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A grating-assisted resonant-cavity-enhanced optical displacement detection method for micromachined sensors

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Abstract

We present an integrated optical displacement sensing method for microscale sensors which is based on an asymmetric Fabry–Perot etalon structure with an embedded phase-sensitive diffraction grating. Analytical modeling of the structure shows that the etalon significantly improves the detection sensitivity as compared to a regular optical interferometer and the embedded diffraction grating enables integration of optoelectronics in a small volume. The efficacy of the method is experimentally validated on a surface micromachined diffraction-based opto-acoustic sensor fabricated on a quartz wafer. A 15 nm silver layer is used to form the bottom mirror of the etalon structure with a sensor membrane and embedded diffraction grating made of aluminum. Comparison of the results with and without the etalon shows an 8 dB increase in detection sensitivity with the etalon structure, which should be further enhanced with the use of low-loss dielectric mirrors.

Optical methods have advantages in microscale displacement sensing applications primarily because the sensitivity is independent of device capacitance. Optical fiber based sensors have commonly been used for optical detection, but integration of optical fibers with micromechanical structures in small volumes is not easy and these sensing methods are susceptible to external mechanical noise sources.^{1,2} Recently diffraction based methods have emerged for compact integration of optical interferometric methods with micromachined structures.^{3–7} Furthermore, vertical cavity surface emitting lasers (VCSELs) enable further integration possibilities due to the small coherence length requirements in microscale interferometric implementations.⁴ These studies have shown that one can implement Michelson interferometers with detection noise levels of $\sim 10^{-4}$ Å/√Hz with 1 mW laser power, assuming shot noise limited detection and a He–Ne laser as the light source. However, applications such as medical ultrasound imaging in the 2–20 MHz range require higher displacement detection sensitivity. Additionally, in cases such as micromachined microphones for hearing aids or battery operated accelerometers where low power consumption is important, enhanced displacement sensitivity is needed to lower laser power requirement.

High finesse symmetric etalon structures formed by semi-transparent mirror layers have been used as a potential solution for increasing optical displacement sensitivity.^{8,9} These structures, however, use detection electronics which are set remotely, so the approach does not leverage on-chip complementary metal–oxide–semiconductor photodetection and electronic integration.

A micromachined opto-acoustic sensor structure based on a phase-sensitive diffraction grating has addressed some of these issues.^{10,11} A simple implementation is schematically shown in Fig. 1, where a reflective membrane is suspended above a grated bottom electrode fixed to a

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rigid, transparent substrate. Structures without the bottom mirror have been analyzed and characterized in Refs. 10 and 11. In this case, illuminating the phase-sensitive grating from the back side with coherent laser light results in a diffracted field consisting of zero and odd-numbered higher diffraction orders. The membrane displacement resulting from acoustic excitation causes intensity variations in these orders, whose positions are fixed in space. Light reflecting from the top membrane (region I in Fig. 1) accrues additional phase relative to the light directly reflecting from the grating fingers (region II in Fig. 1). The intensity of the first diffraction orders versus gap thickness for this scheme is shown in the zero reflectance case of Fig. 2, where the interference curve has $\lambda/2$ periodicity with membrane displacement, where λ is the optical wavelength in air. As suggested by the applied voltage shown in Fig. 1, the use of electrically conductive materials for the membrane and grated electrode enables electrostatic actuation which can be used to tune the displacement sensitivity. Maximum displacement detection sensitivity is achieved at membrane-grating gaps of any odd multiple of $\lambda/8$ where the slope of the interference curve is a maximum. It has been shown, analytically and experimentally, that the displacement sensitivity of this method is equivalent to that of a Michelson interferometer—which results from a linear relationship between displacement and phase difference of the two interfering waves. Since the demand for coherence length is alleviated by the microscale dimensions, VCSELs can be operated in the pulsed mode to reduce average power consumption and form completely integrated sensors with volumes on the order of 1 mm^3 .¹¹

In this letter, a grating-assisted resonant-cavity-enhanced (GARCE) structure is introduced. As illustrated in Fig. 1, the GARCE structure adds a partially reflective mirror beneath the grated electrode. Together with the movable membrane acting as a top mirror of total reflectance, an asymmetric Fabry–Perot etalon with a grating-embedded cavity is formed. As an alternative implementation, the grated electrode can be placed outside of the cavity on the partially reflective mirror. The mirror can be formed using a metal film, a dielectric stack composed of multiple pairs of alternating quarter-wave layers, or a combination of the two.

For the structure shown in Fig. 1, the reflected diffraction efficiency of the m th order in the Fraunhofer approximation can be written as¹²

$$\text{DE}(m) = \frac{1}{4} \text{sinc}^2\left(\frac{m}{2}\right) \left[|r_I|^2 + |r_{II}|^2 + 2|r_I||r_{II}|\cos(\pi m + \varphi_I - \varphi_{II}) \right], \quad (1)$$

where $\text{sinc}(x) = \sin \pi x / (\pi x)$ and the fill factor of the grating is assumed to be 0.5. The complex reflection coefficients $r_I = |r_I| \exp(i\varphi_I)$ and $r_{II} = |r_{II}| \exp(i\varphi_{II})$ represent wave front modulation by thin multilayer structures at normal incidence in regions I and II, respectively, as depicted in Fig. 1. They can be determined using the 2×2 matrix method in layered media.¹³ In the lossless case implemented with ideal mirrors, the reflection coefficients can be expressed as

$$r_I = \frac{\sqrt{R} \exp(-i\varphi_0)}{1 + \sqrt{R} \exp(-i\varphi_0)}, \quad r_{II} = 1, \quad (2)$$

where R is the intensity reflectance of the bottom mirror and $\varphi_0 = 4\pi d/\lambda$ denotes a round-trip optical path in the cavity of thickness d . Then, Eq. (1) is simplified as

$$\text{DE}(m) = \frac{1}{2} \text{sinc}^2\left(\frac{m}{2}\right) [1 + (-1)^m \cos \varphi], \quad (3)$$

with

$$\varphi = 2 \tan^{-1} \left(\frac{1 - \sqrt{R}}{1 + \sqrt{R}} \tan \frac{\varphi_0}{2} \right). \quad (4)$$

Equation (3) is of the same form as that of the regular grating-based detection method. However, the phase term φ deviates from φ_0 significantly for large R due to multiple reflections in the etalon cavity of region I.

Figure 2(a) shows the calculated first-order diffraction efficiency $DE(\pm 1)$ as a function of the relative cavity thickness d/λ for several values of R . The displacement sensitivity, defined as the change in the optical intensity per unit membrane displacement, can be obtained from the slope of the diffraction efficiency curves. Figure 2(b) shows the corresponding sensitivity improvement factor F at the optimal bias position for maximum sensitivity as compared to the regular optical detection method of $R=0$. The sensitivity increases dramatically with R at the cost of reduced detectable displacement range without distortion. Also, the optimal bias position shifts toward an odd multiple of $\lambda/4$ due to strong phase dispersion near these resonances. Assuming that the GARCE sensor is operated such that the output optical power remains unchanged and the detection is limited by the shot noise, the displacement resolution can also be improved by the same factor F . It is noteworthy that, for given mirror reflectance R , the displacement sensitivity of the zero-order diffraction in the GARCE structure is estimated to exceed even that of opto-acoustic sensors based on amplitude-modulated symmetric etalons.⁹

In this letter, a metallic GARCE structure with a silver bottom mirror is considered for initial experimental verification because of ease of fabrication, and its behavior is analyzed for comparison. The GARCE sensor is fabricated by first patterning a 15-nm-thick silver mirror and a 0.2- μm -thick aluminum grating electrode on a quartz substrate via standard lift-off procedures. Then, 1- μm -thick, 160- μm -diam aluminum membranes are sputtered on top of a 2.8- μm -thick sacrificial layer of photoresist, which is later removed via soaking in acetone. Figure 3 shows a topside scanning electron microscope image and a bottom view micrograph of a metallic GARCE acoustic sensor array. Phase-sensitive grating structures without the bottom mirror are also fabricated next to the GARCE structures for comparison.

The corresponding first-order diffraction efficiency $DE(\pm 1)$ is directly calculated from Eq. (1) for various bottom mirror thickness and presented in Fig. 4(a). As the silver thickness increases, the slope of the interference curve becomes sharper and the peak moves toward a multiple of $\lambda/2$. On the other hand, the overall efficiency reduction caused by the optical loss in the metal layers also increases proportionally, which in turn restricts the sensitivity improvement. In this case, the sensitivity is improved by a factor of $F=2.4$ using a 15-nm-thick silver layer. Ideally, the metal mirrors would be replaced by lossless dielectric mirrors to prevent performance degradation and enable higher detection sensitivity.

For experimental evaluation, a He–Ne laser with $\lambda = 633 \text{ nm}$ is used as the light source with focusing optics, and a silicon photodiode followed by a transimpedance amplifier monitors a first-order diffracted beam. The photodiode output is recorded as electrostatic forces pull the membrane toward the grated electrode via the application of a dc bias voltage. This action corresponds to tracing the calculated interference curve in Fig. 4(a) from right to left. The experiment is performed on both device types (i.e., the regular sensor without the etalon enhancement and the GARCE sensor), which have the same physical dimensions. A dc bias sweep of 0–40 V produces a membrane displacement slightly less than one cycle of the interference curve ($\lambda/2$). Since electrostatic actuation involves the nonlinear relation between membrane displacement and dc bias, the applied voltage is converted to displacement using a least-squares fit based on a simple force-balance model. The scaled results are also plotted in Fig. 4(a) for comparison. An asymmetric interference curve is clearly observed for the GARCE

sensor with 15 nm silver mirror thickness, as is expected from the theoretical predictions. By comparing the slope of the interference curve at each sensor's optimal dc bias point of approximately 16 V, a 2.5-fold improvement in displacement sensitivity is observed with the use of the GARCE structure. To further demonstrate the asymmetric interference curve and enhanced displacement sensitivity, the response of the GARCE sensor to an external acoustic source is measured at an optimal dc bias point and a point of equal diffraction order intensity on the opposite, broader slope of the curve. Figure 4(b) shows the measured responses to a four-cycle, 20 kHz tone burst generated by a speaker at dc bias levels of 16.6 and 40 V [points A and B in Fig. 4(a), respectively], illustrating the enhanced sensitivity offered by the steep slope of the interference curve as well as the phase inversion due to change in the sign of the slope.

In summary, a GARCE sensor structure is described. The approach combines a phase-sensitive diffraction grating structure with an asymmetric Fabry–Perot etalon. Experiments with metallic GARCE acoustic sensors fabricated using a 15-nm-thick silver film as the bottom mirror show good agreement with the theoretical model developed, and indicate an 8 dB improvement in displacement detection sensitivity as compared to phase-sensitive grating structures without Fabry–Perot etalon. Further sensitivity enhancements can be obtained by building the GARCE structure with low-loss materials. With these enhancements, the GARCE structure can be used to build micromachined mechanical sensors with integrated, low power optical readout for applications including hearing aid microphones, accelerometers, and ultrasound imaging arrays.

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FIG. 1. Schematic diagram of a grating-assisted resonant-cavity-enhanced (GARCE) acoustic sensor.

FIG. 2.

(a) Calculated first-order diffraction efficiency $DE(\pm 1)$ as a function of the relative cavity thickness d/λ for several values of the bottom mirror reflectance R . (b) Sensitivity improvement factor F at the optimal bias position as compared to the regular optical detection ($R=0$) in the lossless GARCE structure.

FIG. 3.

(a) Scanning electron micrograph of an array of aluminum membranes on a quartz substrate forming an acoustic sensor to test the GARCE structure. (b) Bottom micrograph of the grating structures with 4 μm period. The 15-nm-thick silver mirror layer is left absent on some neighboring membranes so improvements with the GARCE structure can be accurately assessed on devices with nearly identical mechanical structure.

FIG. 4.

(a) Calculated first-order diffraction efficiency $DE(\pm 1)$ and measured detector output of a first diffraction order for the regular acoustic sensor without the etalon enhancement and for the metallic GARCE acoustic sensor with a 15-nm-thick silver film used as the bottom mirror. (b) Measured acoustic response of the GARCE sensor at different dc bias levels in response to a 20 kHz sound wave generated by a speaker.