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IN-PLANE NANO-G ACCELEROMETER BASED ON AN OPTICAL RESONANT DETECTION SYSTEM

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Abstract: We have successfully demonstrated a series of results that push the limits of optical sensing, acceleration sensing and lithography. We previously built some of the most sensitive displacement sensors with displacement sensitivities as low as 12 fm/√Hz at 1 kHz. Using reference detection circuitry in conjunction with correlated double sampling methods, we have lowered the 1/f noise floor to 10 milli-Hz, hence improving the detection limit at low frequencies (10 milli-Hz) from 37 pm/√Hz to 50 fm/√Hz i.e. by 57.3 dB. We have developed the capability to convert these highly sensitive displacement sensors to highly sensitive acceleration sensors through innovative low-stress mass addition and direct mass integration processes. We have built accelerometers with resonant frequencies as low as 43 Hz and thermal noise floors as low as 10 nG/√Hz. We have pushed the limits of shaker table experiments to verify direct acceleration measurements as low as 10 μG/√Hz.

Keywords: Nanograting, optical accelerometer, optical resonant detection, in-plane accelerometer, optical sensing, low-G accelerations.

1. INTRODUCTION

Previously we demonstrated extremely high-sensitivity motion detection with nanophotonic optical resonant sensors [1] based on multi-layer subwavelength-gratings [2] with displacement sensitivities as low as 12fm/√Hz at 1 kHz [2]. These nano-optic sensors comprised of nanogratings that modulate the intensity and polarization of an incident light source. This optical detection technique offers substantial noise reduction in the sensor [1, 2]. In our current work we pushed the limits of our sensor resolution by reducing *1/f* noise using specialized reference detection circuitry and correlated double sampling methods. Next, we added masses to these displacement sensors to build extremely high-resolution (nano-G) accelerometers and compared them to similar accelerometers reported in the past [3, 5, 6].

2. 1/f NOISE

Above several kHz, we can achieve the shot noise limit with commercially available reference detection circuitry. At lower frequencies, however, *1/f* components of both laser relative intensity noise (RIN) and amplifier noise dominate the response. Reducing the *1/f* noise in these optical MEMS sensors extends their range to ultra-low frequencies. In order to reduce laser intensity noise, we built the circuit in *Figure 1* [4] that implements a reference diode to subtract out RIN.

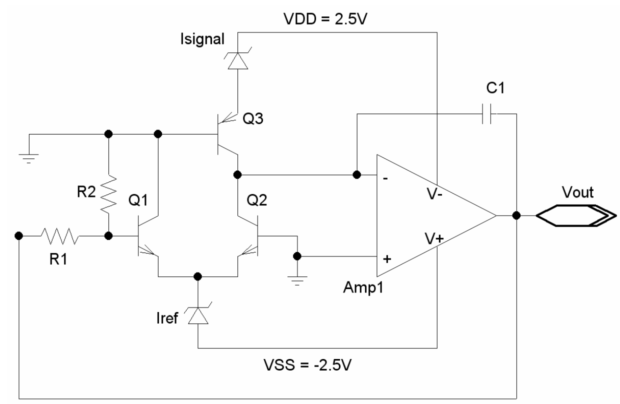

Figure 1. Readout circuit used to cancel laser relative intensity noise for nano-grating optical sensors.

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To further reduce the *1/f* corner and allow ultra-precise position measurement at very low frequencies a correlated double sampling (CDS) scheme was implemented. Combining custom reference detection circuitry and correlated double sampling reduced the *1/f* noise corner from *3kHz* to *10mHz* and improved the detection limit at low frequency (*10mHz*) from *37pm/√Hz* to *50fm/√Hz* or by *57dB (Figure 2)*.

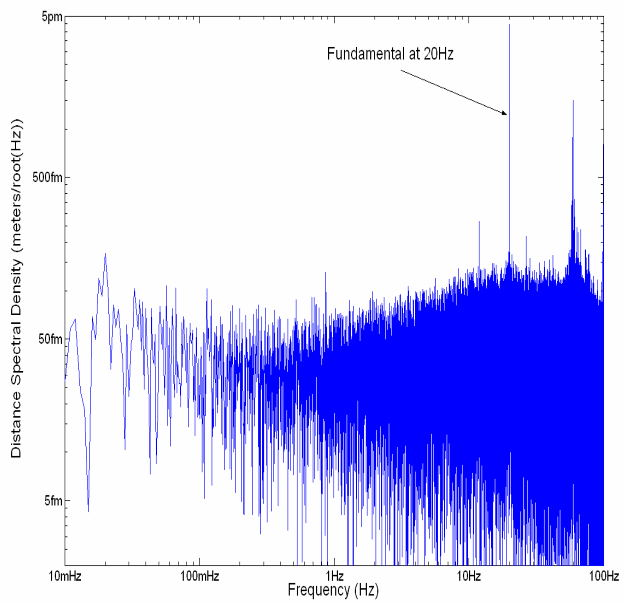


Figure 2. Displacement power spectral density of the reference detection circuit with correlated double sampling scheme when interfaced with an improved MEMS device. The detection limit, 50 fm/√Hz extends down below 10 mHz. The reference detection and correlated double sampling techniques described above have improved the displacement detection limit at low frequencies (10 mHz) by 740 or 57.3 dB.

3. NANO-G ACCELEROMETER

3.1 DESIGN

Next, adapting these high-sensitivity displacement sensors to measure nano-G accelerations (1nG = $9.8*10^{-9}$ m/s^2) requires decreasing their resonant frequencies based on the following equations:

$$a=\omega_o^2 x \tag{1}$$

where, 'a' is acceleration, 'x' is displacement and 'ω_o' is resonant frequency given by

$$\omega_o^2=k/m \tag{2}$$

where, 'k' is the sensor mechanical spring constant and 'm' is the sensor mass.

In this accelerometer design (*Figure 3*), both the mass and gratings are fabricated in silicon/polysilicon. A gimbal provides thermal isolation from the substrate to minimize expansion/contractions from thermal effects that affect the relative motion of the proof mass and optical sensor. The mass springs are designed for large motion in one direction with very high cross-axis rejection. Both analytical and finite-element models were used to optimize the gimbaled mass-spring system design. Through-wafer holes accommodate transmission detection schemes with the facility to package VCSELs and photodetectors above/below the device.

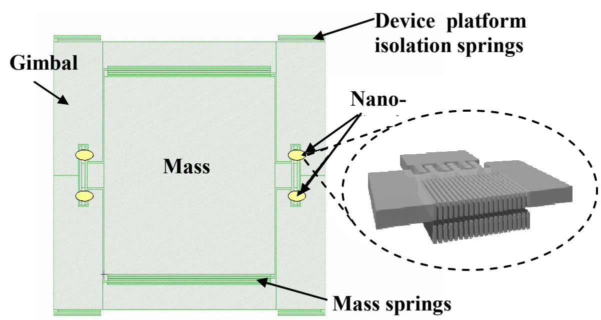


Figure 3. Integrated mass accelerometer design with device isolation platform and multiple nanogratings for differential sensing.

3.2 FABRICATION

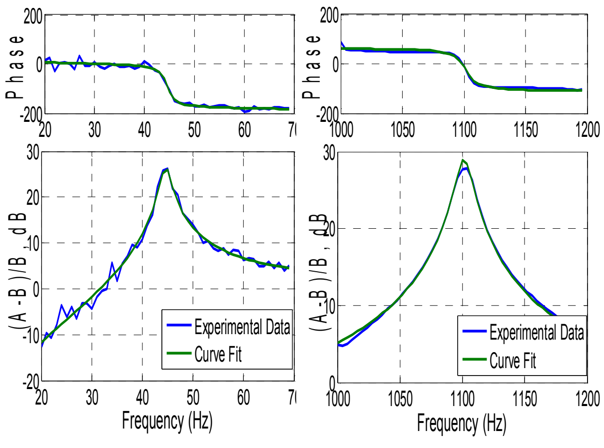
The accelerometers were fabricated at the Microsystems Development Laboratory (MDL) and Compound Semiconductor Research Laboratory (CSRL) within Sandia National Labs. The fabrication process combined surface micromachining and deep reactive ion etching (DRIE). The optical nanogratings were fabricated in polysilicon in a surface micromachining process while the proof-mass and related springs were defined in a through-wafer DRIE etch. These devices had proof-mass dimensions ~ $4500\mu m^2$ X $400\mu m$ i.e. mass of *18.9mg*.

3.3 RESULTS

We used a Laser Doppler Vibrometer (LDV) and shaker table to perform both dynamic and static mechanical tests on these nanograting accelerometers. We measured mass resonances as low as *43Hz (Table 1) (Figure 4)*.

Table 1. Nanograting accelerometer dynamic characteristics measured in air

Device	Resonant Freq. (Hz)		Q	
	Mass	Gimbal	Mass	Gimbal
1	44	1101	22	83
2	43	1131	18	113



(a) (b)

Figure 4. Phase/Amplitude frequency response characteristics (in air) for nanograting accelerometer (device 1): (a) Mass (b) Gimbal

To the best of our knowledge, these are the lowest resonances for MEMS accelerometers measured to date. We observed large mode separation between adjacent modes with spring constant ratios: $k_y/k_z>100$ and $k_y/k_x>10^5$. Spring constant ratio between gimbal and mass, $k_{y\_gimbal}/k_{y\_mass}=625$. Hence, this design provides significant decoupling between modes in the x, y and z directions for the sensor. These devices are inherently sensitive to handling and require specialized packaging.

We verified static displacement of the device for applied accelerations within the measurement system limits. A linear relationship between the nanograting displacements and applied acceleration was observed *(Figure 5)*. The measured results were 8X better than the simulation results. This can be attributed to the mechanical springs being weaker than the original designs due to overetching in the DRIE process.

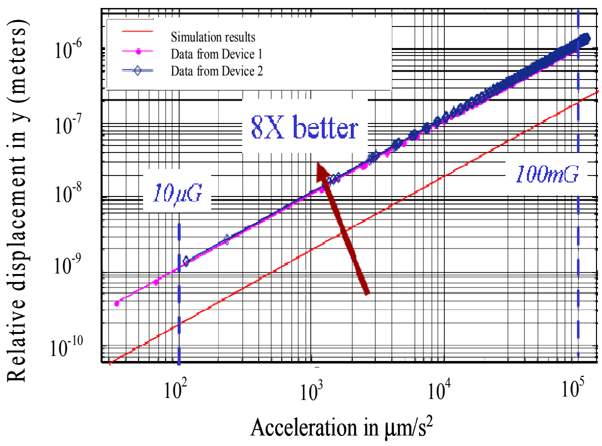


Figure 5. Verification of static characteristics of nanograting accelerometer using LDV setup on shaker table. Device performance is better than predicted because fabricated mass springs were weaker than the original design.

We measured displacements ~1nm for accelerations ~10µG and ~1µm for accelerations ~10mG. This yields an electronic noise floor of 0.5 nG/√Hz at frequencies as low as 10 milli-Hz. The proof mass thermal noise floor calculated from the following equation is *<10 nG/√Hz:*

$$a_{noise,rms} = \sqrt{\frac{4k_b T\omega_0}{mQ}} \quad (3)$$

where k_b = Boltzmann constant, and T = Absolute Temperature(K). To the best of our knowledge, these are the most sensitive MEMS accelerometers built to date and are 40dB more sensitive than the best reported in-plane MEMS accelerometers [5-6].

Considering the extreme sensitivity of these devices, they are inherently fragile and difficult to handle. Their tolerance for shock is very low and need special packaging for handling. We are currently in the process of developing more robust packaging for better shock survivability of these devices.

4. CONCLUSIONS

In this work, we successfully demonstrated a nanograting based optical accelerometer. We have previously shown displacement measurements of 12 fm/√Hz at 1 kHz based on this optical transduction mechanism. Here we have used innovative circuit techniques to extend this sensitivity to very low frequencies i.e. 50 fm/√Hz at 10 milli-Hz. We have successfully developed capabilities to integrate large masses to fragile surface micromachined nanogratings and create extremely sensitive accelerometers. We have built integrated masses with resonant frequency as low as 43 Hz which corresponds to a thermal noise floor of 10 nG/√Hz. To the best of our knowledge these are the most sensitive accelerometers made to date. Due to the extreme sensitivity of these devices, we developed custom packaging to compensate for the inherent fragility of these devices.

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