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A NANOMACHINED TUNABLE OSCILLATOR CONTROLLED BY ELECTROSTATIC AND OPTICAL FORCE

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ABSTRACT

We develop a miniaturized electrostatically tunable optomechanical oscillator, whose frequencies can be electrostatically tuned by as much as 10%. By taking advantage of the optical and the electrical spring, the oscillator achieves a high tuning sensitivity without resorting to mechanical tension. Particularly, the high-Q optical cavity greatly enhances the system sensitivity, making it extremely sensitive to the motional signal, which is often overwhelmed by background noise.

INTRODUCTION

MEMS oscillators [1] typically have large footprint and high resonant frequency at the expense of large mechanical stiffness, which makes frequency tuning difficult. The optomechanical oscillator, instead, can achieve high resonant frequency with optical force utilized [2] while maintains the mechanical compliance. The high stability and low phase noise of the resonant optomechanical oscillator have been widely reported [3-4]. On the other hand, the resonant frequency tunability, another important potential property of the oscillator, remains unexplored. In fact, cavity optomechanical device is a good candidate for resonant frequency tuning because of its inherently nonlinear optical spring effect [5-6]. Here, we adapt a new method to tune the optical spring by making use of the electrostatic force. The electrostatic force changes the relative detuning of the input light, making the mechanical frequency of the optical resonator shift with optical spring changing. The small motional signal can be detected due to the high quality factor of the optical cavity, which greatly enhances the system sensitivity.

The proposed tunable nano mechanical oscillator are controlled by both the electrostatic force and the optical force. By taking advantage of the large nonlinearity of the optical force, the oscillator achieves a high tuning sensitivity without resorting to mechanical tension. The tunable optomechanical oscillator have merits such as small dimension, low power consumption and little requirement for complex feedback systems, which makes it a good candidate in future applications in silicon photonic circuits and on chip signal processing.

DESIGN AND WORKING PRINCIPLE

The proposed optomechanical oscillator consists of a cantilever, two metal pads, a ring resonator and a bus waveguide, as shown in Fig. 1(a). A high power drive light is pumped into the bus waveguide through the input port and coupled into the ring resonator. Due to the evanescent wave overlapping, the attractive optical force is generated between the ring resonator and the cantilever. By taking advantage of large optomechanical coupling coefficient, the blue-detuned pumping reduces the mechanical damping rate and leads to regenerative amplification of the thermal motion. As a result, the cantilever starts to oscillate. A low power signal light is then pumped into the bus waveguide which induces a small optical force on the cantilever. Meanwhile, an electric DC voltage is applied between the two metal pads and induces electrostatic force on the cantilever. The electrostatic force and the optical force by the signal light on the cantilever modulates the cantilever oscillation frequency. As the cantilever modulates the resonance frequency of the ring, the moved distance of the cantilever can be precisely detected by measuring the frequency shift at the output.

Figure 1: Schematic of the tunable nanomachined oscillator. The electrostatic force can drive the doped silicon cantilever to tune the frequency.

The strong optical spring effect can be easily tuned by changing the electrostatic force to reach the softening and

hardening regimes. The finite element method (COMSOL Multiphysics) simulation on the cantilever deformation is shown in Fig. 2 (a). The ring has a diameter of 30 μm and the length of the cantilever is 7 μm . The electrostatic force and the optical force are in opposite direction. Compared with the optical force, the electrostatic force dominates in the deformation of the cantilever. The total structure can be reduced to a lumped theoretical model, which is shown in Fig. 2(b). Considering the nonlinearity of the optical and electrostatic force, the effective spring constant of the structure consists of three parts: the optical spring constant, the electrical spring constant and the original mechanical spring constant. The effective spring constant can either be increased or decreased when the optical spring constant is negative or positive, correspondingly, which depends on the relative detuning. It provides a good platform to realize a tunable oscillator.

Figure 2: (a) Finite element method simulation of the deformation of the cantilever and (b) working principle of the effective spring model.

The optical energy stored in the ring resonator can be expressed as [7]

$$|a|^2 = \frac{k_e}{(k/2)^2 + (w_c - w_r - g_{om}x)^2} P_{in} \quad (1)$$

where the power of the control light is P_{in} , k is the full-width at half-max linewidth of the optical resonance, k_e is the external coupling rate, w_c is the frequency of the control light, and w_r is the unperturbed resonance frequency of the ring, g_{om} is the optomechanical coupling coefficient and x is the mechanical deformation. The optical force can be expressed as [8]

$$F_0 = \frac{|a|^2 g_{om}}{w_l} \quad (2)$$

(a)

(b)

(c)

Figure 3: (a) Deformation of the cantilever at the

electrostatic and optical force. (b) The spring constant is function of the deformation and (b) the sensing principle by the ring cavity.

The strong light confinement in the ring makes the optical mode frequency highly sensitive to the gap between the ring and the beam with a theoretical optomechanical coupling coefficient $g_{om} = 1.2 \text{ GHz/nm}$. The typical loaded optical quality factor for the fundamental TE mode is $Q = 1.8 \times 10^4$ (Finesse $F = 171$). The electrical actuators are formed by the metal pads and the highly doped silicon cantilever. The electrostatic force induced by a voltage V can be expressed as

$$F_e = \frac{\alpha A \epsilon \epsilon_0}{2(d-x)^2} V^2 \quad (3)$$

where d is the capacitor gap and α is correction parameter for the fringing effect. Electrostatic force leads to the contraction of the capacitors, resulting in a wavelength shift of the cavity resonance.

To investigate the optical spring effect, we extend the optical force at the equilibrium point to second order expressed as

$$F_{\text{optical}} = F(x_0) + k_{o1} \delta x + k_{o2} \delta x^2 \quad (4)$$

where k_{o1} is the spring constant and k_{o2} is the quadratic coefficient. In fact, the quadratic term can be neglected for the primary resonance. Therefore, the spring constant is dominant on the primary resonance of the cantilever beam. The electrical spring constant can also be derived through the Taylor extension. The effective spring constant of the structure can be expressed as

$$k_{\text{effective}} = k_{o1} + k_{e1} + k_m \quad (5)$$

Figure 3(a) shows the deformation of the cantilever by the optical and electrostatic force. Compared with the optical force, the electrostatic force is much bigger. Therefore, the deformation of the cantilever is largely determined by the electrostatic force. However, the optical spring constant is much bigger than the electrical spring constant even at so much difference. The optical and electrical spring constant is shown in Fig. 3(b). The optical spring is not only bigger than electrical spring, but also shows negative or positive spring effect depending on the deformation. Figure 3(c) shows the sensing principle of the oscillator. A signal light is pumped into the bus waveguide to detect the small motion of the cantilever. Due to the high quality factor of the ring, the sensitivity of the system is very high.

FABRICATION PROCESSES

The scanning electron microscope (SEM) graphs of the tunable optomechanical oscillator are shown in Fig. 4. The oscillator with a footprint of $45 \mu\text{m} \times 30 \mu\text{m}$ is fabricated on silicon-on-insulator (SOI) wafer with structure layer

thickness of 220 nm. The actuator is patterned by deep UV lithography and etched by plasma dry etching. The waveguide is covered by a layer of SiO_2 cladding (2 μm thick) which is deposited using plasma enhanced chemical vapor deposition (PECVD). In the release process, a 50-nm amorphous silicon layer is used as the hard mask to protect the structures not to be released. Then the buried-oxide layer is removed using HF-vapor with precise time control. The width of the suspension beam is 200 nm and total length is 7 μm , so that it can provide a spring constant comparable with the optical spring and be more sensitivity to the driven force. The suspension beam are highly doped to serves as a movable capacitor. The doping concentration is $2 \times 10^{14} \text{ cm}^{-3}$. A pair of inversed mode converters was used to couple light into and out of the device on the waveguide alignment system platform. The device is tested in a vacuum chamber.

Figure 4: SEM images of the tunable oscillator.

EXPERIMENTS AND DISCUSSIONS

The measured transmission spectra of the waveguide at different electric voltage are shown in Fig. 5. When increasing the voltage from 0 V to 11 V, the cantilever is pulled against the ring, leading to the wavelength blue-shift with $\Delta\lambda = 0.58 \text{ nm}$. The shift of the resonant frequency is

linear to the voltage in small range. At the same time, due to the small deformation, the tension in the cantilever can be neglected. The voltage can effectively control the deformation of the cantilever and tunes the optical spring constant. We use a high power drive light to stimulate the oscillation of the cantilever and then tune the frequency by applying different voltages. The measured RF spectra of the cantilever oscillation are shown in Figure 6. It can be seen that the oscillation frequency is increased from 4.2 MHz to 5 MHz when the voltage increases from 7.2 V to 9 V.

Figure 5: Transmission spectra of the cavity when increasing the voltage.

Figure 6: Resonance frequency of the oscillator tuned by the voltage.

CONCLUSIONS

In this work, an electrostatically tunable optomechanical oscillator is designed, fabricated and experimentally tested. The doped cantilever can be deformed by the electrostatic force, resulting in the shift of

the ring resonance. The tuned optical spring constant changes the resonance frequency of the oscillator. The frequency is shifted from 4.2 MHz to 5 MHz in the experiment with the applied voltage increasing from 7.2 V to 9 V. The oscillator in the experiment shows a high tuning sensitivity without resorting to the mechanical tension. The tunable optomechanical oscillator have merits such as small dimension, low power consumption and little requirement for complex feedback systems, which makes it a good candidate for future applications in silicon photonic circuit and on chip signal processing.

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