Design and Analysis of a Micro-Optical Position Readout for Acceleration Sensing

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ABSTRACT

Sandia National Laboratories is developing a MEMS-based trajectory safety subsystem, which allows enablement of critical functions only after a particular acceleration environment has been achieved. The device, known as an Environmental Sensing Device (ESD), consists of a suspended moving shuttle that translates a given distance when exposed to an appropriate acceleration environment. The shuttle contains an embedded code, consisting of grating structures, that is illuminated and optically read using a semiconductor laser and detector integrated together in a GaAs-based Photonic Integrated Circuit (PIC) flip-chip bonded to the assembly. This paper will describe the optical design and performance analysis of the embedded code features in the shuttle.

Keywords: raytrace, micromachines, photonic integrated circuit, accelerometers

1. INTRODUCTION

Micromachines are devices fabricated using photolithographic and other semiconductor fabrication-based technologies. They promise a variety of mechanical functions, including rotary and linear actuation, as well as position sensing at the micron scale. Micromachine accelerometers offer a way to enable critical functions only when a system encounters a particular acceleration environment. Possible applications for this class of device include switches for airbag deployment and safing and arming of rocket boosters and ordinance, as well as other aerospace environments.

Optical sensing is non-contact, massless, frictionless, has wide dynamic range, and is well adapted to binary counting and position encoding schemes, as compared to electrostatic capacitive sensing which can be degraded by parasitic capacitance, charge buildup, grounding and shielding problems, and circuit loading effects.

This paper describes the geometric optical analysis of an optical readout of a surface micromachine accelerometer environmental sensing device (ESD). The ESD contains a suspended moving part, called a shuttle, that contains a unique 24-bit code pattern consisting of a series of grating structures. A photonic integrated circuit (PIC) contains a waveguide laser and photodetector and is flip-chip bonded above the shuttle structure. The laser illuminates a single code feature with an elliptical beam projected at a 45 degree angle. Light is either backscattered to, or forward scattered away from the detector, depending upon whether the code feature is a binary "1" or "0". As the shuttle translates due to an applied acceleration load, each code is read successively. When the code is completely and accurately read, a subsequent critical function is activated. Details of the mechanical design and fabrication of the ESD are described elsewhere.^{1,2}

The goal of the optical analysis is to understand how much laser light will be returned to the detector on the PIC as a function of lateral shuttle position, shuttle thickness, separation between PIC and shuttle and other mechanical parameters. All of this is necessary to determine the optimal design for manufacturing considerations.

2. CODE FEATURE DESIGN

The ESD PIC/shuttle design as developed is shown in Figures. 1 and 2. The shuttle contains code features that consist of binary "1's" and "0's". Each binary "1" consists of an array of etched walls that are 17 μm long in the z-direction, 1 μm wide in the x direction, 3.0 μm thick in the y direction, and spaced apart on 7 μm centers in the x-direction. There are 13 parallel walls, forming 14 pits giving a total length of each code feature of 97 μm and a width of 17 μm . A binary "0" feature is just the unetched reflective substrate surface, also having overall dimensions 17 by 97 μm . The shuttle is spaced above the substrate a distance of 0.5 μm . Laser light emanates from a 5 μm wide laser waveguide in the PIC, hitting a 22.5 degree fold mirror microetched into the PIC substrate and reflects down onto the shuttle at a 45 degree angle. Figure 3 shows the

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operation of the retro-reflective code features. If the laser beam illuminates a binary "1" code feature, more than half of the laser light is retro-reflected or backscattered from the substrate and the wall of the vane in a "roof mirror" configuration and back to a photodetector neighboring the PIC fold mirror, as shown in Fig. 3a. If a code feature is not present (a binary "0"), all of the laser light reflects once off of the top of the shuttle and away from the detector (Figure 3 b). Subsequent multiple reflections between the PIC and the balance of the shuttle do not strike the detector and are scattered away from any other PIC detectors. A total of 24 code features ("1's" and "0's") will be present in the eventual ESD, requiring a total motion in the z-direction of nearly 500 μm for acceleration activation.

3. PIC DESIGN

The PIC laser is modeled as a divergent point source with an anamorphic Gaussian irradiance beam spread whose beam strikes an out-of-plane fold mirror. The model places the focus of the beam several microns in front of the location of the PIC fold mirror. The beam is modeled with a divergence of 18.8 degrees (FWHM) in the vertical (y) plane and a horizontal (z) divergence of 6.9 degrees (FWHM), based upon laser beam propagation models provided by the PIC designer³. The anamorphic beam illuminates only a single code feature at a time. This permits narrower code features in the z direction than otherwise possible with a circular beam. This minimizes the overall required z-motion of the shuttle. The PIC fold mirror model can be independently rotated to reflect the beam anywhere onto the shuttle. The photodetector is in proximity to the fold mirror and intercepts the backscattered laser beam from the shuttle.

4. ANALYSIS TOOLS

The model for the PIC/Shuttle was constructed using ASAP 6.0⁴ a non-sequential raytrace code that can assign optical surface properties to CAD structures and propagate optical rays between these surfaces according to geometrical and physical optical laws. Optical flux values are assigned to each ray in accordance to the radiance distribution function appropriate to the optical source. The ASAP geometrical model includes motion of the shuttle relative to the PIC and substrate. The lateral position and height of the shuttle relative to the PIC is also modeled. The intended shuttle motion is in the z-direction indicated in Figure 2. Figure 4 shows a perspective view of the ASAP representation of the ESD system. Using the ASAP model, one can plot the resultant flux on any given surface as a function of any geometric variable associated with the model.

The calculations performed are the result of incoherent geometric raytracing. While the ASAP program permits calculation of coherent superposition of laser light, the accuracy of such a calculation is questionable for structures having a features less than about twenty wavelengths of the incident radiation. Nevertheless, it was believed that an incoherent geometric raytrace analysis would be sufficiently accurate to confirm the basic operation of the system. In this analysis, reflectivity of all surfaces were presumed to be perfect, although the model could be modified to incorporate absorption, scattering, and polarization. While each array of pits can be described as a grating structure, the significant retroreflection is almost purely geometric. The first order diffraction angle of a grating of this scale is on the order of 5 degrees, which is well within the scatter angle of the PIC detector.

5. ANALYSIS RESULTS

Figure 5 shows a profile view of an ASAP raytrace, and Figure 6 shows the beam footprint on the shuttle and return beam pattern onto the PIC detector for the original detector configuration. The original detector design encompassed the fold mirror in a "U" configuration. It had been originally assumed that the diverging laser beam would walk off onto the detector because the grating structure would operate as an array of two mirror roof reflectors, rather than as a perfect retroreflector. Instead, the analysis shows that about 80 percent of the retro-reflected light would not, in fact, hit the active detector area, but would be reflected back toward the fold mirror and the surrounding inactive area. It was observed that a rotation of the fold mirror axis about the y (vertical) axis would reflect the beam to one side of the active detector area, allowing the collection of about five times more light than before. If the rotation angle is too great, then the pattern projected on the shuttle covers more than a single code feature, degrading the shuttle position response function. The optimum mirror rotation angle was found to be about 4 degrees. From this analysis, the detector was offset in the z direction, as shown in Figure 7

The resulting response function is shown in Figure 8. A very high contrast signal vs. position is the result. The results of several values of shuttle-to-PIC separation are shown. Several separations between the PIC and shuttle were modeled in order to study the effect of assembly tolerances. They confirm that for a separation of $40 \pm 10 \mu\text{m}$ there is little degradation in the signal response. An assembly tolerance of $\pm 10 \mu\text{m}$ was deemed reasonable.

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Other cases were performed in the analysis of this model, including slope of the walls due to erosion during ion milling or wet etch undercutting during fabrication (Figure 9-Figure 11), and rotation and roll misalignment of the shuttle relative to the PIC during assembly. (Figure 12).

The effect of wall slope is shown in Figure 10 (undercut wall) and Figure 11 (base of wall thicker than top). These two conditions separate the return radiation spots, but a large enough detector captures most of the radiation.

The effect of in-plane rotation of the shuttle about a point directly beneath the PIC fold mirror is shown in Figure 12. This is an issue for assembly, as the PIC must be mechanically aligned and flip-chip bonded to the supporting substrate. These results showed that the system response was relatively insensitive to misalignment for angles in excess of 5 degrees. It should be noted, however, that with an in-plane rotation, the response relative to the lateral shuttle position does shift over a lateral distance of about 4 μm . This can become a position detection/timing issue.

6. CONCLUSION

The optical analysis of the TSSC demonstrated that rotation of the PIC mirror and repositioning of the detector was required to improve the collection of radiation by the detector. Otherwise, the assembly appears to work well within expected manufacturing tolerances like PIC to shuttle separation and rotation. Additional analysis incorporating optical properties of the semiconductor materials that comprise the device can be added to the model as they are better understood. The geometric optical modelling of this relatively complex micro-optical structure has proved to be a very insightful task.

7. ACKNOWLEDGEMENTS

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4. ASAP 6.0 (Advanced System Analysis Program) is a product of Breault Research Organization, Inc., Tucson, AZ.

Figure 1 Perspective view of PIC/Shuttle

Figure 2 Profile view of PIC and Shuttle

Figure 3 Backscatter-based code pattern. a) 1-bit (retroreflective) b) 0-bit (forward scatter)

PLOT

100,220.3

Y
X
Z
-150,-120.3,50 microns

ASAP Basic v6.5

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Figure 4 PIC/Shuttle as modeled in ASAP--perspective view

Figure 5 ASAP Raytrace--side view

Figure 6 Original configuration--detector straddles PIC mirror

Figure 7 PIC mirror rotated 4 degrees, detector offset

Figure 8 Detector response vs. shuttle position for a number (position response function) of standoff distances between PIC and shuttle

Figure 9 Raytrace Profile. Wall angle undercut (5 deg angle) need to replace this figure w/ clearer profile

Figure 10 Undercut wall (angle = -5 deg)

Figure 11 Tapered wall (angle = 5 deg)

Response vs. Shuttle Translation for Several In-plane Shuttle Rotations
Shuttle to PIC Separation = 50 μm

Figure 12 Effect of rotational misalignment of shuttle to PIC--Position response function