Two-Wavelength Grating Interferometry for MEMS Sensors

Onur Ferhanoglu, M. Fatih Toy, and Hakan Urey

***Abstract*—Diffraction gratings integrated with micro-electro-mechanical-systems (MEMS) offer shot noise limited sub-nanometer displacement detection sensitivities but are limited in detection range for mechanical transducers. A two-wavelength readout method is developed that maintains high sensitivity while increasing the detection range, which is demonstrated using a MEMS spectrometer with integrated diffraction grating. The two-laser illumination extended the detection range from 105 nm to 1.7 μm assuming the readout sensitivity is maintained at $>50\%$ of the maximum sensitivity.**

***Index Terms*—Grating interferometry, micro-electro-mechanical-systems (MEMS), optical sensing, two-wavelength interferometry.**

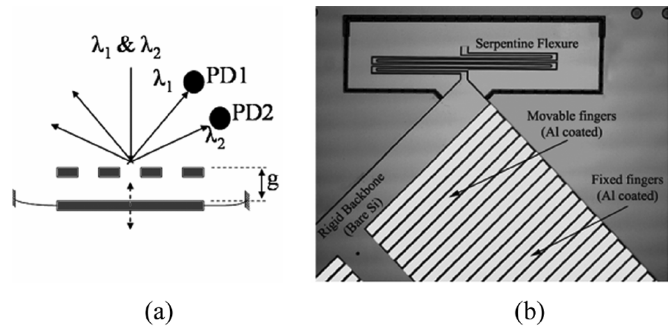

Fig 1. (a) Side view of the setup with fixed grating and the moving platform for gap modulation. (b) MEMS IR spectrometer where alternating fingers of the grating are movable.

I. Introduction

Diffraction grating interferometry is an attractive method for micro-electro-mechanical-system (MEMS) devices to detect subnanometer displacements due to its high sensitivity with shot noise level detection capability [1]. However, the maximum detectable range is limited to $\lambda/4$ of the readout wavelength. In this paper, we present a two-wavelength readout method, which offers high sensitivity and long operation range, extending the capabilities of MEMS grating-based optical sensors.

The main advantages of the grating based optical readout are that gratings can be micromachined and integrated with single or array of MEMS devices for ultrasonic sensor and atomic force microscopy (AFM) applications [1], [2], thermo-mechanical infrared (IR) detector array applications [3], [4], and can serve as comb actuators for Fourier transform spectroscopy applications [5], or other MEMS sensing and actuation applications such as biosensors and accelerometers [6]–[8].

Multiple-wave interferometry is an old technique demonstrated with classical interferometers [9]–[11]. In this paper, a sensitivity and range analysis were developed and the technique is modified for grating interferometry and demonstrated using MEMS devices with integrated diffraction gratings for increased performance.

II. Theory

Consider Fig. 1(a). The fingers and the moving mirror form a phase grating. Incoming light that is reflected from the fingers and the bottom mirror creates an interference pattern. The normalized first-order diffracted light intensity can be expressed as [1]

$$I_n(\lambda, g) = 0.5\left[1-\cos\left(\frac{4\pi}{\lambda}g\right)\right] \quad (1)$$

where g is the distance between the grating and the membrane and λ is the wavelength of the illuminating laser. I_n is a sinusoidal function of g with values in the range 0 and 1 with a period $\lambda/2$. Due to the periodic nature of the output intensity, the dynamic range of the grating interferometer is limited to $\lambda/4$ when a single monochromatic source is used. It is possible to overcome the range limitation by introducing a second (or more) laser light source.

Sensitivity is defined as the change rate of I_n with g and expressed as a simple sinusoid

$$S(\lambda, g) = \left|\frac{\partial I_n}{\partial g}\right| = \frac{2\pi}{\lambda}\left|\sin\left(\frac{4\pi}{\lambda}g\right)\right|. \quad (2)$$

The highest sensitivity for each wavelength is achieved at $g = \lambda/8 + m\lambda/4$, where m is an integer and results in the minimum detectable displacement (MDD) for the sensor. The best MDD value reported with single wavelength readout is 2×10^{-4} Å/Hz$^{1/2}$ at 20-kHz noise bandwidth (BW), corresponding to MDD of <3 pm using $\lambda = 650$ nm laser diode [1].

When a diffraction grating is illuminated by two lasers, the first-order intensities will be modulated with the gap according to their wavelengths as in (1). One can define the overall normalized sensitivity of the two-wavelength readout scheme as

$$S_{2\lambda}(\lambda_1, \lambda_2, g) = \left[\frac{\min\{\lambda_1, \lambda_2\}}{2\pi}\right]\max\{S(\lambda_1, g), S(\lambda_2, g)\}. \quad (3)$$

$S_{2\lambda}$ as a function of g is illustrated in Fig. 2. $S_{2\lambda}$ is dimensionless and periodic with period D, which can be calculated as

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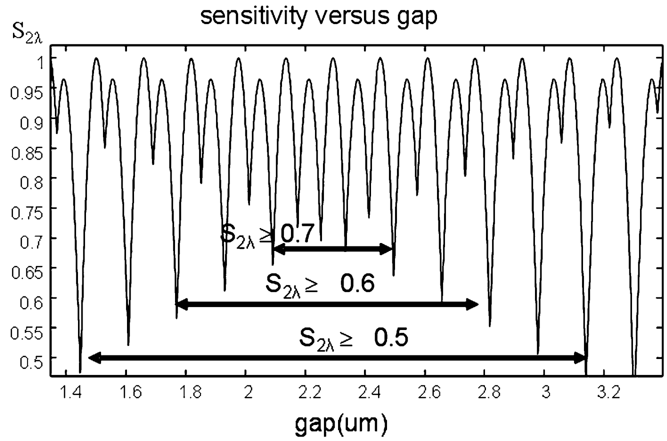

Fig. 2. Calculated normalized-sensitivity $(S_{2\lambda})$ versus gap using laser wavelengths of 633 and 656 nm. Horizontal arrows indicate ranges for different minimum sensitivity values.

TABLE I
RANGES FOR DIFFERENT SENSITIVITIES FOR ONE-WAVE READOUT (633 nm) AND TWO-WAVE READOUT (633 nm AND 656 nm) FULL RANGE GIVES THE PERIOD OF THE SENSITIVITY CURVE

	S > 0.7	S > 0.6	S > 0.5	Full range
1-wave readout	80 nm	95 nm	105nm	158 nm
2-wave readout	0.4 um	1 um	1.7 um	4.5 um

$$D = \frac{\lambda_1 \lambda_2}{4|\lambda_1 - \lambda_2|}. \quad (4)$$

The best range is achieved around a nominal gap value of $D/2$. The detection ranges can be found based on the predefined minimum acceptable sensitivity values, as illustrated in Fig. 2 with arrows.

The maximum possible unambiguous detection range is equal to D with compromise in sensitivity, and the range converges to that of one wavelength readout as the normalized sensitivity approaches unity. The range can be optimized by the selection of the two wavelengths. Range versus sensitivity values for single and two-wavelength grating interferometer are compared in Table I. Range values may be extended with smaller wavelength difference between the sources at the expense of a drop in normalized sensitivity.

III. EXPERIMENTAL RESULTS

The theory was tested on a MEMS Fourier transform spectrometer illustrated in Fig. 1(b), [5]. Comb fingers serve the purpose of both electrostatic actuation and moving diffraction grating. To achieve low-frequency nonresonant mode operation, some tests were conducted using part of the gratings and a separate moving micromechanical platform as illustrated in Fig. 1(a).

The device was illuminated using lasers with 633-nm and 656-nm wavelengths and the diffracted first orders were focused on two photodetectors. The MEMS device was actuated sinusoidally at 60 Hz. The data obtained from the photodetectors (PD) is shown in Fig. 3. Since the gap was modulated sinusoidally, the PD signals are chirped sinusoids.

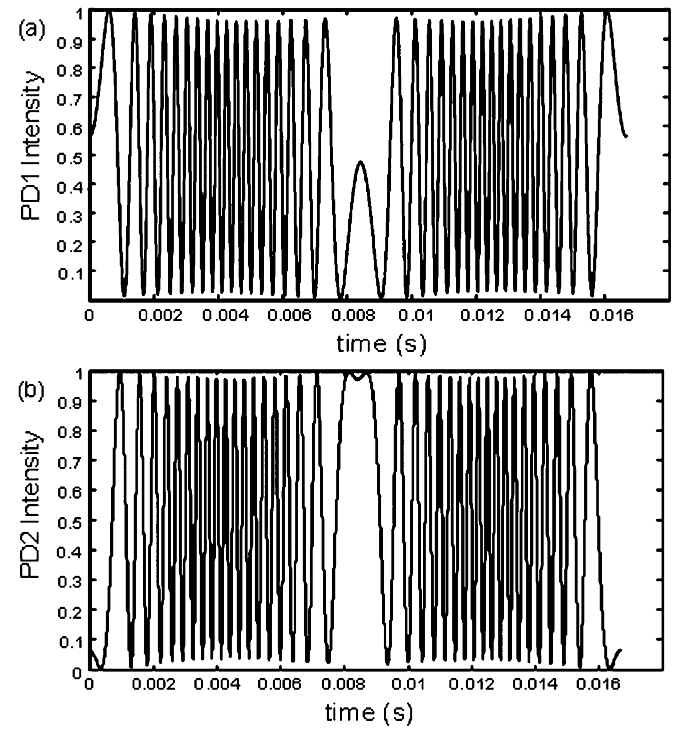

Fig. 3. Experimental photodetector data for two laser diode sources at (a) $\lambda_1 = 656$ nm and (b) $\lambda_2 = 633$ nm.

Using the two PD intensities, it is possible to back calculate the possible gap values for each wavelength

$$g_{\lambda_1} = \frac{\lambda_1}{4\pi}\cos^{-1}(1 - 2I_{\lambda_1}) \pm m_1 \frac{\lambda_1}{2}$$
$$g_{\lambda_2} = \frac{\lambda_2}{4\pi}\cos^{-1}(1 - 2I_{\lambda_2}) \pm m_2 \frac{\lambda_2}{2} \quad (5)$$

where m_1 and m_2 are constant integers. To converge to a unique solution, a particular m_1 and m_2 combination is selected to minimize the error function $g = |g_{\lambda 1} - g_{\lambda 2}|$. Of the two solutions $g_{\lambda 1}$ and $g_{\lambda 2}$, the one with the higher sensitivity S_n at that particular gap value is used as the resultant solution. For a specific time instance, gap value that is closest to the gap value at previous time instance is selected. Such a thresholding avoids sudden jumps and enables gap calculations exceeding the full range. The corresponding peak-to-peak displacement was calculated to be about 6 um using the normalized intensities as shown in Fig. 4. The displacement curve shows sinusoidal behavior at the same frequency with the driving signal as expected.

A calibration measurement has to be taken from each sensor to determine the maximum and the minimum intensities corresponding to each photodiode output. When one is dealing with deflections smaller than $\lambda/4$, a similar procedure should apply and the peak intensities determined prior to the experiment would be needed. Laser noise reduction and active calibration can be performed by simultaneously monitoring the zeroth-order light for each wavelength, which gives the best sensitivity results.

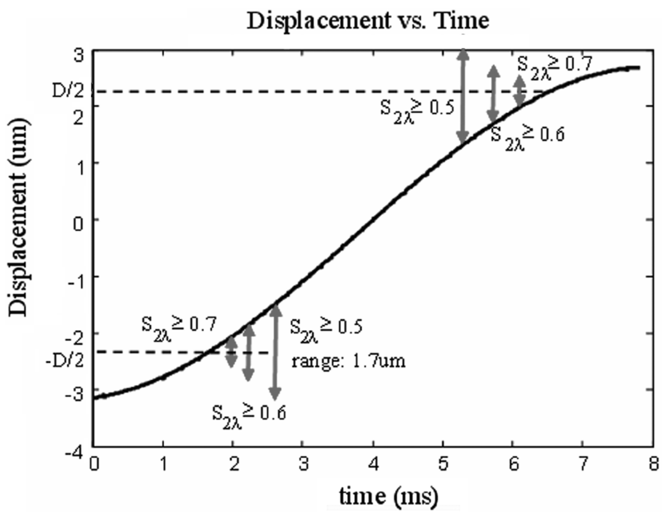

Fig. 4. Calculated displacement curve using PD1 and PD2 data in Fig. 3. Arrows indicate ranges for different minimum sensitivity levels around nominal gap: $\pm D/2$.

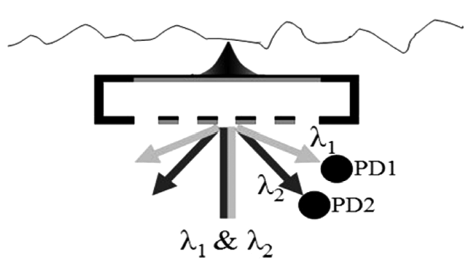

Fig. 5. Illustration for nanoimaging application.

Another important issue is related to the grating feature size. When the minimum feature size is comparable to the readout wavelengths, intensity changes with respect to the displacement deviates from the sinusoidal behavior [12]. Special care should be taken while calculating the displacement from the PD intensities. However, the majority of the MEMS applications stay out of this limitation and the intensity variation with gap can be modeled with sinusoids.

IV. Applications and Conclusion

The wide-range capability enables this technique to be used in dynamic measurements such as the experiment presented here. This technique is capable of measuring very small deflections at all frequencies including dc and limited by the PD amplifier response to $<$ 100 MHz (Note that MDD increases with square root of bandwidth for shot noise limited detection). Laser Doppler vibrometers (LDVs), on the other hand, measure velocity and cannot operate in dc. Upper frequency limit in commercial LDVs is in the order of a few megahertz.

The optical sensor readout method presented in this paper is suitable for membrane-based transducers, thermal sensor arrays, and grating spectrometers [1], [4], [5]. Another important application is the nanoimaging device illustrated in Fig. 5, [13]. Shot-noise limited deflection measurement capability was demonstrated in [1] with integrated probe and grating interferometer but the measurement range was limited due to the single wave readout. The two-wavelength grating interferometer method can be used to improve the range to several microns, which relaxes requirement on gap fabrication and active control of the gap. Likewise, multiple probes can be integrated and readout remotely using the same pair of laser light sources.

In conclusion, two-wavelength interferometry is adapted to MEMS applications involving integrated optical readout, for displacement measurement. The change of the range with respect to the sensitivity is investigated. An experiment was conducted on a MEMS spectrometer to illustrate the method. The results show that displacements of several microns can be detected while maintaining high sensitivity. Future work involves shot-noise limited performance demonstration by canceling the laser noise and various mechanical noise sources using both the first and zeroth diffraction orders. Lastly, the technique can also be demonstrated using only a single PD by activating the laser light sources in a time-sequential manner at the expense of increased noise BW.

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