Sensors and Actuators A 145–146 (2008) 283–290

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

In-plane MEMS-based nano-g accelerometer with sub-wavelength optical resonant sensor

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ARTICLE INFO

Article history:
Received 30 June 2007
Received in revised form 11 March 2008
Accepted 11 March 2008
Available online 28 March 2008

Keywords:
Nano-grating
MEMS optical accelerometer
Optical resonant detection
In-plane accelerometer
Optical sensing
Low-g accelerations

ABSTRACT

We have successfully demonstrated a series of results that push the limits of optical sensing, acceleration sensing and lithography. Previously, we built some of the most sensitive displacement sensors with displacement sensitivities as low as 12 fm/$\sqrt{\text{Hz}}$ at 1 kHz. Using reference detection circuitry in conjunction with correlated double sampling methods, we lowered the 1/*f* noise floor to 10 mHz, hence improving the detection limit at low frequencies (10 mHz) by 77 dB to 50 fm/$\sqrt{\text{Hz}}$. We converted these highly sensitive displacement sensors to highly sensitive acceleration sensors through a direct mass integration processes. Our accelerometers have resonant frequencies as low as 36 Hz and thermal noise floors as low as 8 nG/$\sqrt{\text{Hz}}$ (where 1 G = 9.8 m/s^2). We have pushed the limits of shaker table experiments to independently verify acceleration measurements as low as 10 μG/$\sqrt{\text{Hz}}$. Direct measurements with our integrated sub-wavelength optical nano-grating accelerometers have shown device sensitivities of 590 V/G and noise floors corresponding to 17 nG/$\sqrt{\text{Hz}}$ (at 1 Hz).

1. Introduction

There is growing interest in extremely high-sensitivity, compact accelerometers (nano-g sensitivity where 1 nano-g = 9.81 × 10^{-9} m/s^2) for a growing list of applications including high-precision inertial navigation and seismic sensing for geophysical and oil-field applications. Such applications require measurement of extremely small acceleration signals (nG/$\sqrt{\text{Hz}}$) at very low frequencies (<100 Hz). Currently there are no chip-scale, compact accelerometers that meet these high-sensitivity and low-bandwidth requirements.

The fundamental challenges in building such a device include designing very high sensitivity displacement sensors with low thermo-mechanical noise and minimizing 1/*f* noise. A practical challenge in building these accelerometers on a micro-scale is in integrating a large enough proof mass to the displacement sensor and meet the sensitivity requirements for the device (since larger mass relates to better sensitivity).

Our first step in building this accelerometer was to identify and demonstrate a high-sensitivity optical displacement/motion sensing mechanism. Previously, optical sensing mechanisms based-on diffraction-gratings have been used to demonstrate sub-angstrom scale sensitivity [1]. Advantages of optical detection techniques compared to capacitive or piezoresistive methods include high sensitivity and performance close to the Brownian noise limits of the mechanical structure [2,3].

An in-plane nanophotonic resonant sensor based on multi-layer sub-wavelength optical gratings was developed [2–4]. This nano-optic sensor comprised of two sets of nano-gratings that modulate the near-field intensity and polarization of an incident light source based on the relative lateral motion of the two gratings. The in-plane sensing mechanism offers the advantage of single-chip solutions to multiple axis motion/acceleration detection. We have previously published results from these sensors demonstrating displacement sensitivities as low as 12 fm/$\sqrt{\text{Hz}}$ at 1 kHz [2,3].

Further, we improved sensor performance at lower frequencies to suit our target applications such as precision inertial navigation and seismic applications. We dramatically improved sensor resolution by reducing 1/*f* noise limits in our detection circuitry through design and implementation of specialized reference detection circuitry and correlated double sampling methods [5]. Next, we added masses to these delicate sub-wavelength nano-grating-based displacement sensors to build extremely high-resolution accelerometers and compared them to similar accelerometers reported in the past [7,8].

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0924-4247/$ – see front matter
doi:10.1016/j.sna.2008.03.017

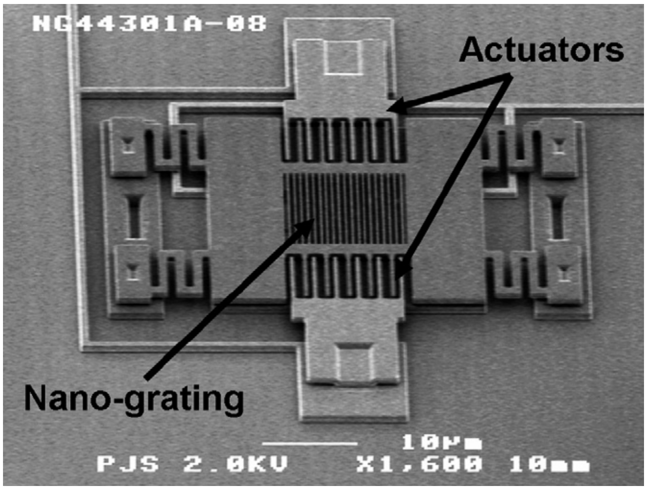

Fig. 1. MEMS optical near-field resonant displacement sensor based on vertically stacked sub-wavelength nano-gratings. The nano-gratings are attached to electrostatic actuators to control their motion and characterize their displacement sensitivity [3].

2. MEMS optical displacement sensor

Previously, we demonstrated a new class of nano-grating based optical MEMS resonant sensors with extremely high lateral displacement sensitivities ($12\,\mathrm{fm}/\sqrt{\mathrm{Hz}}$ at 1 kHz) and greater than 120 dB of open loop dynamic range [3]. As mentioned earlier, these sensors consist of two vertically offset layers of sub-wavelength polysilicon nano-gratings separated by an air gap. They modulate the near-field intensity and polarization of an incident light source in response to relative motion of the nano-gratings [2,3]. The reflected/transmitted optical beam intensity from the nano-gratings is measured as a function of the relative lateral positions of the nano-gratings. Electrostatic actuators were integrated into the sensor to control nano-grating motion and measure the displacement sensitivity. Typical devices showed 10%/nm change in reflectance vs. lateral position. [2]. A detailed description and principle of operation of this near-field MEMS optical resonant sensor can be found in [4]. An SEM of this device is shown in Fig. 1. The high sensitivity of this sensor made it a natural choice to be the basis for our accelerometer design.

3. 1/*f* noise

Above several kHz, we can achieve the shot noise limit with commercially available reference detection circuitry. However, at the lower frequencies needed for our applications outlined earlier, 1/*f* components of both laser relative intensity noise (RIN) and amplifier noise dominate the response. This degrades the sensitivity of the nano-grating sensors in applications that require excellent sensitivity at frequencies below 100 Hz. Reducing the 1/*f* noise in these optical MEMS sensors is critical in extending their range to these ultra-low frequencies.

In order to reduce 1/*f* noise, we designed and built reference detection low noise readout circuitry that cancels laser relative intensity noise (RIN) to frequencies as low as 0.7 Hz [5]. The low frequency bandwidth of the sensor system was further reduced to <10 mHz using a new MEMS correlated double sampling technique that canceled low frequency RIN, drift, and circuit 1/*f* noise by greater than 77 dB [5].

The reference detection circuit (Fig. 2) implements the architecture presented in [6] but optimized for low frequency performance. An additional reference diode is included in the circuit that cancels laser RIN. Details of this laser noise cancellation circuitry and related analysis are published in [5].

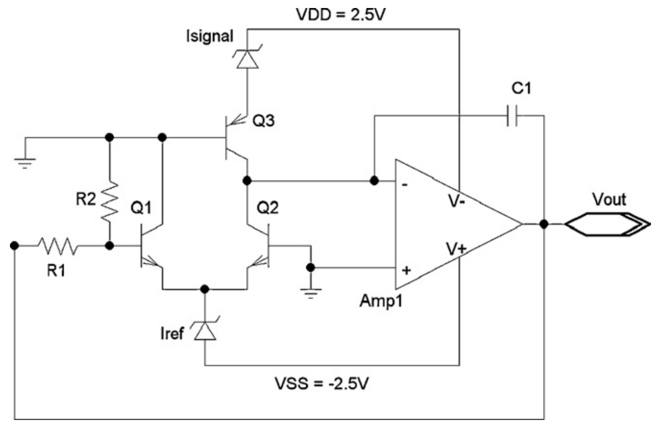

Fig. 2. Readout circuit used to cancel laser relative intensity noise for nano-grating optical sensors [5].

While the reference detection circuitry rejects over 60 dB of laser RIN, more rejection is needed to achieve the low frequency performance requirements for our target applications. To further reduce the 1/*f* corner and allow ultra-precise position measurement at very low frequencies a micromechanical correlated double sampling (CDS) scheme was implemented [5].

The correlated double sampling technique uses the MEMS grating element to perform the sampling. First, the electrostatic actuators drive the nano-grating (shown in Fig. 1) to a known position (Ex: zero displacement). This first sample position measurement is quantized. This measurement is used as a reference for the actual displacement measurement. The two signals are subtracted digitally to further reduce the 1/*f* laser noise at the output. This method requires the bandwidth of the electrostatically driven MEMS device and the associated readout circuit to be at least three times the sampling frequency to implement this scheme. Because of aliased RIN, shot, and circuit noise the white noise floor is increased by $\sqrt{6}$. However, this technique does cancel any low frequency noise in the laser, position sensor, photodiodes, or reference detection circuitry due to 1/*f* noise, drift, or thermal effects.

Hence, combining custom reference detection circuitry and correlated double sampling methodology, we reduced the 1/*f* noise corner to 10 mHz and improved the detection limit at low frequency (10 mHz) by 77 dB to $50\,\mathrm{fm}/\sqrt{\mathrm{Hz}}$ (Fig. 3).

4. Nano-g accelerometer

4.1. Operating principle

Building accelerometers from these high sensitivity displacement sensors involves the integration of an appropriate proof mass. The acceleration experienced by of this proof mass is directly proportional to its displacement as shown in the following equation:

$$a = \omega_0^2 x \tag{1}$$

where a is acceleration experienced by the proof mass, x is its displacement and ω_0 is resonant frequency of the proof mass given by

$$\omega_0^2 = \frac{k}{m} \tag{2}$$

where k is its mechanical spring constant and m is its mass.