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An integrated low phase noise radiation-pressure-driven optomechanical oscillator chipset

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requests for materials
should be addressed to
X.L. (xl2354@
columbia.edu); Y.H.
(yh2663@columbia.
edu) or C.W.W.
(cww2104@
columbia.edu)Xingsheng Luan¹, Yongjun Huang^{1,2}, Ying Li¹, James F. McMillan¹, Jiangjun Zheng¹, Shu-Wei Huang¹, Pin-Chun Hsieh¹, Tingyi Gu¹, Di Wang¹, Archita Hati³, David A. Howe³, Guangjun Wen², Mingbin Yu⁴, Guoqiang Lo⁴, Dim-Lee Kwong⁴ & Chee Wei Wong¹¹Optical Nanostructures Laboratory, Columbia University, New York, NY 10027, USA, ²Key Laboratory of Broadband Optical Fiber Transmission & Communication Networks, School of Communication and Information Engineering, University of Electronic Science and Technology of China, Chengdu, 611731, China, ³National Institute of Standards and Technology, Boulder, CO 80303, USA, ⁴The Institute of Microelectronics, 11 Science Park Road, Singapore 117685, Singapore.

High-quality frequency references are the cornerstones in position, navigation and timing applications of both scientific and commercial domains. Optomechanical oscillators, with direct coupling to continuous-wave light and non-material-limited $f \times Q$ product, are long regarded as a potential platform for frequency reference in radio-frequency-photonics architectures. However, one major challenge is the compatibility with standard CMOS fabrication processes while maintaining optomechanical high quality performance. Here we demonstrate the monolithic integration of photonic crystal optomechanical oscillators and on-chip high speed Ge detectors based on the silicon CMOS platform. With the generation of both high harmonics (up to 59th order) and subharmonics (down to 1/4), our chipset provides multiple frequency tones for applications in both frequency multipliers and dividers. The phase noise is measured down to -125 dBc/Hz at 10 kHz offset at ~ 400 μ W dropped-in powers, one of the lowest noise optomechanical oscillators to date and in room-temperature and atmospheric non-vacuum operating conditions. These characteristics enable optomechanical oscillators as a frequency reference platform for radio-frequency-photonics information processing.

Until now the most widely used commercial frequency references are based on quartz crystal oscillators which, after more than eight decades of development, have achieved remarkable low phase noise performance. However, due to the incompatibility with standard CMOS processes, the quartz oscillator is also well-known as one of the last electronic components that have yet to yield to silicon integration. Thereby there is a strong motivation to develop high-quality silicon oscillators as early as 1980s. Compared with quartz oscillators, silicon oscillators have smaller size, lower cost and power consumption and most importantly, can potentially be fabricated by standard CMOS processes with ease of integration to silicon electronic circuits. Recently the emergence of optomechanical oscillators (OMO)¹ as a photonic clock provides an alternative approach towards stable chip-scale radio frequency(RF) references^{2,3}.

In optomechanical oscillators, the mechanical resonator and optical cavity are designed on the same device to maximize the optomechanical coupling. With carefully-tuned high quality factor (Q) and tight sub-wavelength confinement of selected optical cavities, large radiation pressure forces⁴ can be possible, modifying the motion of micro/nano-mechanical resonators⁵⁻⁷. When the input (drive) optical power exceeds the intrinsic mechanical damping losses, the mechanical resonator becomes a self-sustained oscillator^{8,9} with quantum backaction limited linewidth¹⁰. The optical amplified periodic motion of the mechanical resonator perturbs the optical cavity resonance, transducing the mechanical motion into the intracavity optical field. Such periodic modulation can be optically read out by measuring the optical transmission from the cavity, thus making an on-chip photonic-based RF reference^{2,3,11,12}. Unlike quartz crystal oscillators, the optomechanical oscillator performance is not limited by the $f \times Q$ product of the material¹³ and their linewidth is limited only by quantum dynamical backaction¹⁰ and phase noise of drive laser¹⁴. Recent efforts in improving the performance of mesoscopic optomechanical oscillators include development of several novel optomechanical frequency stabilization techniques^{15,16} and realization of different optomechanical cavity configurations^{8,12,17,18}.



However, for chip-scale operations with integrated electronics, CMOS-compatibility remains as a challenge for further applications of optomechanical oscillator. For example, a fully monolithically-integrated OMO with on-board detector and electronics can provide a portable frequency reference, potentially lower close-to-carrier (e.g. 1 kHz or less) phase noise, and allows as much RF power into the detectors as possible for signal processing. Although integration with Ge detectors was recently examined with ring oscillators¹⁹, the optomechanical transduction for ring optomechanical oscillators are about one to two orders-of-magnitude weaker than photonic crystal optomechanical cavities^{20–23}, resulting in high pump power operation¹¹, weak signals that demand vacuum operating requirements, and/or the auxiliary of an electric driving force¹⁹ which could introduce extra noise. Here we demonstrated the monolithic integration of photonic crystal optomechanical oscillators with on-chip Ge detectors, with large zero-point optomechanical coupling strength ~ 800 kHz and a resulting high-harmonic up to ~ 7 GHz. Furthermore, we observed novel fractional sub-harmonics generation and demonstrated injection locking of fundamental mode and high-order harmonics simultaneously in our CMOS-compatible chipset. Consequently we report for the first time the optomechanical chipset with low phase noise down to -125 dBc/Hz at 10 kHz offset, one of the lowest noise optomechanical oscillators to date and with ambient (atmosphere, non-vacuum, and room temperature) operations^{2,3,11,24}. The integration of the photonic crystal OMO with active optoelectronics is non-trivial, involving high-performance nanomembrane optical cavities with 120 nm critical dimensions next to Si-Ge molecular beam epitaxial growth, junction electronics, and optimized optical components across multilayer planarization and processing.

Figure 1a shows the fully integrated optomechanical cavity oscillator and on-chip Ge detector chipset, with the optical waveguide path denoted in green (detailed description in Supplementary Information I). Laser is first coupled from free-space lenses into a low-loss inverse oxide coupler at the chip facet (left side of Figure 1a), propagating then from the oxide coupler into a silicon waveguide. Before entering the PhC cavity, another inverse taper is also designed to ensure high efficiency tunneling into the photonic crystal waveguide and the cavity center. The transmitted light is split equally into two paths: one into the integrated Ge detector and the other coupled out from the inverse oxide coupler to off-chip lenses for external test diagnostics. Such test design allows us to monitor the comparative signal from the integrated Ge detector and external detector simultaneously. The optomechanical oscillator examined is a slot-type photonic crystal (PhC) cavity consisting of two ($16.0 \mu\text{m} \times 5.5 \mu\text{m}$) air-bridged photonic crystal slabs separated by a narrow 120 nm air slot with 250-nm thickness, as shown in Figure 1b to 1d. Slot-type PhC have been studied previously via electron-beam lithography^{25–27}, with a slot-guided cavity mode of optical quality factor $\sim 10^6$. These optical modes couple to the fundamental mechanical mode with a vibration frequency ~ 100 MHz and quality factor $\sim 10^3$ in room temperature and atmosphere^{12,28}. The tight photon confinement in optomechanical photonic crystals^{12,21,28} allows large radiation pressure effects, especially in our sub-wavelength slot cavities, which has a strong vacuum optomechanical coupling strength ~ 2.5 MHz in modeling²¹ and ~ 800 kHz in experiment¹². The localized slot guided mode is formed by first introducing a line-defect through removing and shifting a central line of air holes in a periodic optical lattice (see Figure 1b to 1d). The line-defect width, defined as the distance between the center of adjacent holes, is set to be $1.2 \times \sqrt{3}a$ (W1.2) where a is the lattice constant, enabling a higher optical quality factor, compared with a W1 design for fixed slot widths²⁵. The W1.2 slot cavity resonance also has less dependence on slot width compared to the W1 slot cavity resonance, important to improve the deep-UV (DUV) nanofabrication tolerances. While optical quality factor is higher for narrower slots and 80 nm slots

have been fabricated with electron beam lithography, in this work we designed and worked with 120 nm slot widths to be compatible with the current design rule of our CMOS photolithography processes.

To achieve the integrated deeply-sub-wavelength PhC slot and the epitaxial active Ge detectors simultaneously, we developed the nanofabrication process flow principle to start first with the 120 nm slot optomechanical oscillator definition, followed subsequently by the monolithic *p-i-n* Ge detector epitaxy, vias, and electrode contact pads definition, and later by the input/output coupler fabrication and PhC nanomembrane release. The integration consists of 20 multi-level masks alignments and about 280 optimized nanofabrication process steps, across the 8" wafer sets. Figures 1b to 1d illustrate the nanofabricated slot cavities with high yield. We note that, first, a 100 Å oxide is deposited on pristine silicon-on-insulator wafers to: (1) achieve the 120 nm slots in a 248-nm DUV lithography stepper, (2) protect the Si surface for subsequent epitaxy growth on a clean Si lattice, and (3) protect the patterned PhC surface during the Ge detector process steps. This is followed by a *p+* implantation to define the bottom contact of the Ge detectors.

For the deeply-subwavelength slots, the patterned resist profile is rigorously numerically modeled and optimized for a 185 nm slot line width, which is then tightly process controlled with sloped oxide etching to transfer into a 120 nm slot in the silicon devices as shown in Figure 1c and 1d. All the PhC cavities, lattices, and subsequent process steps are aligned across the wafer. Next a monolithic Ge layer is epitaxially grown as described in earlier studies^{29,30}, followed by top *n+* implantation, vias definition, and metallization steps (as shown in Figure 1e). To maintain planar surfaces in the complete process, four planarization steps are introduced and interspaced across the entire process flow, involving oxide backfilling and multiple chemical-mechanical polishing with ~ 200 Å (initial levels) to ~ 1000 Å (latter levels) thickness variations in the multilayers across the wafer. Subsequently the input/output couplers are defined with an oxide over-cladded coupling waveguide (as shown in Figure 1f) and silicon inverse tapers, for input/output coupling loss less than 3-dB per facet.

Figure 2a shows the DC I–V diode characterization for the vertical *p-i-n* detector. The measured dark current is 500 nA at -1 V bias for our $4 \mu\text{m} \times 25 \mu\text{m}$ Ge detectors while a dark current of 1 μA is the typical upper bound for our high-bandwidth detectors^{29,30}. The measured 3-dB bandwidth of the detector is 9 GHz at 0 V bias and 18.5 GHz at -1 V bias as shown in Figure 2b, which agrees with our theoretical estimates detailed in Supplementary Information II. The oscillator-integrated detector responsivity is measured as 0.58 A/W at 0 V and 0.62 A/W near -0.5 V under 1550 nm illumination of 200 μW . With the integrated on-chip detector-oscillator, the measured optical signal-to-noise is ~ 10 dB from the spectrum analyzer measurement and the detector noise-equivalent-power is determined to be ~ 16 pW/ $\sqrt{\text{Hz}}$.

Figures 2c and 2d illustrate examples of the measured optical transmission spectra of the slot cavity resonances (see Methods and Supplementary Information I). Two-mode resonances are observed in the transmission, corresponding to the fundamental (~ 1541.5 nm) and higher-order mode excitations in the photonic band gap^{12,26}, and with typically loaded optical quality factors in the range of 60,000 to 150,000 for the fundamental mode (estimates of intrinsic quality factor are detailed in Supplementary Information III). The higher-order mode shows loaded quality factor typically in the range of 20,000 to 100,000. The modeled $|E|^2$ field distributions of the two resonances are shown in Figure 2c inset, with intrinsic quality factor of $\sim 800,000$ for the fundamental mode.

Figures 2e and 2f show the measured RF spectra of the integrated optomechanical oscillator at blue detuning and below/above the threshold power, respectively. The fundamental in-plane mechanical mode induced by radiation pressure is detected between 110 MHz to 120 MHz, depending on different sizes of the air-bridge (rectangular) holes in our design. As an example, for a dropped-in power about

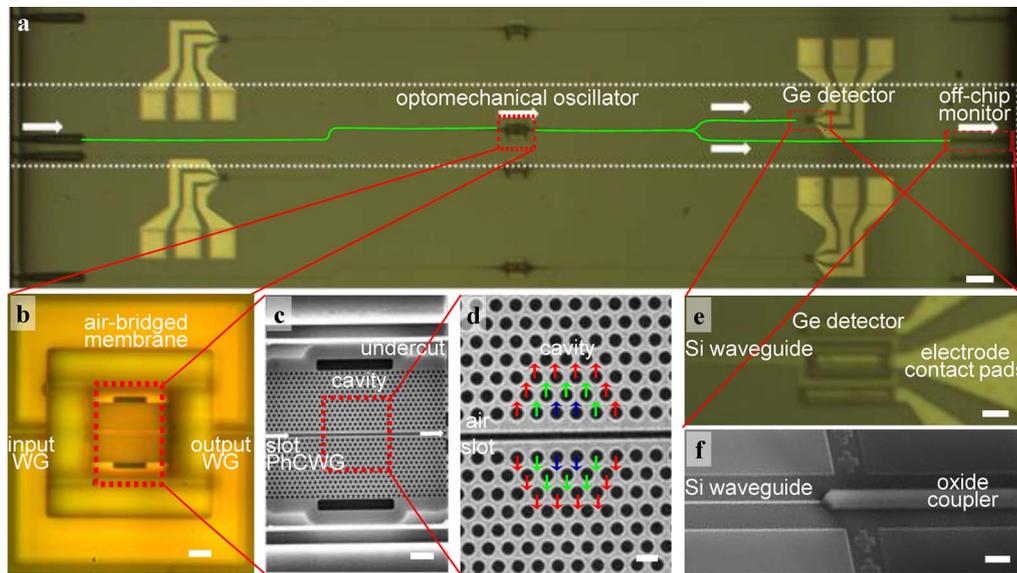


Figure 1 | An integrated optomechanical oscillator chipset. (a), Optical image of designed integrated optomechanical oscillator (OMO). The dashed white box highlights the single device set, with the waveguide light paths shown in green. Drive laser is from the left, with two detection ports – an integrated monolithic Ge detector and an external monitor. Scale bar: 100 μm . (b), Zoom-in optical image of designed optomechanical oscillator with in-line input/output waveguides (WG). Scale bar: 5 μm . (c), Zoom-in scanning electron micrograph (SEM) of air-bridged photonic crystal slot cavity, along with optimized design input/output slot waveguides. The lattice constant a is 510 nm and the ratio between hole radius and lattice constant a is 0.3, centering the optical resonance within the photonic band gap and at 1550 nm. Scale bar: 2.5 μm . (d), Zoom-in SEM of the slot cavity, formed by differential perturbative shifting of the nearest neighbor holes from a periodic lattice and denoted by the arrows (red: 5 nm; green: 10 nm; blue: 15 nm). Scale bar: 500 nm. (e), Zoom-in optical image of designed Ge detector with tapered silica waveguide (left) and tapered electrode contact pads (right). Scale bar: 10 μm . (f), Isometric view SEM of input silica waveguide with buried silicon inverse taper, for better impedance matching from fiber into the silicon waveguide. Scale bar: 500 nm.

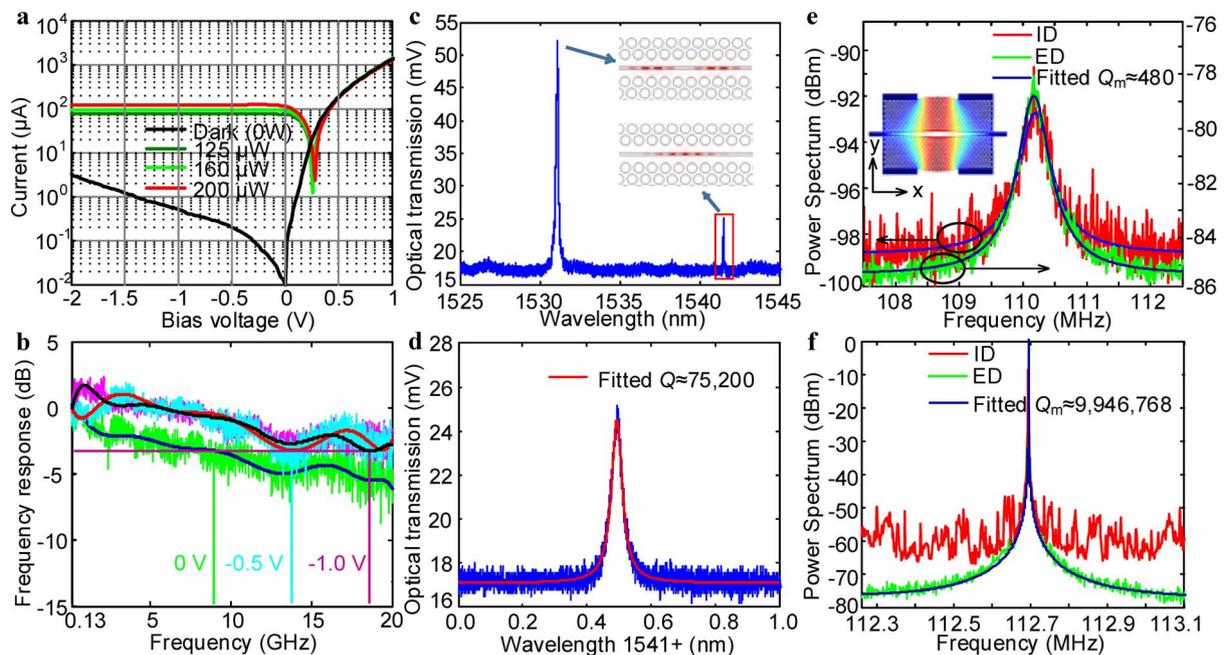


Figure 2 | Photoresponse and optical/mechanical transmission of the monolithic detectors and optomechanical cavity. (a), Measured DCI–V curve for integrated Ge detector under dark and illumination conditions with different laser powers. (b), Integrated Ge detector bandwidth under different reverse biases. Black (thicker) lines are the 9th degree polynomial fit for each bias. (c), Transmission spectra with the two-mode resonances of the slot cavity. Inset: $|E|^2$ -field distribution of the fundamental and higher-order resonances. (d), Zoom-in of the fundamental (longer wavelength, and boxed in panel c) resonance with loaded Q at 75,200. (e), RF spectra with integrated Ge detector and external photodetector, of cold cavity regime before oscillation. Inset: Finite-element model of the fundamental eigenmode. (f), RF spectra with integrated Ge detector and external photodetector of another device which shows mechanical mode centered near 112.7 MHz, under larger input laser power above threshold for oscillation mode. The output signals of both integrated Ge detector and external photodetector are amplified (~ 40 dB and ~ 10 dB, respectively) by low noise amplifiers to reach the typical power requirements of the signal source analyzer (Agilent 5052A).



−15 dBm, the measured RF spectra for both detectors in room temperature and atmosphere show the fundamental mechanical resonance at 110.3 MHz and a cold cavity mechanical quality factor Q_m of about 480. The modeled modal resonance displacement field is shown in the inset. By comparing results from external detector and integrated detector simultaneously, we note that our integrated Ge detector has low background noise floor that can go down to approximately −98 dBm (Figure 2e). The integrated oscillator-detector chipset, however, has a lower signal-to-noise ratio (SNR) due to the current short length (and effective length) of the Ge detector, which give ~50% absorption while on the other hand ensures a higher frequency response bandwidth. Excess noise spikes arise from the measurement background from the low signal when electrically read out from the chip. When driven (~400 μW) above threshold (~127 μW in this example), the intrinsic mechanical energy dissipation is overcome and the optomechanical resonator becomes a self-sustained OMO with narrow linewidths (~11 Hz in this example)³¹, as illustrated in Figure 2f. We note that in Figure 2f the RF spectrum from the integrated Ge detector is amplified so that the output signals are at the same power levels for comparison. The vacuum optomechanical coupling rate is determined experimentally by introducing phase modulation on the input laser and comparing the peak density power for modulation frequency and mechanical frequency^{23,32}. The vacuum optomechanical coupling rate is determined to be ~800 kHz which is much larger than other non-PhC optomechanical cavities²⁰, important to reduce the OMO threshold power and improve the transmitted SNR. The discrepancy of optomechanical coupling strength in simulation and experiment is due to coupling to other flexural modes^{12,28}. Pertinent details of the oscillation threshold, optomechanical coupling rate, and loss channels are detailed in Supplementary Information IV.

Figure 3a shows the high-order harmonics (captured by a 12 GHz external photodetector) from our monolithic OMO-detector chipset with increased pump power, due to the nonlinear optomechanical transduction from the optical lineshape. With increased dropped-in power up to 3.2 mW (25 times of the threshold power, see Supplementary Information IV), we observed RF harmonics up to 6.9 GHz, the 59th harmonic in this device case, which is bounded by the spectrum analyzer measurement range. Such high-harmonics can serve as high frequency reference. While the linewidth of the high-harmonic modes can be broadened, harmonic-locking schemes can also be introduced to stabilize the entire OMO frequency spectra^{33,34}. The higher-order harmonics can also be locked to optical transitions of atomic clock to improve the OMO long-term stability²⁴. As an example, we demonstrated the injection locking of OMO by introducing amplitude modulation of the input laser at frequency close to OMO's fundamental frequency as shown in Figure 3b and 3c. By sweeping external modulation frequency towards OMO fundamental frequency, we observed the transitions from frequency pulling/mixing to quasi-locking, and then to fully-locked regimes. When the OMO fundamental frequency is locked to the external modulation drive, the high-order harmonics are also stabilized and have very narrow linewidth, as shown in Figure 3c for the 31st harmonics at 3.63 GHz. Moreover, we also observe the cooperative interaction between the OMO displacement, free carrier density, and temperature in a single device which leads to the generation of rich subharmonics³⁵. As shown in Figure 3d, under various laser-cavity detunings and dropped-in powers, we can selectively excite one-half, one-third, and one-quarter subharmonic frequencies and their respective high-order harmonics. With the generation of both harmonics and subharmonics, our OMO device can be tuned to function both as a frequency multiplier and also a frequency divider in a single optomechanical cavity.

For the RF reference applications of OMOs, phase noise is an important character of a self-sustained oscillator. The phase noise performance of a OMO has been examined theoretically¹⁴ and

experimentally^{2,11} in prior studies. Figure 4a shows the single-sideband phase noise spectra of our free-running OMO chipset, for a 112.7 MHz carrier (see Methods). In room temperature and atmospheric non-vacuum, our integrated OMO chipset exhibits a phase noise of approximately −103 dBc/Hz at 1 kHz offset and −125 dBc/Hz at 10 kHz offset, one of the lowest noise to date in reported OMOs^{2,11,24}. For a comparison, phase noise measurements from the on-chip Ge detector and external detector are presented in Figure 4a. The integrated Ge detector exhibits lower phase noise at close-to-carrier offset (100 Hz to 10 kHz) and relatively higher phase noise at far-from-carrier offset (10 kHz to 10 MHz). We note that at higher frequency offsets (such as 1 MHz or more), the noise floor is limited only by our detector currently as the phase noise measured simultaneously by external detector can get as low as −165 dBc/Hz at 10 MHz offset. The higher phase noise at far-from-carrier offsets for the integrated Ge detector is a direct result of low SNR and large white noise floor from the RF amplification as indicated in the RF spectrum of Figure 2f. Figure 4a also plots the phase noise of the commercial electrical RF signal generator (Stanford Research System, Model SG384, DC-4.5 GHz) for comparison. As we can see, for offsets close-to-carrier frequency, our free running OMO has very significant amount of $1/f^3$ whereas for offsets far-from-carrier frequency ($f > 100$ kHz), our OMO actually has a lower phase noise performance.

The free-running OMO phase noise can be described by a closed-loop Leeson model^{2,13,36} and consists a dependence of $1/f^3$ between 100 Hz and 1 kHz and a dependence of $1/f^2$ between 1 kHz and 10 kHz. From Leeson model, the $1/f^3$ and $1/f^2$ phase noise are due to $1/f$ flicker noise and $1/f^0$ white noise in the system. The Leeson frequency and corner frequency then obtained through a power-law fit of the phase noise plot as $f_L = 3$ kHz and $f_c = 20$ kHz respectively (the theoretical power-law model³⁶ is detailed in Supplementary Information V). Note that the measured f_L is much larger than the oscillation linewidth (~11 Hz, see Figure 2f) measured by spectrum analyzer. This indicates our system has excess $1/f$ flicker noise component at low frequency offset which comes from slow environmental fluctuation such temperature or stage position shift. This explains the phase noise measured by integrated Ge detector has a lower phase noise in the close-to-carrier offset, since it is integrated in the same chip and less sensitive to drifts in stage positioning and optical coupling (see Supplementary Information V for more information). We also note that, for both phase noise curves, there are further drops in phase noise level after the $1/f^0$ white phase noise as shown in the 1 to 10 MHz offset in Figure 4a. The phase noise behavior is beyond the classic Leeson model and is contributed from the pump laser phase noise, as theoretically predicted in Ref. 14.

The $1/f^3$ flicker frequency noise of the OMO can also be greatly reduced by introducing active or passive locking schemes with external master frequency references. We measured the phase noise of the OMO chipset under injection locking^{33,34}. One distinct difference from the phase noise of free-running OMO is that the $1/f^4$ random walk frequency noise and $1/f^3$ flicker frequency noises are significantly suppressed below the 1 kHz offset. The reference phase noise shown in Figure 4b are measured by tuning the amplitude-modulated laser wavelength far from resonance, and measuring with the on-chip Ge detector. External RF gain is used before phase noise analyzer to keep the reference signal with the same RF power as the injection locking measurement. Comparing the phase noise directly from RF signal generator, we also note that additional components such as the electro-optic modulator (EOM) can add white noise at high offset frequencies due to the frequency transfer from the electronic circuits to optical carrier as shown in Figure 4b. This again demonstrates the unique advantage of OMOs in optical-RF signal processing without requiring electronic intermediates.

The timing jitter of the oscillator is calculated from the measured phase noise (see Supplementary Information V). For our free-running

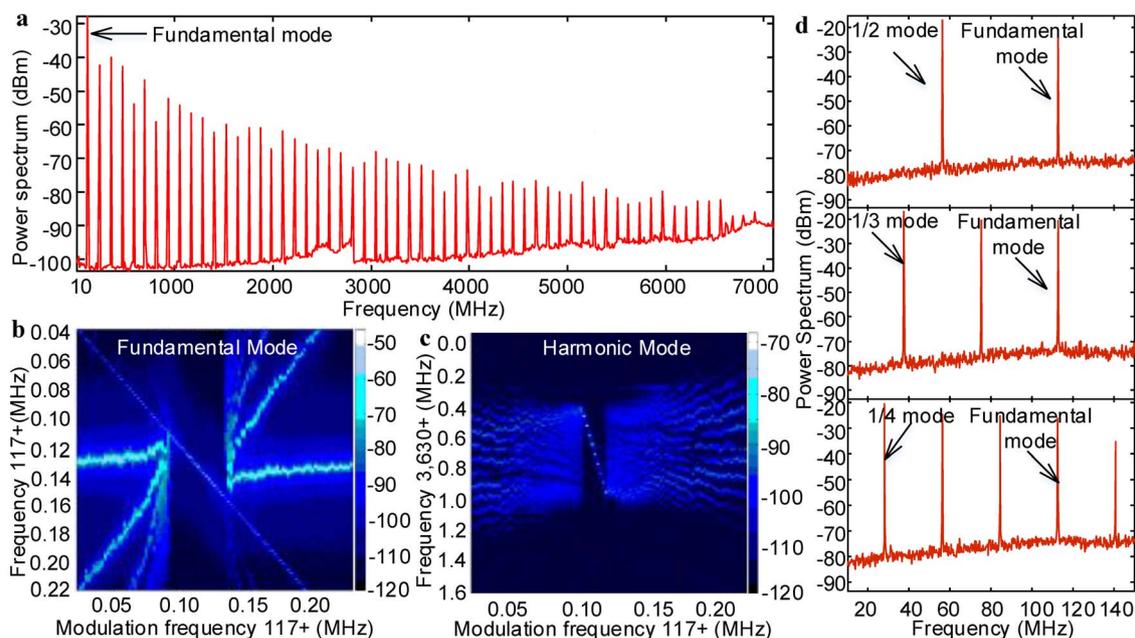


Figure 3 | Integrated RF and harmonics measurements of monolithic radiation-pressure-driven optomechanical oscillator. (a), RF harmonics above threshold of the oscillator, up to the 59th harmonic at 6.9 GHz, with dropped-in power 3.2 mW. A 12 GHz photodetector (New Focus Model 1544) was used here to capture the harmonics. The resolution bandwidth (RBW) is 1 kHz and the video bandwidth (VBW) is 100 kHz. (b), 2D spectra of the OMO signal with injection locking characteristics, with the horizontal axis as the tuned modulation frequency and the vertical axis as the RF spectra. (c), 2D spectra of the high-order 31st harmonic at 3.63 GHz for the OMO signal with injection locking characteristics. (d), RF subharmonics of the oscillator for (from top to bottom) half mode, one third mode, and quarter mode.

OMO the root-mean-square timing jitter, integrating the phase noise from 100 Hz to the carrier frequency (112.7 MHz), is 3.42 ps for the integrated detector and 10.01 ps for the external photodetector, with performance close to commercial electronic frequency standards. Allan deviation is another time-domain metric to characterize the frequency reference stability, computed from the oscillator phase noise by³⁶

$$\sigma(\tau) = \sqrt{\sigma^2(\tau)} = \sqrt{\int_0^{\infty} \frac{4f^2 L_{\phi}(f) \sin^4(\pi f \tau)}{v_0^2 (\pi f \tau)^2} df}.$$

Here $L_{\phi}(f)$ is the oscillator phase noise and v_0 is the carrier frequency. Figure 4c shows the open-loop Allan deviations calculated from raw phase noise and power-law fitted phase noise for the free-running OMO. The consistency between different methods can be seen in Figure 4c where there is small phase noise discrepancy at the close-to-carrier and far-from-carrier offsets. Figure 4d shows the Allan deviations under injection locking scheme which also illustrates the longer term of stability.

In summary, we illustrated a CMOS-compatible integrated RF oscillator chipset, where PhC optomechanical cavities with deeply-subwavelength slot widths are monolithically integrated with high-bandwidth epitaxial Ge *p-i-n* photodetectors. Optomechanical cavities with optical quality factor of $\sim 100,000$ are co-fabricated with high-yield across full wafers with DUV lithography and multiple planarization processes, for chip-scale integrated optomechanical oscillators. Our oscillator demonstrates a CMOS-integrated radiation-pressure-driven oscillator with high 59th harmonic up to 6.9 GHz and selectively excited subharmonic tones. For practical applications in frequency references, we demonstrated the single-sideband phase noise of -125 dBc/Hz at 10 kHz offset with 112.7 MHz carrier frequency in room temperature and atmosphere, one of the lowest phase noise optomechanical oscillators to date. The chip-monolithic Allan deviation is observed down to 5×10^{-9} at

1-millisecond integration, also at ~ 400 μ W dropped-in powers, and likewise in room temperature and atmosphere operating conditions. Our work presents a promising step towards fully on-chip applications of optomechanical oscillators in the optical-RF information processing architectures.

Methods

Chipset nanofabrication. The CMOS-compatible process consists of 20 masks and multi-level alignments and about 280 optimized nanofabrication process steps, on a 8" silicon wafer with 250-nm device thickness at the foundry. The designed process flow principle starts with definition of the 120 nm critical dimension slot widths in the optomechanical oscillator (on substrate, without membrane release), followed by the epitaxial and vertical *p-i-n* Ge photodetector growth and vias/electrode contact pads definition.

To achieve the deeply-subwavelength slots on a 248-nm DUV lithography stepper, the resist profile is patterned with a 185 nm slot line width, which is then transferred into the oxide, with a residual slope in the oxide etch. The bottom 120 nm oxide gap is then etched into the silicon device layer through tight process control in the silicon etch, with resulting cavities shown in Figure 1c and 1d. Next all the PhC cavity and lattice patterns are aligned to the slot arrays across the 8" wafer and optimally etched into the device layer, to create the optomechanical cavity (unreleased). *p+* implantation for the bottom contact is implemented before the 500 nm Ge epitaxial growth for the detector. Vertical vias are next patterned and metal layer deposited for the contact holes and the patterned electrode pads as shown earlier in Figure 1e. Multiple planarization steps are interspaced across the entire process flow, critical for the success and high-yield of the OMO chipset. After fabricating the integrated Ge detectors, the optical input/output couplers are defined, with silicon inverse tapers and oxide over-cladded coupler waveguides with coupling loss less than 3-dB per facet. The silicon taper and oxide over-cladded waveguide has a modelled 98% coupling efficiency. The PhC cavity is next carefully released by etching the bottom oxide with buffered-oxide etch and tight process control.

Device design. The device design consists three steps. In the first step we simulate and optimize optical performance of the device. The photonic crystal band structure is simulated by MPB mode solver³⁷. The field distribution and the quality factor of the slot-guided mode are simulated by free finite-difference-time-domain (FDTD) based solver MEEP³⁸ and finite-element-method (FEM) based commercial software COMSOL, for a comparison. Then we simulate the mechanical modes' displacement field and quality factor with the structure mechanics module of COMSOL. Finally, both optical and mechanical simulation result is combined in MATLAB to calculate the optomechanical coupling rate.

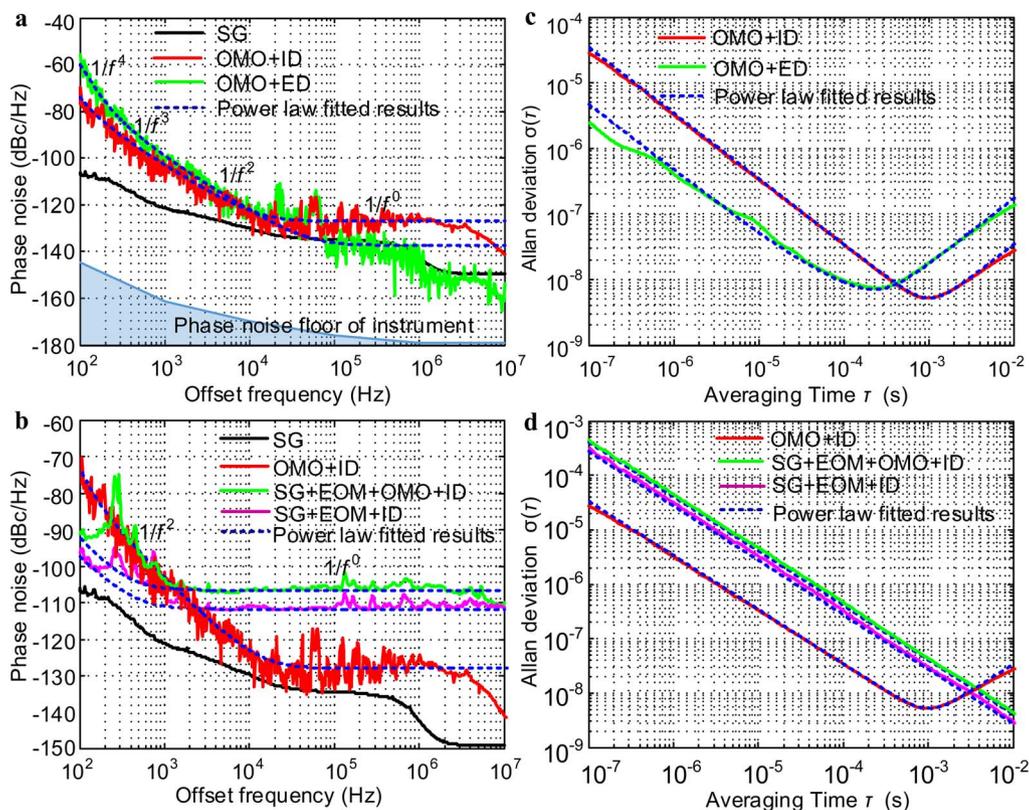


Figure 4 | Phase noise and Allan deviation results. (a), Phase noise results for both integrated Ge detector and external photodetector at 400 μW dropped-in power. The phase noise of signal generator and the phase noise floor of the Agilent instrument are also shown in this panel for comparisons. The two blue dashed curves are the power-law fitted phase noise for the two detectors. (b), Phase noise results for the injection locking and a signal generator modulated laser at off-resonance mode wavelength. The Phase noise of signal generator and the free-running OMO are also shown in this panel for comparisons. The three blue dashed curves are the power-law fitted phase noise. Note a slight noise peak between 200 Hz to 1 kHz in this free-running OMO data. (c), The corresponding Allen deviation results converted from the measured phase noise results for both detectors in panel a. The blue dashed lines are the corresponding power low fitted results. (d), The corresponding Allen deviation results converted from the measured phase noise results in panel b. The blue dashed lines are the corresponding power low fitted results.

RF and optical measurements. The drive tunable diode laser is the Santec TSL-510C, tunable from 1510 to 1630 nm. A fiber polarization controller and a polarizer is used to select the transverse-electric (TE) state-of-polarization to drive the optomechanical oscillator. The external photodetector is a New Focus 125 MHz detector used to monitor the RF spectra, along with a slow detector to simultaneously track the optical transmission. When an optical amplifier is used, an isolator is included to protect the amplifier against potential damage from large optical reflections. For the RF spectrum measurements of integrated Ge detector, a RF probe (Picoprobe GSG-100-P, GGB Industries, Inc.) is contacted onto the aluminum pads.

Phase noise measurements. The output signals of both integrated Ge detector and external photodetector are amplified by low noise amplifiers to reach the typical power requirements of the signal source analyzer (Agilent 5052A). Different RF amplification (between the detector and the signal source analyzer) is used for the integrated and external detectors so that the photodetector power is kept the same for proper phase noise comparison. The amplified signals are passed through a narrow-band filter to suppress the subharmonics and/or high-order harmonics. In the measurements, to identify the real phase noise of our OMO, the IF gain and correlation of the Agilent instrument for phase noise measurement are set as 50 dB and above 128, respectively. For injection locking measurement, an external RF reference modulates the laser by using an EOM (JDS Uniphase, OC192 10 Gb/s Amplitude Modulator) before coupling into the chipset.

- Kippenberg, T. J. & Vahala, K. J. Cavity optomechanics: back-action at the mesoscale. *Science* **321**, 1172–6 (2008).
- Hossein-Zadeh, M., Rokhsari, H., Hajimiri, A. & Vahala, K. Characterization of a radiation-pressure-driven micromechanical oscillator. *Phys. Rev. A* **74**, 023813 (2006).
- Hossein-Zadeh, M. & Vahala, K. An optomechanical oscillator on a silicon chip. *IEEE J. Sel. Top. Quantum Electron.* **16**, 276–287 (2010).
- Van Thourhout, D. & Roels, J. Optomechanical device actuation through the optical gradient force. *Nature Photon.* **4**, 211–217 (2010).

- Notomi, M., Taniyama, H., Mitsugi, S. & Kuramochi, E. Optomechanical wavelength and energy conversion in high-Q double-layer cavities of photonic crystal slabs. *Phys. Rev. Lett.* **97**, 023903 (2006).
- Thompson, J. D. *et al.* Strong dispersive coupling of a high-finesse cavity to a micromechanical membrane. *Nature* **452**, 72–5 (2008).
- Dobrint, J., Wilson-Rae, I. & Kippenberg, T. Parametric normal-mode splitting in cavity optomechanics. *Phys. Rev. Lett.* **101**, 263602 (2008).
- Carmon, T., Rokhsari, H., Yang, L., Kippenberg, T. & Vahala, K. Temporal behavior of radiation-pressure-induced vibrations of an optical microcavity phonon mode. *Phys. Rev. Lett.* **94**, 223902 (2005).
- Kippenberg, T., Rokhsari, H., Carmon, T., Scherer, A. & Vahala, K. Analysis of radiation-pressure induced mechanical oscillation of an optical microcavity. *Phys. Rev. Lett.* **95**, 033901 (2005).
- Vahala, K. Back-action limit of linewidth in an optomechanical oscillator. *Phys. Rev. A* **78**, 023832 (2008).
- Tallur, S., Sridaran, S. & Bhave, S. a. A monolithic radiation-pressure driven, low phase noise silicon nitride opto-mechanical oscillator. *Opt. Express* **19**, 24522–9 (2011).
- Zheng, J. *et al.* Parametric optomechanical oscillations in two-dimensional slot-type high-Q photonic crystal cavities. *Appl. Phys. Lett.* **100**, 211908 (2012).
- Tallur, S., Sridaran, S., Bhave, S. A. & Carmon, T. Phase noise modeling of optomechanical oscillators. *Paper presented at 2010 IEEE Int. Freq. Control Symp.*, Newport Beach, CA, pages 268–272, Institute of Electrical and Electronics Engineers, DOI: 10.1109/FREQ.2010.5556330 (June 2010).
- Matsko, A., Savchenkov, A. & Maleki, L. Stability of resonant opto-mechanical oscillators. *Opt. Express* **20**, 16234–16244 (2012).
- Gavartin, E., Verlot, P. & Kippenberg, T. J. Stabilization of a linear nanomechanical oscillator to its thermodynamic limit. *Nature Commun.* **4**, 2860 (2013).
- Antonio, D., Zanette, D. H. & López, D. Frequency stabilization in nonlinear micromechanical oscillators. *Nature Commun.* **3**, 806 (2012).
- Wiederhecker, G. S., Chen, L., Gondarenko, A. & Lipson, M. Controlling photonic structures using optical forces. *Nature* **462**, 633–6 (2009).



18. Safavi-Naeini, A. H. *et al.* Two-dimensional phononic-photonic band gap optomechanical crystal cavity. *Phys. Rev. Lett.* **112**, 153603 (2014).
19. Sun, X., Xu, K. & Tang, H. X. Monolithically integrated, ultrahigh-frequency cavity nano-optoelectromechanical system with on-chip germanium waveguide photodetector. *Opt. Lett.* **39**, 2514 (2014).
20. Aspelmeyer, M., Kippenberg, T. J. & Marquardt, F. Cavity Optomechanics. arxiv:1303.0733 (March 2013). <http://arxiv.org/abs/1303.0733>.
21. Li, Y. *et al.* Design of dispersive optomechanical coupling and cooling in ultrahigh-Q/V slot-type photonic crystal cavities. *Opt. Express* **18**, 23844–56 (2010).
22. Chan, J. *et al.* Laser cooling of a nanomechanical oscillator into its quantum ground state. *Nature* **478**, 89–92 (2011).
23. Gavartin, E. *et al.* Optomechanical coupling in a two-dimensional photonic crystal defect cavity. *Phys. Rev. Lett.* **106**, 203902 (2011).
24. Beyazoglu, T. *et al.* A multi-material Q-booster low phase noise optomechanical oscillator. Paper presented at 2014 IEEE Int. Conf. MEMS, San Francisco, CA, pages 1193–1196, Institute of Electrical and Electronics Engineers, DOI: 10.1109/MEMSYS.2014.6765861 (Jan 2014).
25. Yamamoto, T. & Notomi, M. Design of a high-Q air-slot cavity based on a width-modulated line-defect in a photonic crystal slab. *Opt. Express* **16**, 13809–13817 (2008).
26. Gao, J. *et al.* Demonstration of an air-slot mode-gap confined photonic crystal slab nanocavity with ultrasmall mode volumes. *Appl. Phys. Lett.* **96**, 051123 (2010).
27. Di Falco, A., O'Faolain, L. & Krauss, T. F. Dispersion control and slow light in slotted photonic crystal waveguides. *Appl. Phys. Lett.* **92**, 083501 (2008).
28. Safavi-Naeini, A. H., Alegre, T. P. M., Winger, M. & Painter, O. Optomechanics in an ultrahigh-Q two-dimensional photonic crystal cavity. *Appl. Phys. Lett.* **97**, 181106 (2010).
29. Ang, K., Liow, T. & Yu, M. Low thermal budget monolithic integration of evanescent-coupled Ge-on-SOI photodetector on Si CMOS platform. *IEEE J. Sel. Top. Quantum Electron.* **16**, 106–113 (2010).
30. Liow, T., Ang, K., Fang, Q. & Song, J. Silicon modulators and germanium photodetectors on SOI: monolithic integration, compatibility, and performance optimization. *IEEE J. Sel. Top. Quantum Electron.* **16**, 307–315 (2010).
31. Rokhsari, H., Kippenberg, T. J., Carmon, T. & Vahala, K. J. Theoretical and experimental study of radiation pressure-induced mechanical oscillations (parametric instability) in optical microcavities. *IEEE J. Sel. Top. Quantum Electron.* **12**, 96–107 (2006).
32. Gorodetsky, M., Schliesser, A., Anetsberger, G., Deleglise, S. & Kippenberg, T. J. Determination of the vacuum optomechanical coupling rate using frequency noise calibration. *Opt. Express* **58**, 11 (2010).
33. Hossein-Zadeh, M. & Vahala, K. J. Observation of injection locking in an optomechanical rf oscillator. *Appl. Phys. Lett.* **93**, 191115 (2008).
34. Zheng, J. *et al.* Feedback and harmonic locking of slot-type optomechanical oscillators to external low-noise reference clocks. *Appl. Phys. Lett.* **102**, 141117 (2013).
35. Luan, X. *et al.* Subharmonics generation based on synchronization of self-pulsation and optomechanical oscillation in a monolithic silicon cavity. *Postdeadline paper presented at the Confrence on Lasers and Electro-Optics*, San Jose, CA, paper JTh5B.5, Optical Society of America, DOI:10.1364/CLEO_AT.2014.JTh5B.5 (June 2014).
36. Rubiola, E. *Phase noise and frequency stability in oscillators*. (Cambridge University Press, New York, 2008).
37. Johnson, S. G. & Joannopoulos, J. D. Block-iterative frequency-domain methods for Maxwell's equations in a planewave basis. *Opt. Express* **8**, 173 (2001).
38. Oskooi, A. F. *et al.* MEEP: A flexible free-software package for electromagnetic simulations by the FDTD method. *Computer Physics Commun.* **181**, 687 (2010).

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Author contributions

X.L., Y.H., Y.L., J.F.M., S.W.H., T.G., A.H. and D.A.H. performed the measurements, J.Z., J.F.M., P.C.H. and C.W.W. performed the designs and layouts, M.Y., D.W., G.Q.L. and D.L.K. provided the nanofabrication and samples, and X.L., Y.H., G.W. and C.W.W. put together the manuscript with contributions from all authors.

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