^{m_{L1}=1} \sum_{m_{L2}=-1}^{m_{L2}=1} \eta_{m_{L1}} \eta_{m_{L2}} E_{m_{L1}, m_{L2}}(x, y) \quad (1)$$

Each irradiance distribution in the summation is weighted by the product of the diffraction efficiencies, η_i , of Lenslet 1 and Lenslet 2 [Figure 8(a)-(i)]. This example NSRT analysis illustrates how to quantitatively determine cross-talk and stray-light effects in compact micro-optical systems that include multiple sources and photodetectors.

Figure 8. Receiver-plane irradiance spatial distributions associated with diffraction orders of the two diffractive lenslets in Figure 7. Diffraction orders of each lenslet are indicated in parentheses: (m_{L1}, m_{L2}) . The receiver area measures 8 mm (H) by 6 mm (V). Peak irradiance within the receiver area is indicated for each plot in $\mu\text{W}/\text{mm}^2$. The receiver plane is located at the paraxial focal plane of Lenslet 2 (Figure 7).

5. CONCLUSION

The methodology for zero-alignment micro-optical system described in this paper takes advantage of state-of-the-art lithography fabrication techniques and bulk-micromachining of silicon. The MOT concept encompasses the accurate placement of passive and active optical elements on a silicon substrate. The placement accuracy is due to accurate patterning achieved with photomasks written on sub-micron grids with sub-micron electron-beam spots.

The silicon substrate itself offers the potential to combine micro-optical and electronic components in one micro-optical system package. The main application area will be optical data storage and the associated development of MOT/photronics-cube systems such as miniaturized optical pick-up units (OPUs).

We have performed preliminary MOT assembly experiments. The MOT was fabricated by bulk micromachining a silicon wafer. Optical elements were fabricated by patterning zone plates and optomechanical mounting structures in a hybrid sol-gel material layer on a glass substrate. Two optical elements were mounted in a prototype MOT substrate (see Figure 6).

In the initial fabrication experiments, we achieved a thickness of the HSGM layer of 4 μm . More recently, we have succeeded in depositing a relatively thick layer of HSGM and then in patterning it. The HSGM layer thickness was measured to be 13 μm . The corresponding *rms* surface roughness was measured to be 20 nm.

We have presented an example of non-sequential ray trace analysis applied to micro-optical systems. Such analysis can be used to determine the effects of stray light in optical systems that contain multiple passive optical elements as well as light sources and photodetectors.

We are continuing work on refining the design of optomechanical features on the optical elements and within the MOT mounting-slot cross-section. The goal of this effort is tighter control over the optical element's position within the mounting slot.

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- ¹¹ *LightTools* is a product of Optical Research Associates, Pasadena, California, CA 91107; <http://www.opticalres.com>.