130-MHz Optomechanical Vibrating Sensor: Towards High Bandwidth / Ultrasensitive Measurements

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ABSTRACT

We show all-optical operation of a VLSI optomechanical micro-resonator designed for high resolution sensing applications. Mechanical resonance frequency is above 100 MHz with Q-factor of 1 000 in air, yielding measurement bandwidth above 100 kHz. We demonstrate low thermomechanical noise floor resolved with exquisite motion detection limit down to 4.10^{-16} $m.Hz^{-0.5}$. This performance, enabled by optomechanical transduction, paves the way for very high-speed and ultra-sensitive sensing applications.

INTRODUCTION

MEMS technologies and transductions have played a key role in the sensing field, for example by the development and fabrication of force sensors vibrating in the kHz-MHz range [1,2]. As fabrication technological processes developed, sensors' dimensions were shrunk in NEMS, looking for a twofold advantage: higher sensitivity and higher bandwidth, enabled by scaling laws and frequency increase. However, displacement transduction schemes usually at play in MEMS, like the capacitive one, are generally not applicable to NEMS [3]. Thanks to different integrated transduction means, NEMS have however proven their effectiveness in many sensing fields providing for example, 43 MHz cantilevers, piezoresistive nanowire gauges detected, for gas chromatography [4] and chemisorptive mass sensing with piezoresistive metal film detection of a 127 MHz cantilever resonance [5].

To reach mechanical frequencies greater than the MHz, another path followed is to exploit bulk or in-plane modes instead of shrinking dimensions of cantilever beams resonating on flexural modes. This idea was applied for ring-shaped force sensors [6], achieving a 13 MHz breathing mode frequency record in AFM probes with a novel capacitive detection scheme based on microwave reflectometry, allowing high-bandwidth measurements without compromises on the femtometer resolution.

To go further, one needs to increase the frequency even higher and seek for higher displacement sensitivity to keep a reasonable signal-to-noise ratio due to the decrease in amplitude when the mechanical frequency raises. Consequently, force sensors vibrating above 100 MHz with picometer amplitudes imply once more drastic constraints on usual integrated electromechanical transduction schemes and locks are met in terms of measurement resolution [7], calling for a change in transduction mean.

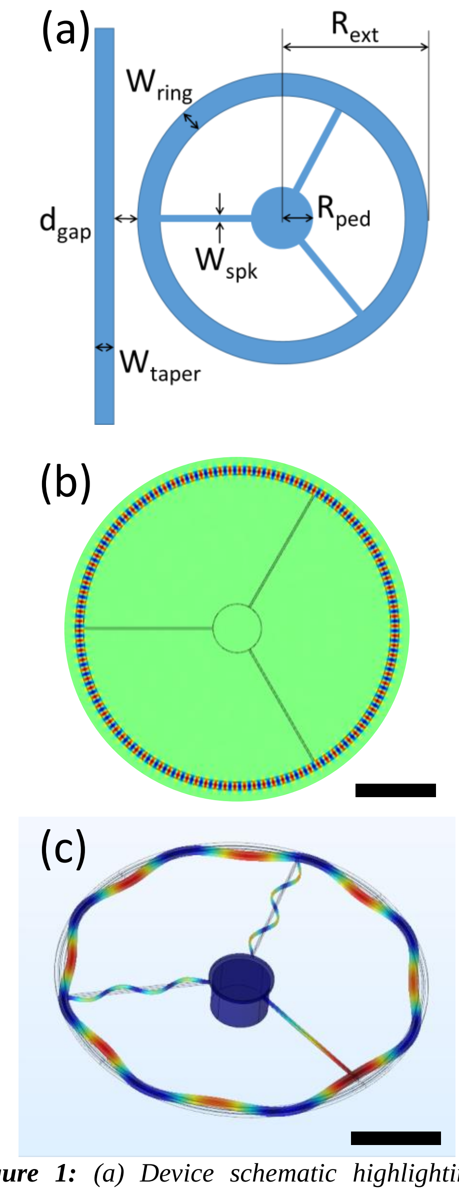


Figure 1: *(a) Device schematic highlighting the main dimensions of the tested sensor structure:* $R_{ext} = 10\ \mu m$, $R_{ped} = 1.5\ \mu m$, $W_{ring} = 500$ nm, $W_{spk} = 100$ nm, $W_{taper} = 475$ nm *and* $d_{gap} = 300$ nm.
(b) Optical and (c) mechanical finite element modeling of the optomechanical sensor, consisting in a 20 µm diameter silicon ring with 3 spokes anchoring to a 1-µm high pedestal, allowing mechanical motion. Electrical field amplitude and displacement resonance mode are respectively simulated. The optical and mechanical resonance wavelength and frequency are $\lambda=1.55\ \mu m$ *and* $f_{m\ simulated}=134$ *MHz respectively, scale bars: 5 µm.*

Concurrently, quantum experiments at mesoscale [8] pushed understanding and engineering capability of optomechanical transduction at play in whispering gallery mode (WGM) resonators. This growing interest lead to III-V material integrated sensors resonating above 100 MHz with ultimate motion sensitivity down to 10^{-17} m.Hz$^{-0.5}$[9]. This technology was successfully applied to scanning probe technique [10] and transferred to silicon photonics and very large scale integration facility in the last years [11].

To address the need in resonating devices for physical sensing applications with unprecedented performances, namely higher frequency, bandwidth and sensitivity, we present the design, fabrication and first characterization of a fully integrated, optically sensed, resonating sensor based on cavity optomechanics fabricated using a VLSI silicon photonics platform. The 130 MHz-frequency resonator presented hereafter offers an exquisite detection limit of 4.10^{-16} m.Hz$^{-0.5}$ and a measurement bandwidth of 130 kHz, being ruled by the relaxation time.

OPTOMECHANICAL SENSOR DESIGN

The sensor consists in a 20 µm diameter ring WGM optical cavity (Fig. 1a) standing in air on a 1-µm-high pedestal with three anchoring spokes. An optical waveguide evanescently couples the 1.55 µm laser light in and out the optical mode. The ring is designed from the mechanical point of view to reach a 134 MHz first order breathing mode that is simulated by finite element method (FEM) with a g_{om}=7.8 10^{18} Hz/m optomechanical factor. For applications in mass or force sensing, one needs to seek the location of the lowest effective mass or stiffness of the resonator. This is reached at a location of the resonance mode shape where the vibration amplitude is maximal (See Fig. 1c). For the device presented in this study, effective mass and stiffness are calculated by FEM to be 6.10^{-14} kg and 40 000 N/m respectively at a point of maximum of vibration.

Principle of operation of the optomechanical device is as follows. Mechanical breathing motion of the resonator during its vibration modulates the cavity optical length and thus its optical transmission. This benefits from sensitivity enhancement by the WGM optical quality factor Q_{opt}=60 000. Gap distance between the coupling waveguide and the ring cavity and dimensions of the sensor were designed to maximize the contrast times optical quality factor product.

FABRICATION

The ring sensor is fabricated using VLSI silicon photonics SOI technology on a 200 mm wafer. First, a deep UV lithography step defines the grating couplers enabling top-injection and collection of laser light, respectively in and out of the chip. Then a variable shape beam lithography step defines the ring sensor structure. The patterned silicon structural layer (SiTop) is 220 nm thick on top of a 1-µm thick buried oxide layer (BOx). The BOx layer is then critically timed-etched with vapor-HF in order to form the pedestal on which the sensor is finally standing on. Main steps of the fabrication process and SEM picture of the resulting sensor are depicted in figure 2.

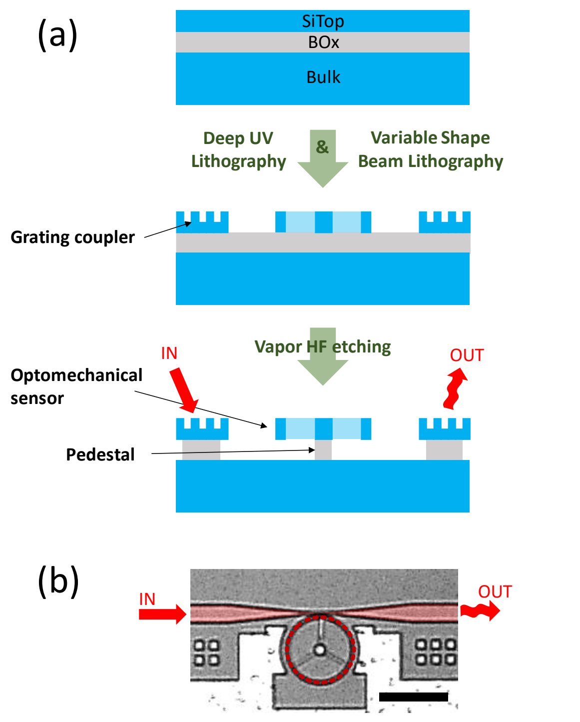
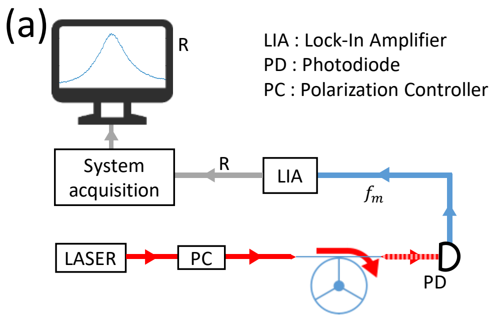


Figure 2: *(a) Main fabrication steps of the optomechanical sensor. The silicon layer SiTop in which the optomechanical sensor is patterned is 220 nm thick. The 1-µm thick buried oxide layer (Box) is then etched to let only a 3 µm diameter pedestal for the sensor to stand on. (b) Colorized SEM image of the resulting optomechanical sensor featuring the coupling waveguide (plain red) and the optical cavity (dotted red). Scale bar: 20 µm.*



(b)

Function	Piece of material
Tunable LASER	*Photonetics* OSICS-ECL-1560-P6
EOM	*Thorlabs* LN58S-FC
LIA	*Zurich Instruments* HF2LI
PD	*Thorlabs* DET01CFC

Figure 3: *(a) Set-up used for experimental characterisations. Laser light evanescently couples to the device. Laser light exiting the sensor then carries the mechanical resonance motion. Sensing signal from the photodiode is processed by a lock-in amplifier acting as a spectrum analyzer. (b) Table of the main equipment used to acquire the measurement data displayed in this manuscript.*

CHARACTERIZATION SET-UP

Experimental characterizations are performed in air. A lock-in amplifier (LIA) allows frequency characterization of the sensor (Fig. 3). Laser light is top-injected with fibers in the silicon chip via grating couplers optimized for optical C-band operation. Polarization controllers ensure that light is injected in the ring matching coupling polarization. A 1500-1600 nm tunable laser allows to match optical modes of the ring cavity. Transmitted light, modulated by the resonator motion, is then collected by a 1.2 GHz bandwidth photodiode. Because of thermo-optic effect, the laser wavelength is blue-detuned which could enhance resonance through optical back-action. Injected power was thus limited to 1mW to prevent from this enhancement effect.

RESULTS & DISCUSSION

Thermomechanical (Brownian) motion is resolved (Fig. 4), at f_m=130.6 MHz with a 3% difference with simulated breathing mode frequency, and Q_m=1 000 in air. Air fluid dissipation hinders the intrinsic mechanical Q-factor that would be obtained in vacuum, expected to be Q_{m_vac}=10 000 from numerical calculations. Brownian motion detection, routinely enabled by optomechanical transduction, is calibrated in two different ways. First, we use the equipartition theorem (See "Thermomechanical noise displacement" formula in Table 1) which yields a 7.10^{-16} m.Hz$^{-0.5}$ displacement noise density at the mechanical resonance frequency. The measured value, calibrated from the parameters of the detection chain, gives a 12.10^{-16} m.Hz$^{-0.5}$ value. The small discrepancy is within the uncertainty of the detection chain parameters and gains. Using this latter calibration value, the limit of detection of the measurement set-up is estimated to be below 4.10^{-16} m.Hz$^{-0.5}$. By assuming an operation of the device in driven mode, a 63 dB SNR could be attained for a vibration amplitude of 1 pm, which is better than for other devices in the same frequency range as presented in Table 1. Thanks to its high mechanical resonance frequency, our optomechanical sensor reaches a bandwidth of 130 kHz in air, ruled by the f/Q_m ratio, still competitive with regards to other resonating sensors (Table 1).

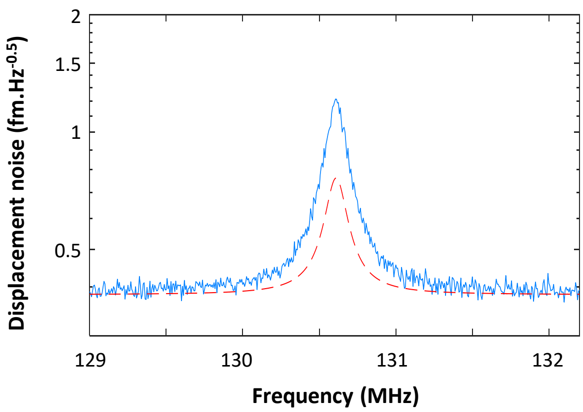


Figure 4: *(Blue) Brownian motion of the optomechanical resonator measured at 1-Hz bandwidth. Resonance frequency is f_m=130.6 MHz. The sensor's quality factor attains Q_m=1000 in air. The signal is calibrated via detection chain. (Red) Brownian motion theory given by the equipartition theorem with same noise floor. The 1.7 factor between theoretical and measured noise amplitude is within detection parameters uncertainty.*

CONCLUSION

An optomechanical ring resonator, mechanical frequency being up to 130 MHz, is fabricated using VLSI silicon photonics technology and characterized with an exquisite 4.10^{-16} m.Hz$^{-0.5}$ detection limit, allowing clear resolution of the thermomechanical motion. Those exquisite performances put high-bandwidth sensing along with femtometer displacement resolution within grasp.

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				Ring sensor [6]	Simple-clamped beam [12]	Simple-clamped beam [5]	Present work
Transduction				Capacitive	Piezoresistive NW	Piezoresistive film	Opto-mechanical
VLSI				No	Yes	No	Yes
Frequency	f	MHz		13	43	127	130
Quality factor	Q	in air		760	165	400	1 000
Stiffness	k	N/m		200 000	27 000	32	40 000
Thermomechanical noise displacement	A_{th}	fm/$\sqrt{\text{Hz}}$	$\sqrt{\frac{2k_BTQ}{\pi f k}}$	0,9	0,6	16	0.7
Limit of detection	LOD	fm/$\sqrt{\text{Hz}}$		1,5	3	39	0.4
Bandwidth	BW	kHz	f/Q	16	260	317	130

Table 1: *Main characteristics of various MNEMS resonating sensors*

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