Ultrahigh-frequency nano-optomechanical resonators in slot waveguide ring cavities

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We demonstrate integrated nano-optomechanical systems with driven flexural resonance up to 760 MHz in the ultrahigh frequency band. The mechanical element of the device is embedded in a slot waveguide racetrack optical resonator with an optical quality factor of 60 000. Displacement sensitivity of 0.45×10^{-15} m/$\sqrt{\text{Hz}}$ at 127 MHz is achieved in this circuit cavity configuration. © *2010 American Institute of Physics*. [doi:10.1063/1.3513213]

Recent development in nano-optomechanical systems (NOMS) marries the fields of nanomechanics and nanophotonics on a monolithic device platform.[1–3] In NOMS devices, optical fields and mechanical modes interact via strong gradient forces. The high actuation and detection efficiency of optical methods promise to have wider bandwidth for operating nanomechanical devices than conventional electrical methods. Using light as the signal carrier circumvents common transduction difficulties in electromechanical systems such as impedance mismatching and signal cross-talking.[4–6] High vibration frequencies of nanomechanical devices are desired for mass sensing applications.[4,7] Furthermore, operating optomechanical devices at high frequencies directly links the signal domains at rf and microwave frequencies in optical channels, thus avoiding large overhead of optoelectronic signal conversion.[8] Further implementation will find promising applications in rf optomechanical signal processing.[9]

Various microscale and nanoscale optical cavities have been widely employed to improve the detection sensitivity of nanomechanical devices and to explore optomechanical backaction effects.[10–12] To enhance the coupling strength of an optomechanical device, a powerful approach involves increasing the coupling area while maintaining a small coupling gap.[2,3,13] However, this increased coupling strength often comes at the expense of a relatively larger size of the resonator. In this work, we scale down the dimensions of the nanomechanical resonators and embed them in a slot racetrack cavity [Fig. 1(a)]. As shown in Fig. 1(b), the optical field in slot waveguides is strongly confined in the small void region between two dielectric slabs.[14] Because of the high index-contrast at the interface of the air gap and the dielectrics, large field gradient and corresponding strong gradient optical force is generated on both slabs. For a silicon slot waveguide consisting of 350 nm wide slabs and an 80 nm air gap (mode index 1.92), we calculate that the gradient force amounts to 15 pN/μm/mW.[15] This force is 30 times larger than the previously demonstrated optical force on a single waveguide coupled to a silicon dioxide substrate. When the slot waveguide is released from the substrate [inset of Fig. 1(a)], the gradient optical force pulls both beams together and reduces the air gap between them. This mechanical displacement changes the effective mode index of the slot waveguide and induces a phase shift. Using a ring cavity configuration, not only the circulating optical power (thus the optical force) is enhanced inside the cavity but also the optical phase detection is enhanced by the cavity's finesse, providing improved displacement sensitivity.

We fabricated the devices on standard silicon-on-insulator substrates, with 220 nm thick silicon and 3 μm buried oxide layers. The photonic structures were patterned with high-resolution ebeam lithography and etched with plasma dry etching based on chlorine chemistry. The nanomechanical beams of 2 μm length were defined by laser direct write photolithography. To release the beams from the substrate, the substrate was etched in buffered oxide etching solution. A pair of grating couplers was used to couple light into and out of the device.

The coupling coefficient from the input waveguide to the racetrack depends on the slot waveguide and racetrack dimensions and the coupling distance between them. By measuring devices with varying geometries, we determined the critical coupling distance between input waveguide and the racetrack to be 180 nm (for a slot waveguide with 350 nm slab and 80 nm air gap). Figure 2 shows a typical transmission spectrum of a device after the releasing process, displaying a good extinction ratio of 20 dB. The measured free spectral range of the ring cavity (total length 331.2 μm) is 1.65 nm at 1540 nm wavelength, corresponding to a group index of 4.34 which is consistent with our theoretical analysis. The loaded optical quality factor is 60 000 (the corresponding finesse is 64) [Fig. 2(b)]. We note that differing from a single waveguide coupled vertically to the substrate,[1] the releasing process does not induce significant insertion loss in the slot waveguide or degrade the optical quality factor, because the optical mode is highly confined in the void region. Alternatively, a horizontal slot waveguide configura-

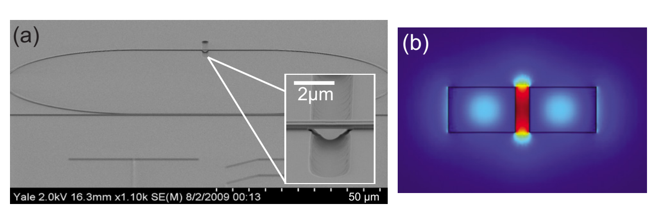

FIG. 1. (Color online) (a) Scanning electron microscope image of the racetrack cavity and coupling waveguide. Inset: the released slot waveguide inside the racetrack cavity. (b) The TE mode of the slot waveguide.

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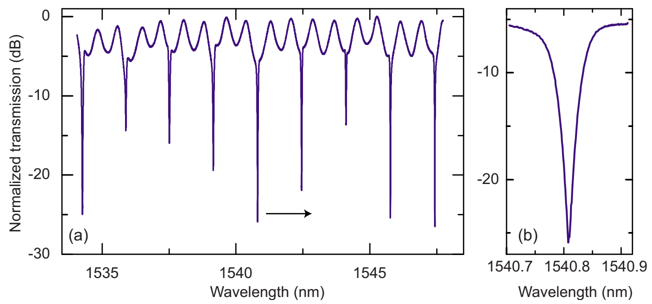

FIG. 2. (Color online) (a) Measured transmission spectrum of the racetrack cavity device after the releasing of the nanomechanical beams. (b) The best optical quality factor is 60 000.

tion can be employed for adiabatic embedment of released waveguides that couple strongly with the substrate.[16]

We first measure the noise spectrum of the mechanical resonance from the transmitted optical signal of the device. The input laser frequency is slightly detuned from the optical resonance of the cavity to detect the phase variation caused by the mechanical motion of the beams. In the noise spectrum shown in Fig. 3(a), two resonance peaks at 118 and 127 MHz can be observed, corresponding to the in-plane fundamental vibration modes of each waveguide beam. The mechanical quality factors in vacuum were 2400 and 2600, respectively (in atmosphere, quality factors are reduced to ~300). With 10 mW input power on the waveguide, the calibrated displacement sensitivity is 450 am/$\sqrt{\text{Hz}}$, limited by the noise of the photodetector (New Focus model 1611). This value represents two orders of magnitude improvement in displacement sensitivity at very-high frequency over what was achieved with electrical detection methods,[6] and compares favorably with the sensitivity achieved with superconducting devices at lower frequency.[17] The integrated circuit layout of our systems also eliminates the need for fiber alignment at the nanoscale and therefore offers higher stability. Even higher sensitivity could in principle be achieved with larger optical power to reach the shot-noise limited regime. However, the viable power level in our silicon devices is limited by the instability of the cavity at high optical power, which is mainly induced by two photon absorption and the subsequent thermo-optical effect of silicon.[18,19] This limitation can be circumvented by using a wide band gap dielectric material such as silicon nitride.

The strong gradient force in the slot waveguide can efficiently excite the mechanical motion of the beams. We employ the pump-probe technique described in our previous work to directly excite and measure the response of the device. Besides the probe laser, a pump laser was applied with its frequency tuned to a separate optical resonance of the cavity in order to maximize the optical power density inside the cavity. The intensity of the pump laser was modulated with an electro-optical modulator to generate dynamic optical force inside the slot. Using a network analyzer, the device's amplitude and phase responses were both measured as shown in Figs. 3(b) and 3(c). In addition to the fundamental mechanical mode, the optical force is large enough to excite the third order mode at 760 MHz. Even-order mechanical modes cannot be detected due to the symmetry of the slot waveguide mode. The mechanical quality factor of the third mode is 500. This degradation of mechanical quality

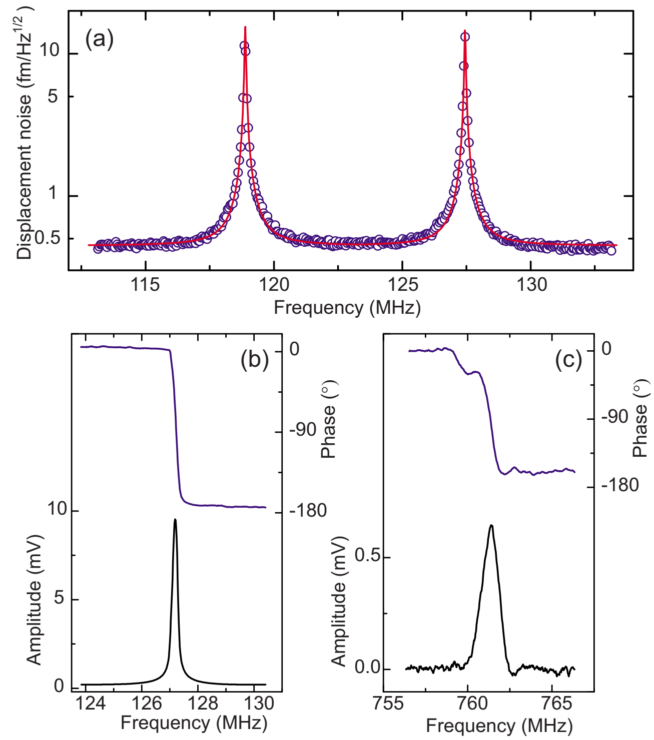

FIG. 3. (Color online) (a) Output noise spectrum of the optical probe signal, showing thermomechanical peaks of the two beams' fundamental in-plane modes. Displacement sensitivity of 0.45×10^{-15} m/$\sqrt{\text{Hz}}$ is obtained at very high frequency. (b) and (c) Driven response in amplitude and phase of one nanomechanical beam at its fundamental (b) and third (c) mechanical modes.

factor is attributed to the unoptimized clamping points that are defined by the wet etching process and thus introduces more clamping loss for mechanical modes with higher stiffness.[4,20] This clamping loss can be further reduced by utilizing photonic crystal structures to provide better mechanical support.[21]

In conclusion, we demonstrated nano-optomechanical devices with ultrahigh frequencies integrated in a high quality photonic cavity on a silicon photonics platform. Obtaining ultrahigh and eventually multiple gigahertz resonance frequency of nanomechanical devices is not only highly desirable for many practical sensing applications but also lowers the thermal occupation number at currently obtainable cryogenic temperatures prior to applying cavity optomechanical backaction cooling.[10,22] Further progress of our demonstration with improvement in both optical and mechanical quality factors is the key to achieve such a goal.

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