Optical readout of micro-accelerometer code features

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ABSTRACT

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Micromachine accelerometers offer a way to enable critical functions only when a system encounters a particular acceleration environment. This paper describes the optical readout of a surface micromachine accelerometer containing a unique 24-bit code. The readout uses waveguide-based optics, which are implemented as a photonic integrated circuit (PIC). The PIC is flip-chip bonded over the micromachine, for a compact package. The shuttle moves 500 μm during readout, and each code element is 17 μm wide. The particular readout scheme makes use of backscattered radiation from etched features in the accelerometer shuttle. The features are etched to create corner reflectors that return radiation back toward the source for a "one" bit. For a "zero" bit, the shuttle is not etched, and the radiation scatters forward, away from the detector. This arrangement provides a large signal difference between a "one" and "zero" signal, since the "zero" signal returns virtually no signal to the detector. It is thus superior to schemes that interrogate the code vertically, which have a limited contrast between a "one" and a "zero". Experimental results are presented for mock shuttle features etched into a silicon substrate. To simulate the shuttle moving under a fixed PIC, a commercially available waveguide source was scanned over the mock code.

Keywords: MEMS, accelerometer, optical readout

1. INTRODUCTION

At Sandia National Laboratories, work is underway to develop a micro trajectory safety subsystem.^{1,2} Trajectory safety subsystems function as energy gates to regions that contain critical components. They prevent energy from entering this region until receiving correctly coded information. Two MEMS components are used in the system, an Environmental Sensing Device (ESD) and a shutter mechanism that interprets the information generated by the ESD. The ESD is a device which actuates after sensing an appropriate velocity change by mechanically integrating an acceleration input over time. The output from the ESD is a unique 24-bit coded information signal that is passed on to the shutter mechanism. To read the code, a Photonic Integrated Circuit (PIC) is flip-chip mounted above the ESD. The information read by the PIC is sent to an ASIC that converts each bit into an appropriate drive signal for the actuators used by the shutter mechanism. The shutter is a mechanical locking mechanism that blocks energy from reaching critical components until receiving a correct 24-bit code. If the correct code is received, the shutter unlocks and energy passes through the device. If the wrong code is received, the shutter irrevocably locks up. The motivation for this work is based on occurrences known as "high consequence" events, where an inadvertent operation could result in the loss of life, property, or damage to the environment.

Surface microsystems often present a measurement challenge. System dimensions are on the order of tens to hundreds of microns, and sense mechanisms move from fractions to hundreds of microns, depending on the application. Electrostatic (capacitive) sensing has been proposed for measuring the state of microsystems. It offers the ability to integrate directly on the same chip as the micromachine. Generally, this approach has encountered significant problems due to the inherent small size of the signals obtainable at the scale of silicon microsystems. Sources of the problems include parasitic capacitance, grounding and shielding, charge build-up due to mechanical motion in the micromachine, and circuit loading (impedance) effects. Many of these concerns have been addressed in commercially available integrated accelerometers.^{3,4} We are examining approaches based on capacitive sensing, but we feel that they currently do not offer the unambiguous signal generation (generating a correct code only in the desired environment) desired for high-consequence safety systems. The capacitive readout of a mechanical code embedded on the accelerometer, which would satisfy the need for unambiguous code generation, is problematic because of the necessary small size of the code features. It might be suggested that the measurement would be enhanced by using high frequency (microwave) electronics; however, microwave circuitry is generally not compatible with the degree of miniaturization obtained with silicon micromachines.

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Optical techniques offer the potential for real-time position detection on the order of the dimensions of the micromachine itself. Optical methods have been used for some time to measure the performance of various microengines. Gabriel *et al.* developed a laser-based probe for measuring real-time deceleration of unpowered turbines and gears.⁵ In their probe, a beam from a HeNe laser was focused onto the turbine or gear teeth and the scattered light was collected directly by a photodiode. The resulting signal allowed them to count teeth and thus measure turbine position versus time. For LIGA-fabricated micromotors, Guckel *et al.*⁶ and Sun *et al.*^{7,8} used integrated optical shaft encoders to record device motion. These encoders utilized photodiodes positioned below the device rotor and illuminated from above. Ruther *et al.* measured the bending of cantilevered beams with an integrated displacement sensor consisting of three fibers and a movable mirror in an optical bridge configuration.⁹ Dickey *et al.* developed an optical probe to measure rotational performance of microengines.^{10,11} These optical probes can be tightly integrated with both LIGA-based and surface fabrication-based microengines.^{12,13} The optical probe approach is analogous to techniques used in optical shaft encoders¹⁴ and optical disk technology.¹⁵ Linear micro encoders, consisting of two sources and detectors positioned in quadrature phase with respect to a pattern have also been constructed.¹⁶

2. SURFACE MICROMACHINE ACCELEROMETER AND READOUT

This paper describes the optical readout of an ESD that contains a surface micromachine accelerometer, shown in Fig. 1. The accelerometer contains a shuttle-mass with an embedded code and a spring suspension system that suspends the shuttle-mass above the substrate. Attached to one end of the shuttle-mass is a rack and pinion transmission and verge-escapement mechanism that provides a means for mechanical damping. Attached to the other end is a latch mechanism that is used to hold the shuttle-mass into position when the device is fully actuated. Under the influence of an appropriate acceleration environment, the suspended shuttle-mass will move 500 μm from the reset position to the fully actuated position. Mechanical stops are used to define the limits of travel. As the shuttle-mass translates, a verge-escapement mechanism mechanically damps the motion. This mechanism is similar to one found in a mechanical wristwatch. Verge escapement devices are commonly used as timing devices for safety mechanisms that must operate under various acceleration environments.

Fig. 1. MEMS accelerometer. The shuttle-mass measures 2.5 mm x 1.5 mm.

Fig. 2. Motor-driven version of accelerometer shuttle for laboratory testing. The shuttle-mass measures 1.3 mm x 0.6 mm.

Fig. 2 shows a motor-driven version of the accelerometer that is used to test the readout scheme in a laboratory setting. The shuttle mechanism uses a gold layer to improve reflectivity. A gold film 2000 Å thick is evaporated on the shuttle by a shadow masking process. Currently we are pursuing a gold lift-off process where the gold can be lithographically defined.

Embedded in the shuttle-mass are a series of slotted holes that represent four channels of information, two clock channels, one data channel (upper left in figures) and a reference channel (right of data channel in figures). The optical readout reads the four channels as the shuttle-mass translates past. The ESD uses the clock channel measurements and quadrature logic to read the data channel. This logic requires a data bit to be measured every time a clock channel changes state. The timing bits in the clock channels are set up so that as the shuttle-mass moves forward, clock one always changes state before clock two. Thus a means to determine the direction of translation is established. For example if the shuttle-mass were to move forward slightly and then return, clock one would change from a low state to high state and then back to a low state. The ESD is designed to read the data channel after clock one changes state from low to high, ignore clock one's change of state from high back to low, and wait for clock two to change from a low to high state before reading the next data bit. The reference channel is used by the ESD to establish the on and off states for the optical readout, so that the device compensates for changing signals due to aging or alignment effects.

The readout uses waveguide-based optics, which are implemented as a photonic integrated circuit (PIC). The PIC is flip-chip bonded over the micromachine, for a compact package, as shown in Fig. 3. The shuttle moves 500 μm during readout, and each code element is 17 μm wide. Where there are two or more adjacent "one" or "zero" bits, the code elements are made continuous. As shown in Fig. 3, the PIC contains an integrated laser that is incident upon a mirror at 22.5°. The mirror reflects the radiation at 45°, where it travels down to the accelerometer shuttle. The particular readout scheme makes use of backscattered radiation from etched features in the accelerometer shuttle, as illustrated in Fig. 4. Return radiation from "one" bits is collected by a detector located to the side of the mirror. The shuttle is etched to create corner reflectors that return radiation back toward the source for a "one" bit. The signal reflects from the shuttle wall and the substrate below the shuttle. For a "zero" bit, the shuttle is not etched, and the radiation scatters from the top of the shuttle in the forward direction, away from the detector. This arrangement provides a large signal difference between a "one" and "zero" signal, since the "zero" signal returns virtually no signal to the detector. It is thus superior to schemes that interrogate the code vertically, which have a limited contrast between a "one" and a "zero."

Fig. 3. Optical readout scheme. (a) The PIC is mounted above the moving shuttle. (b) Side view.

Fig. 4. Optical readout scheme for (a) a "one" bit and (b) a "zero" bit.

The PIC for this readout is currently in fabrication. Fig. 5 shows enabling technologies for the device. In Fig. 5(a), a waveguide splitter directs radiation to four channels, where it is directed at 45° to the waveguide plane by integrated mirrors. Fig. 5(b) shows an enlarged view of the integrated mirror designed to reflect the radiation at 45° to the waveguide plane. The final mirror contains a concave shape that focuses the beam at the shuttle in the axis of the shuttle motion. This allowed us to reduce the code width to $17\ \mu\text{m}$ per bit and thus reduce the total shuttle movement required. For signal detection, we originally located the detector around the mirror, to capture the backscatter radiation most efficiently. However, simulations showed that the backscatter mainly concentrated at the mirror, and little spread over to the detector.¹⁷ We then modified the layout by locating the detector to the side of the mirror, and rotating the mirror by 4° in an axis normal to the PIC plane to steer the return beam to the detector. This modification made fabrication of the mirror more difficult, but it greatly increased the return signal.

To test the backscatter/forward scatter readout scheme, a mock shuttle code was constructed by etching features into a silicon substrate. These features differed slightly from the actual shuttle implementation in that the mock code did not contain the $0.5\ \mu\text{m}$ gap between the shuttle and the substrate. The mock shuttle was also gold-coated. The mock shuttle was first examined under a microscope as shown in Fig. 6. The objective was to determine the contrast between "one" and "zero" bits. Fig. 7(a) shows a micrograph of a "one" code bit in normal view. Fig. 7(b) shows the same code bit tilted at 45° , with illumination from above. The code features are visible, but the surrounding substrate is dark. This shows how these features offer a wide dynamic range between "one" and a "zero" bits. The output from the camera was digitized, and the signal difference between the code and substrate signals was greater than 100 to 1. Fig. 7(c) shows the code bit tilted at 45° , with the illumination from the side. Now, the substrate reflects the illumination up to the camera while the code elements are dark. The contrast for an actual MEMS shuttle was also measured by using a microscope objective to focus an incoming beam on the shuttle and by measuring the return radiation with a detector. The uncoated MEMS shuttle had a contrast between "one" and "zero" bits of greater than 200 to 1, and gold-coated shuttles had a contrast of greater than 400 to 1.

Fig. 5. Enabling technologies for photonic integrated circuit (PIC) readout.
(a) Waveguides producing out-of-plane source signals. (b) Close-up of mirror.

Fig. 6. Scheme to examine forward and backscatter from mock code.

Fig. 7. Mock code features. (a) Normal incidence. (b) Code at 45° with light from above. (c) Code at 45° with light from the side.

3. SIMULATED READOUT SYSTEM

To simulate the shuttle moving under a fixed PIC as it would in an acceleration environment, a commercially available waveguide source was scanned over the mock code, as shown in Fig. 8. The single mode waveguide was connected to a HeNe laser source. A multimode fiber mounted below the waveguide collected the backscattered radiation. This arrangement was not ideal, because the backscattered light tended to return to the source waveguide rather than the collection fiber. The waveguide thus had to be backed away further from the code than desired, in order to capture sufficient return signal. The spot on the code was thus larger than would occur with the PIC device. This effect is seen in the micrograph of the simulated readout device shown in Fig. 9. The microscope was viewing the code at 45°, so the code is reflecting the backscattered illumination from the "one" bits back into the camera. The source radiation from the waveguide readout is also seen. The visible extent of the signal is much wider than the width of a code element. An isolated "one" bit is visible on the right. Nevertheless, the simulated arrangement provided a usable signal, as shown in Fig. 10. The figure shows the detected signal from the 24-bit code sequence, as the waveguide was scanned over the mock code (from right to left in Fig. 9). The figure also shows the signal from an ideal readout mechanism for comparison. The signals from "zero" bits that were surrounded by "one" bits did not completely return to zero. This is a consequence of the optical spot being larger than desired, and thus reading information on the boundaries of the desired code element. The effect is greatest for isolated "zero" bits.

Fig. 8. Simulated readout system. Detected signal as waveguide was scanned over mock pattern.

Fig. 9. Micrograph of simulated readout system signal on code element.

Fig. 10. Detected signal as waveguide was scanned over mock pattern.

4. CONCLUSIONS

This paper described the optical readout of a micromachine accelerometer. This particular readout scheme produces a unique binary signal that has a statistically low probability of being reproduced in an unintended environment. It is also relatively immune to noise sources due to its high contrast between the binary levels. Scanning a readout system over a fixed, mock code simulated the motion of the accelerometer under an optical readout. Even though the simulated readout produced a larger spot on the code than was desired, it still produced a usable signal. The final configuration of the device with a PIC readout is designed to produce an optical readout spot that is compatible with the width of a code element. It should thus produce a higher-contrast signal.

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