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Micromachined Accelerometers With Optical Interferometric Read-Out and Integrated Electrostatic Actuation

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Abstract

A micromachined accelerometer device structure with diffraction-based optical detection and integrated electrostatic actuation is introduced. The sensor consists of a bulk silicon proof mass electrode that moves vertically with respect to a rigid diffraction grating backplate electrode to provide interferometric detection resolution of the proof-mass displacement when illuminated with coherent light. The sensor architecture includes a monolithically integrated electrostatic actuation port that enables the application of precisely controlled broadband forces to the proof mass while the displacement is simultaneously and independently measured optically. This enables several useful features such as dynamic self-characterization and a variety of force-feedback modalities, including alteration of device dynamics *in situ*. These features are experimentally demonstrated with sensors that have been optoelectronically integrated into sub-cubic-millimeter volumes using an entirely surface-normal, rigid, and robust embodiment incorporating vertical cavity surface emitting lasers and integrated photodetector arrays. In addition to small form factor and high acceleration resolution, the ability to self-characterize and alter device dynamics *in situ* may be advantageous. This allows periodic calibration and *in situ* matching of sensor dynamics among an array of accelerometers or seismometers configured in a network.

Keywords

Acceleration measurement; diffraction; feedback system; optical interferometry

I. Introduction

HIGH RESOLUTION accelerometers with sub- μg performance have applications including inertial navigation, seismometry, and a variety of general diagnostic and instrumentation applications (note: $1\text{ g} = 9.81\text{ m/s}^2$). The realization of such sensors typically requires designs with both low thermal mechanical noise as well as high resolution displacement sensing of an integrated proof mass. Micromachined or MEMS-based accelerometers have the ability to address applications where both high resolution performance and small size and weight are important to ensure high-fidelity, nonintrusive measurements. A variety of displacement measurement principles have been employed in MEMS-based accelerometers, including piezoresistive, electron-tunneling, and optical methods [1], [2].

Piezoresistive methods have been used to achieve the state-of-the-art in small package-size, with the demonstration of 0.034 mm^3 fully packaged accelerometers aiming to address many biomedical applications [2]. The state-of-the-art in resolution has been achieved using electron-tunneling methods which have the ability to resolve remarkably small proof mass displacements—on the order of $10 \text{ fm}/\sqrt{\text{Hz}}$. A $20 \text{ ng}/\sqrt{\text{Hz}}$ thermal noise limited sensor has been demonstrated, which also incorporated an electrostatic force rebalance scheme to achieve a high bandwidth of 1.5 kHz [1]. Reference [1] incorporates a comparison of these noise and bandwidth figures with respect to many MEMS and non-MEMS accelerometers.

Optical-based methods also have the potential to address high resolution applications. Compact integration of MEMS-based optical accelerometers has been demonstrated with a direct intensity modulated scheme (i.e., noninterferometric) and integration of photodiodes (PDs) and readout electronics on the same chip [3]. Loh *et al.* [4] recently demonstrated a MEMS-based optical accelerometer employing an inter-digitated diffraction-grating-based interferometer to measure displacements of an integrated bulk-silicon proof mass with subangstrom resolution. In this case, a set of grating fingers attached to the proof mass is interleaved with and moves vertically with respect to a reference grating at the surface. Several advantages of this optical approach were demonstrated including a simple and versatile fabrication process, a flexible and versatile mechanical design space, and $40 \text{ ng}/\sqrt{\text{Hz}}$ acceleration resolution enabled by subangstrom displacement resolving capability of the interferometric readout.

In this work, we introduce an optical accelerometer with these same benefits and with a similar sensing structure, but more directly influenced by architectures employed in microphones, ultrasound transducers, and atomic force microscope probes we have been developing over the past several years [5]-[7]. Three unique contributions of this work are: 1) the demonstration of a novel device structure with a bulk silicon proof mass and a large mechanical design space—enabling both low-frequency designs and broadband designs with over 10 kHz bandwidth, 2) optoelectronic integration of the sensor into a robust subcubic millimeter package, and 3) the demonstration of a variety of features enabled by a monolithically integrated electrostatic actuation port. These include a self-tuning feature of the interferometer, a self-dynamic characterization capability, and a variety of force-feedback modalities that can be used for enhanced dynamic range and for alteration of the device dynamics *in situ*.

The sensor architecture is summarized schematically in Fig. 1. The silicon structure consists of a bulk silicon proof mass anchored to surface-micromachined springs and suspended above a rigid diffraction-grating back-electrode. An integrated semiconductor laser such as a vertical cavity surface emitting laser (VCSEL) on a separate substrate illuminates the structure, with a portion of the incident light reflecting directly off of the grating and a portion traveling between the grating fingers and to the vibrating proof mass to accrue additional phase. As described in detail previously, a diffracted field is created consisting of zero and higher orders whose angles remain fixed, but whose intensities are modulated by the proof mass displacement with the sensitivity of a Michelson-type interferometer [8]. As shown in Fig. 1, photodetection electronics are integrated on the same plane as the light source to form compact optoelectronically integrated sensors occupying volumes on the order of 1 mm^3 . The proof-mass and diffraction grating electrode are both made electrically conductive and form an electrostatic actuation port through which internal forces can be applied to the proof mass from dc to over 100 kHz while the resulting proof mass displacement is simultaneously and independently measured with the integrated optical readout. The force feedback electrodes labeled in Fig. 1 residing above the proof mass are optional and allow the proof mass to be actuated in the opposing direction.

In what follows, the design and microfabrication of the silicon structure are discussed and that is followed by a summary of the optoelectronic integration design and implementation. The self-tuning and self dynamic characterization capabilities afforded by the isolated actuation and detection ports are then experimentally demonstrated with integrated sensors. Force-feedback modalities are also demonstrated in a series of experiments where the device response is significantly softened and then stiffened.

II. Design and Microfabrication of Silicon Structure

The silicon structures were fabricated using the SUMMiT-lite process at Sandia, which uses a subset of the layers comprising the full SUMMiT process [9]. A 3-D model cross section of the final structure is shown in Fig. 2. The polysilicon reflector shown in blue in Fig. 2(a) is a circular plate connecting the three proof-mass sections together. Suspension springs are also formed in this polysilicon layer and anchor the plate to the silicon surface. In Fig. 2(b) the reflector is removed to show the details of the support arms, proof mass, and the grating structure. The support arms hold the diffraction grating rigidly in place beneath the vibrating proof mass structure.

The process begins on 6-in silicon wafers with $0.6\text{ }\mu\text{m}$ thermally grown oxide and $0.8\text{ }\mu\text{m}$ low-stress silicon nitride. The grating fingers are formed in this silicon nitride layer, a micrograph of which is shown in Fig. 3(d). The next layer is a $0.3\text{ }\mu\text{m}$ heavily doped polysilicon, which is used for electrical routing and electrode plates. This polysilicon layer exists along the rigid three-arm structure shown in Fig. 2(b) to form the bottom electrode of the electrostatic actuation port. A sacrificial oxide of $2\text{ }\mu\text{m}$ thickness is deposited and planarized using chemical mechanical polishing. Next, a $2.25\text{ }\mu\text{m}$ polysilicon layer forms the top reflector, springs, anchors, and other mechanical structures including the mechanical fuse shown in Fig. 3(b). This fuse is used to support the proof mass during the final processing steps and is destroyed prior to operation by applying a short current pulse. The polysilicon reflector itself forms the top electrostatic actuation electrode. After Bosch etching of features on the back side (optical path for the grating/reflector, support arms, and proof mass sections) and a release etch that removes the sacrificial oxide layers, 100 nm of gold is evaporated from the back side to improve the reflectivity of the grating and the reflector. A variety of designs with varying size and boundary conditions were fabricated, including the spring mounted structures shown in Fig. 3(a) and (b), and clamped structures designed for broadband applications shown in Fig. 3(c).

III. Optoelectronic Design and Integration

For simplicity, the schematic in Fig. 1 depicts the incident and diffracted light beams as collimated rays, while in reality the beams may exhibit significant divergence. Excessive divergence is problematic and causes overlap between the zero and higher diffracted orders, and consequently, reduction in modulation efficiency due to blending of their complementary signals [8]. Some degree of divergence, however, enables the conceptual integration embodiment summarized in Fig. 4(a) which shows a mask layout of the GaAs substrate in Fig. 1 from the topside view. In this design, a VCSEL mesa is centered among a three-element PD array designed to capture the returning zero order beam at the center and the $+1$ and -1 diffracted orders at each side. In this design, the departing beam from the VCSEL aperture has a typical beam waist on the order of several micrometers, while the returning zero order reflected beam fills the center PD labeled “PD(0)” in Fig. 4(a). The output signal from the sensor is then derived by subtracting the zero and first order photocurrents. This integration approach is robust—it being ultraminiature, entirely surface-normal, and free of any critical tilt or alignment problems. The feedback of the reflected zero order beam power back into the VCSEL can be minimized below a fraction of a percent by virtue of divergence.

A custom near-field Fourier optics code has been developed and utilized to study the critical design parameters of this approach, including the distance between the VCSEL plane and the grating, and the geometric parameters defining the PD array. The code takes into account complexities of the source beam (ex. divergence of the source beam which results in the illumination of the grating system with highly curved rather than planar wavefronts) by decomposing the source plane into a spectrum of plane waves, subsequently processing the plane wave components and their interaction with the grating, and re-assembling the plane wave components via inverse fast Fourier transform (FFT) operations to create the physical intensity field resulting at the plane of the PD array. The output of the model is a 2-D mapping of diffracted order intensities at the photodetector plane [i.e., plane of the GaAs substrate in Figs. 1 and 4(a)].

An example simulation output is shown in Fig. 4(b), where a single mode VCSEL with 850 nm wavelength and $7\text{ }\mu\text{m}$ Gaussian beam waist is input as the light source, and the VCSEL-grating separation is $700\text{ }\mu\text{m}$. These source properties result in approximately 3° divergence angle (full-width at half-maximum), which is, for example, characteristic of single mode VCSELs with integrated refractive μ -lenses [10]. The PD array from Fig. 4(a) is superimposed on the simulation output in Fig. 4(b) to emphasize how the simulation results directly influence the chip layout. As the dimensions of the x -axis and y -axis in Fig. 4(b) make clear, the essential optoelectronic integration hardware is contained within a $600\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ footprint, and a 0.042 mm^3 volume given the $700\text{ }\mu\text{m}$ working distance.

The GaAs components housing the custom VCSEL and PD array have been fabricated using the advanced fabrication capabilities of the Compound Semiconductor Research Laboratory at Sandia National Labs [11], [12]. A micrograph of a packaged GaAs die is presented in Fig. 4(c). The silicon structure is rigidly mounted above this structure as highlighted in Fig. 3(a) to form integrated prototypes used for experimental characterization. In addition to the custom fabricated GaAs components housing the VCSEL and PD array on a single chip, implementations employing multiple discrete PD and VCSEL components were also successfully developed which provide more versatility with respect to PD array dimensions, etc, while prototyping. Both types of implementations have been used to obtain the data presented in this manuscript and, in all cases, the overall optics package remains below 1 mm^3 . Furthermore, in all cases, a lensless embodiment is used with a single mode VCSEL divergence of approximately 8° .

IV. Experimental Results and Discussion

The impulse response of an accelerometer provides both the quality factor (Q) and frequency of the resonance which determine the useable bandwidth and, together with the known mass, the theoretical thermal noise level of the sensor. With the sensor technology under development, this critical data can be derived using the electrostatic actuation port to impart precisely controlled broadband forces to the proof mass while the resulting vibration is measured optically. This is experimentally demonstrated in Fig. 5(a), where the displacement of the proof mass is recorded in response to a broadband force impulse of $1\text{-}\mu\text{s}$ duration. In this experiment, the integrated sensor is placed in a reduced pressure environment ($\sim 100\text{ mtorr}$) to realize the high Q resonance condition that could be characteristic of silicon structures vacuum packaged at the wafer level [13], [14]. The FFT of the trace in Fig. 5(a) provides the dynamic frequency response of this sensor under these conditions and is shown in Fig. 5(b), where a flat response to approximately 3 kHz and a resonance at 5.4 kHz is observed. This particular structure has 1.5 mm diameter and clamped boundary conditions as illustrated in Fig. 3(c). In this experiment and for the remaining experiments presented in this paper, the photocurrent output from the integrated sensors is amplified with an off-chip transimpedance amplifier placed in close proximity.

Similar tests have been performed on spring-mounted devices designed for lower frequency applications. The dynamic frequency response of a 1.5-mm-diameter spring-mounted structure as illustrated in Fig. 3(b) is presented in Fig. 6. A simple single DOF system model is fitted to the response to accurately extract the resonant frequency and Q . These parameters, together with the mass which can be accurately approximated given the proof mass dimensions and well-known density of silicon, provide the information required to assess the acceleration-equivalent thermal-mechanical noise level, a_{tm} , of this sensor via the relation [15]

$$a_{\text{tm}} = \sqrt{\frac{8\pi k_b T f_0}{mQ}}.$$

The parameters for the device studied in Fig. 6 are: $f_0 = 220$ Hz, $Q = 100$, and $m = 1.2$ mg, providing a fundamental thermal noise limit of $a_{\text{tm}} = 43.7$ ng/ $\sqrt{\text{Hz}}$. These figures are ideal for ground sensing applications which require a sub-100 ng/ $\sqrt{\text{Hz}}$ detection resolution in the 1-200 Hz frequency range. Some additional applications require broadband detection up to 20 kHz, which is in-part the motivation for experimenting with and demonstrating silicon structures with different boundary conditions (i.e., both clamped and springmounted structures). The self dynamic characterization capability illustrated in these experiments may prove useful in applications where one wishes to calibrate a large network of such sensors *in situ* before, periodically during, and after a test sequence to ensure the properties of the sensors remain consistent through the test.

An additional feature enabled by the dual actuation and detection ports is the alteration of the device dynamics through various force feedback modalities. In these cases, the proof mass displacement information is extracted and a reactionary electrostatic force is applied in a closed-feedback configuration to emulate any mechanical impedance desired. For example, forces directly proportional to the measured displacement emulate a mechanical spring and stiffen the device response, whereas forces in proportion to the second derivative of displacement emulate additional mass. This general technique has been used in atomic force microscopy measurement systems where, most commonly, the feedback is used to critically damp the cantilever response for enhanced imaging speed while preserving the low thermal mechanical noise levels characteristic of the open-loop high- Q resonance of the cantilever—a technique referred to as Q -control [16]. Actuation methods in these cases have included remote thermal and magnetic actuation of modified cantilevers, as well as piezoelectric actuation with electrodes integrated directly on the cantilever [16]-[18].

Experimental demonstration of force feedback is presented via measurements on a 1.5-mm-diameter integrated sensor using the setup shown in Fig. 7. The optical accelerometer is rigidly mounted on a broadband commercial Kistler accelerometer (Model # 8636C50) with a known flat frequency response and scale factor (i.e., 0.99 V/g) for calibration purposes. Both accelerometers are rigidly attached to a commercial shaker (Ling Dynamic Systems, Model No V102) as shown in Fig. 7. The shaker is excited with a broadband chirp input while the spectral response of the test accelerometer is normalized to that of the commercial accelerometer to obtain the dynamic frequency response labeled “no feedback” in Fig. 8. To demonstrate force feedback, the displacement output from the optical accelerometer is fed back into its electrostatic actuation port after passing through electronics providing the desired gain and filter function as illustrated by the feedback loop shown in Fig. 7. The ac actuation levels are small (i.e., ~ 100 mV) relative to the dc bias actuation level (i.e., 6.2 V) to ensure linearity in the actuation. The dc bias port (shown in Fig. 7) serves the additional function of adjusting and maintaining the proof-mass position to a point of quadrature¹ of the interferometer, thereby providing a self-tuning feature as has been demonstrated in prior developments [5]. In this demonstration, we stiffen the structure by applying a flat gain—emulating a mechanical spring. The green curve shows the mechanical frequency response with feedback, where the bandwidth

of the structure has been increased at the expense of sensitivity. The resonant frequency of the device has been shifted from 4.5 to 6.4 kHz in this case, corresponding to approximately a doubling of device stiffness. This is consistent with the 6 dB decrease in sensitivity that can also be observed in Fig. 8. A change in sign of the gain emulates a negative spring, and the resulting response in this case is shown in the red trace where a decrease in resonant frequency and Q and an increase in sensitivity can be observed. The ability afforded by the sensor technology to alter and tweak device dynamics quickly and *in situ* may prove valuable in field experiments where realizing matched dynamic properties among elements in a large network of accelerometers or seismometers is advantageous.

A particular implementation of force feedback common to accelerometers is one in which the proof-mass is held motionless by design of the gain function in Fig. 7. With this force rebalance approach, the “signal-output” in Fig. 7 is held to zero as the error function in the feedback loop, and the electrostatic actuation voltage used to counterbalance the input force is derived as the output signal of the device [19], [20]. Generally speaking, this technique demands larger feedback forces and therefore methods for maintaining linearity in the inherently nonlinear electrostatic actuation scheme. The presence of the additional top electrode shown schematically in Fig. 1 is advantageous in this case, as the use of dual actuation electrodes enables a differential actuation scheme in which the quadratic terms in the equations describing the actuator cancel. This linearization technique is one of several summarized by Boser and Howe [19].

The acceleration detection resolution in this measurement set-up for the no-feedback case has been assessed by turning off the shaker and reading the voltage noise spectra at the sensor output which is referred to as units of acceleration using the calibrated sensitivity in Fig. 8. The spectral density at 1 kHz is measured as $24.4 \mu\text{g}/\sqrt{\text{Hz}}$ —most likely limited by ambient vibrations as little effort has been made in these experiments to quiet the surroundings. Rigorous characterization of self-noise for the integrated sensor structure and development of a detailed SNR model incorporating force-feedback operation with experimental validation is the subject of future work. The detailed noise considerations presented by Loh *et al.* [4] in a grating-based interferometer are applicable to this structure as well—given the similarity of the interferometric detection approach. It is therefore anticipated that 20-40 ng/ $\sqrt{\text{Hz}}$ resolution can be achieved in an open loop configuration from structures with approximately 100 Hz mechanical resonance, and that a force rebalance modality similar to that rigorously studied by Liu and Kenny [1] can be used to achieve over 1 kHz bandwidth.

V. Conclusion

We have presented a new micromachined diffraction-based optical accelerometer device structure with a flexible design space accommodating both low frequency and broadband designs. The approach provides a displacement detection sensitivity of the proof mass independent of the mechanical design—uncoupling the mechanical and electrical design space. Furthermore, the optical detection port is isolated from an electrostatic actuation port which enables the application of precisely controlled broadband forces to the proof mass. This ability enables several useful features: 1) dc actuation for self-tuning of the interferometer quadrature; 2) dynamic self-characterization and self-calibration, and 3) force-feedback modalities for altering device dynamics and enhancing dynamic range. These capabilities have been demonstrated on entirely surface-normal optoelectronically integrated prototypes containing integrated VCSELs and photodetection electronics in sub-1 mm³ volumes, the design of which

¹Maintaining quadrature means ensuring the gap thickness between the grating and proof mass corresponds to a point of maximum slope on the optical interference curve (i.e., light intensity versus proof mass displacement curve) to ensure maximum displacement sensitivity and linearity.

has been enabled by a custom nearfield diffractive optics model. Future work on device design for low cross-axis and temperature sensitivity and vacuum packaging at the wafer level for low frequency and nano-*g* resolution may result in a new family of accelerometers and seismometers to address a broad range of applications.

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Fig. 1.
Schematic of the integrated sensor technology.

Fig. 2. Computer-generated 3-D cross sections of the silicon accelerometer structure with (a) the reflector plate shown and (b) the reflector plate removed to show the details of the proof mass and rigid electrode which holds the grating.

Fig. 3. Micrographs of fabricated silicon structures from (a-c) the topside view, and (d) a backside view showing the optical diffraction grating.

Fig. 4.

(a) Mask layout of the GaAs chip housing a VCSEL and four-element integrated PD array with two zero order PDs positioned above and below the VCSEL mesa, and larger +1 and -1 PDs positioned to its right and left, (b) simulated field intensity at the photodetector plane for a design with $700\text{ }\mu\text{m}$ working distance, and (c) micrograph of a fabricated and packaged GaAs die.

Fig. 5.

(a) Measured impulse response of a clamped accelerometer structure designed for broadband applications, and (b) FFT of the impulse response in (a) (i.e., the dynamic frequency response for this device).

Fig. 6. Measured and simulated dynamic frequency response functions of a spring-supported proof mass structure designed for low frequency and high resolution.

Fig. 7.
Schematic of the experimental set-up used for demonstration of force-feedback and alteration of sensor dynamics.

Fig. 8. Measured dynamic response of a clamped accelerometer structure with no force-feedback applied and with positive and negative feedback gain applied for softening and stiffening the response, respectively.