CAVITY OPTOMECHANICAL SENSORS

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ABSTRACT

We report a novel type of fully integrated optomechanical sensor and demonstrate high sensitivity mechanical displacement measurements on chip. We sense the motion of micro and nano-mechanical devices by near field coupling them to high quality factor optical microdisk resonators. In a first geometry, we sense the position of a dielectric ring moved by a micromechanical actuator. Tunable optomechanical coupling of up to GHz/nm results in the photodetector-limited displacement sensitivity of 4.3x10^{-15} m/√Hz with optical excitation power as low as 20 μW. In a second geometry, we sense the thermal motion of a nanoscale cantilever probe. Transduction of the cantilever's MHz frequency vibration is achieved with a displacement sensitivity of 4.4x10^{-16} m/√Hz and a mechanical quality factor of 6000 is measured in vacuum.

I. INTRODUCTION

The performance of many micromechanical sensors and the ability to scale them down to nanoscale dimensions are often limited by the precision of the available techniques for mechanical motion measurement. For example, for high-speed Atomic Force Microscopy (AFM), a small cantilever is desired to obtain a high mechanical frequency and a small spring constant simultaneously [1]. Common integrated electrostatic readout is limited by the available sensor capacitance, often dictated by footprint and mechanical speed requirements. Instead, a single beam bounce optical measurement is most often used to measure AFM cantilever tilt. By adding an external optical resonator cavity, state of the art AFM readout sensors achieve 1 fm/√Hz precision and have an optical probe spot size of 3 μm [2]. For ultrahigh sensitivity, much larger Micro Electro Mechanical Systems (MEMS) have been coupled to high quality factor (Q) optical resonators demonstrating near quantum-limited displacement sensitivity [3]. Wider application of these types of interferometric sensors is hampered by the complexity, size, cost, alignment and stability requirements associated with the external optical cavity. In addition these free space optical systems do not scale well to Nano Electro Mechanical Systems (NEMS) with characteristic sizes below the optical diffraction limit. Alternative approaches involving movable periodic nanostructures [4] and photonic crystals [5] are very promising, however they still require external free-space optical excitation and readout, and so far have not achieved very high optical Q. It is not clear how to scale them to measure individual NEMS.

We demonstrate a novel class of optomechanical transducers that combine high precision optical interferometry with the compactness, stability and robustness of integrated photonics, by microfabricating, on a single chip, a stationary fiber-connectorized high-Q (up to ≈10^6) photonic resonator near-field coupled to a mechanically separate movable structure. Mechanical displacement δG results in a shift of the optical cavity resonance frequency $\delta\omega_c = g_{OM}\ \delta G$, where g_{OM} is the optomechanical coupling coefficient ($g_{OM}=d\omega_c/dG$). The high sensitivity of our approach stems from both the narrowness of the optical resonance as well as the large g_{OM} achieved through the evanescent coupling. Since the movable part remains mechanically separate from all the stationary nanophotonic components, the approach does not strongly restrict the engineering of the mechanical part of the transducer, making it widely applicable for a variety of MEMS and NEMS sensing situations requiring high precision, high bandwidth and small footprint.

We demonstrate the principle using two examples. Both are based on the same 10 μm diameter Si optical microdisk resonator and have a total sensor footprint below 15 μm x 15 μm. The first is a MEMS transducer in which the cavity optomechanical sensor is integrated with an electrostatic actuator for both inducing the mechanical motion as well as mechanically tuning g_{OM} and the corresponding sensor gain [6]. We demonstrate tuning of the gain by well over one order of magnitude, and at the highest gain setting the noise level of the measurement corresponds to the displacement sensitivity of 4.3x10^{-15} m/√Hz.

The second is a simpler device to demonstrate the scaling of the technique to nanoscale mechanical probe readout. It achieves precision optical readout (4.4x10^{-16} m/√Hz) of an integrated NEMS cantilever probe (65 nm x 260 nm x 20 μm) designed for application in high speed AFM [7].

II. EXPERIMENTAL

MEMS Transducers

The device geometry of the MEMS transducer is shown in Fig. 1. A 250 nm thick, 14 μm outer diameter silicon nitride ring is suspended a distance G above a 10 μm diameter, 260 nm thick silicon microdisk, seen at the lower right. An integrated on-chip Si waveguide is provided for coupling the microdisk optical modes through fiber pigtails to an off-chip tunable laser and detector. The microdisk is fixed to the substrate via a silicon nitride anchor, while the ring is attached at the

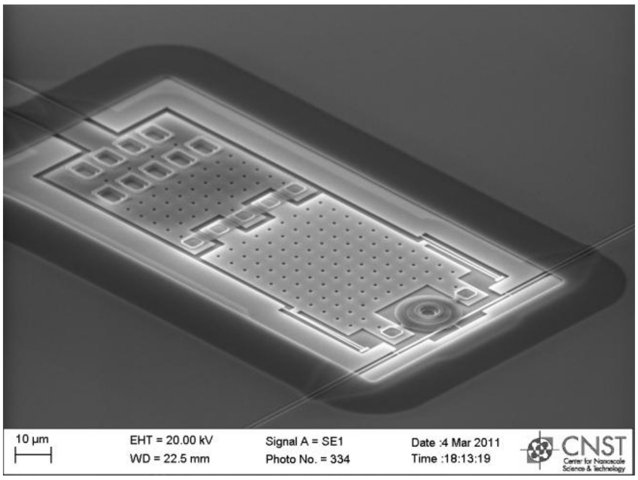

Figure 1. Scanning electron micrograph of the MEMS transducer.

periphery to a MEMS cantilever electrostatic actuator. The actuator is a silicon cantilever fixed to the substrate at nine nitride anchor points at the upper left and consisting of two mechanically connected (via a nitride bridge) but electrically separate parts. The voltage is applied to the first part at the upper left, while the Si substrate, 1 µm below, is kept at the ground potential. This results in the first part of the cantilever bending toward the substrate. The second part of the cantilever, maintained at the ground potential, connects the ring to the first part of the cantilever and serves as a mechanical lever arm to amplify the motion. Thus *G* can be continuously controlled from the initial 800 nm to 0 nm.

The actuator is first characterized with a white light interferometer by measuring the height of the nitride ring surface and deducing *G* as a function of voltage. Fig. 2 shows the measurement results taking into account the estimated sacrificial silicon dioxide thickness of 650 nm between the nitride and the silicon. Note, the measurement uncertainty of the oxide thickness is relatively unimportant in this paper because all the parameters derived from *G* are only related to the derivative of *G*. The measurement statistical uncertainty is ±1.6 nm, which is smaller than the size of the symbol

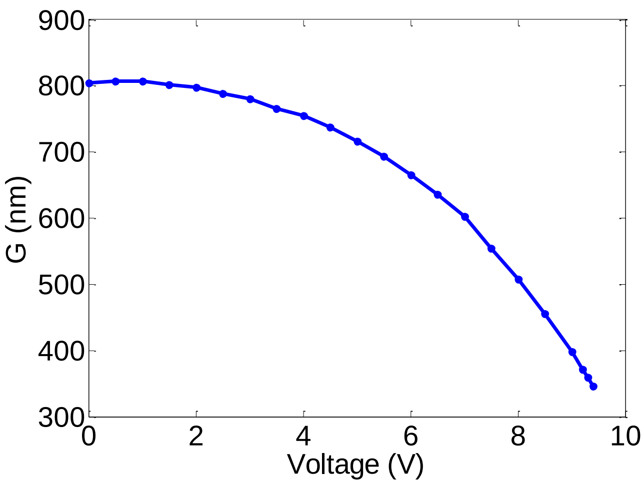

Figure 2. Dielectric ring distance to the silicon microdisk vs. actuator voltage.

in the figure. (For all uncertainties a value of one standard deviation is given. Error bars are not shown in figures if the estimated uncertainty is comparable or below the symbol size.). We then characterize the optomechanical coupling as a function of *G* in two ways.

In a first method, the optical mode resonant frequency is measured as a function of voltage applied to the actuator by measuring the transmission spectra of the optical resonator. Fig. 3 shows a typical spectrum of an optical mode with a quality factor of approximately 4×10^4 and the measured resonant frequency shift as a function of applied voltage. For the data in Fig. 3, at voltages below 8 V, we take the wavelength measurement uncertainty as 1/10 the full width at half maximum (FWHM) of the resonance, which is ≈ 4 pm. At higher voltage, the thermal mechanical noise degrades the spectrum of the resonance, and we take the measurement uncertainty as 1/3 of the FWHM of the resonance, which is ≈ 13 pm. The optomechanical coupling is calculated by taking a derivative of the resonant frequency as a function of *G*.

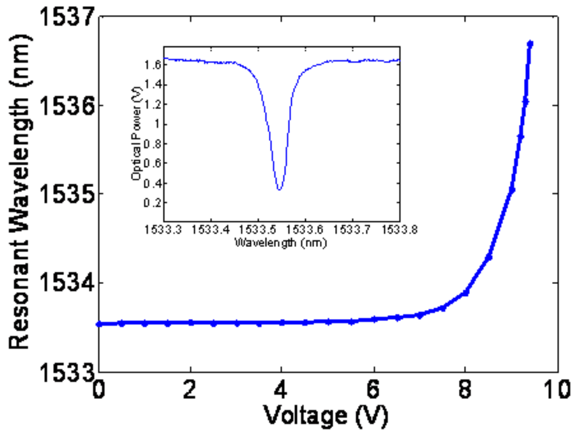

Figure 3. Resonant wavelength vs voltage. Inset: resonant spectrum of an optical mode. Photodetector output voltage proportional to the incident optical power is given in the figure.

In a second method, we induce and measure a small mechanical motion of the device. We fix the laser wavelength at the steepest slope on the side of the optical resonance line at each applied voltage. A small fixed AC modulation at 100 Hz is added to the actuator DC voltage, which result in a small, known mechanical modulation of *G*. A lock-in amplifier is used to detect the resulting optical power modulation, which is proportional to the motion amplitude and the optomechanical coupling. To calibrate the sensor, we use an electro-optic phase modulator (EOM) to apply a known phase modulation of depth $\delta\varphi$ and frequency $\Omega_{mod} = 2\pi \times 50$ MHz to the excitation light. This results in an 50 MHz tone in the detector signal equivalent to an effective sinusoidal mechanical motion with amplitude $x_{mod} = \delta\varphi\, \Omega_{mod} / g_{OM}$. [7] By combining the lockin data and the EOM introduced reference tone, the optomechanical coupling is extracted for each value of *G*.

Fig. 4 shows the optomechanical coupling extracted from both the spectroscopy data and the lock-in data, which agree well with each other. The highest coupling $g_{OM}/2\pi$ = 4.8 GHz/nm ± 0.2 GHz/nm is achieved with an applied voltage of 9.4 V and the measured gap of 345 nm ± 1.6 nm. The lockin measurement was not extended to the highest values of the coupling because at the smallest available AC excitation voltage of 10 mV, the mechanical modulation may exceed the dynamic range of the measurement set by the linear portion of the slope of the resonator line. The uncertainty of the optomechanical coupling from the spectroscopy data is estimated to be below 0.02 GHz/nm for the gap range above 550 nm, and below 0.2 GHz/nm for the remaining data shown in Fig. 4. The estimate is based on the statistical analysis of the uncertainties in measured resonance wavelength and gap vs. applied DC voltage. The uncertainty from the lockin data is estimated to be below ±10 %, taking into account the absolute accuracy of the RF spectrum analyzer.

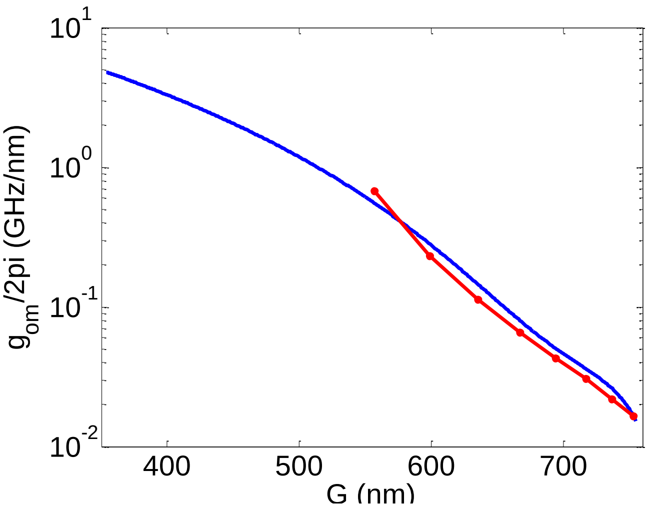

Figure 4. Estimated optomechanical coupling. Continuous line is derived from spectroscopy, line with symbols is derived from lockin data.

We then use the optomechanical coupling together with the measured sensor noise background to estimate the sensitivity. The measured broadband background noise corresponds to a displacement sensitivity of $4.3\text{x}10^{-15}$ m/$\sqrt{}$ Hz ± $0.2\text{x}10^{-15}$ m/$\sqrt{}$ Hz. The current system has an optical resonator with a Q of 40,000 and is measured at a low optical power level: -17.8 dBm (16.6 μW) excitation power, -25.3 dBm (3 μW) at the sensor and -32.8 dBm (525 nW) to the photodetector, accounting for 7.5 dB fiber pigtail coupling losses at both facets. In the near future we expect a sensitivity improvement of at least two orders of magnitude by improving the optical Q to 10^6, which has been demonstrated in our previous work [6], by further increasing the optomechnical coupling with smaller gap and by using a higher optical power to lower the readout noise.

NEMS Cantilever-Microdisk Transducers

In previous work, we have recently demonstrated optical transduction of a subpicogram silicon cantilever's

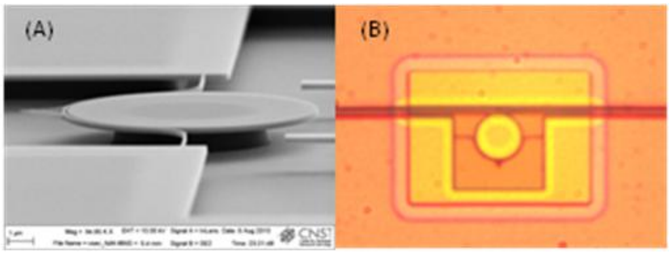

Figure 5. SEM and optical microscope images of two versions of cantilever-microdisk devices. (A) Device for fiber taper coupling; (B) Device with waveguide access.

megahertz frequency thermally driven vibrations with a displacement sensitivity of $4.4\text{x}10^{-16}$ m/√Hz ± $0.3\text{x}10^{-16}$ m/√Hz and bandwidth > 1 GHz. A dynamic range > 10^6 was estimated for a 1 s measurement. In these previous experiments light was coupled to the microdisk via an off-chip fiber taper waveguide (the device geometry is shown in Fig. 5 (A)). We have recently fabricated and measured cantilever-microdisk devices with an on-chip coupling waveguide as shown in Fig. 5 (B). The waveguides fabricated on the same SOI layer were 500 nm wide and positioned 200 nm to 400 nm away from the edge of the microdisk. They were linearly tapered down to a width of 125 nm at their ends for low loss coupling to/from optical fibers. Fibers were actively aligned and glued in v-groves on the same chip for robust coupling of light into and out of the devices.

We placed the fiber pigtailed device in a vacuum chamber and studied the mechanical resonance spectrum as a function of ambient pressure. Inset in Fig. 6 shows the spectra of the thermally excited mechanical motion at various pressure levels. Fig. 6 shows the quality factor of the fundamental mechanical mode as a function of pressure levels. The Q of the nanoscale resonator is increased from ≈5 to ≈6000 when the pressure is reduced from one atmosphere to below ≈100 Pa. Further reduction of the pressure does not improve the mechanical Q significantly.

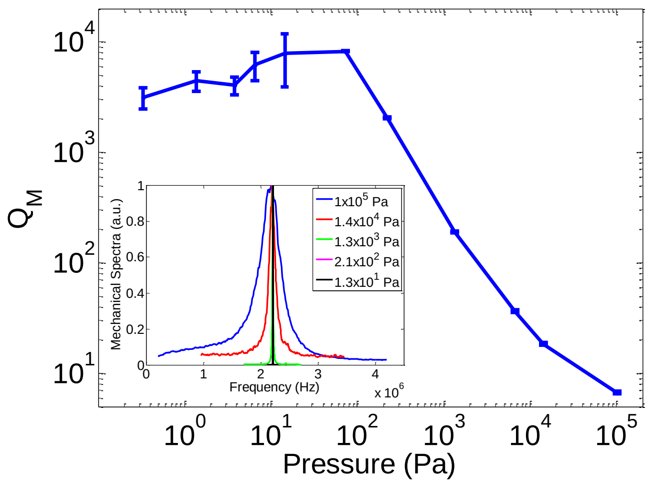

Figure 6. Mechanical Q as a function of pressure. Inset: mechanical spectra at various pressure levels. The error bars are derived by fitting the spectra to Lorentzians. The relative large errors of the Q_M at low pressure are due to the insufficient video bandwidth of our spectrum analyzer.

III. SUMMARY

In summary, we have demonstrated a novel class of fully-integrated cavity optomechnical transducers for MEMS and NEMS position and motion sensing with high precision, high bandwidth and small footprint.

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