NEMS ACTUATOR DRIVEN BY OPTICAL GRADIENT FORCE

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ABSTRACT
A nano-electro-mechanical systems (NEMS) based optical actuator driven by optical gradient force is demonstrated. The actuator consists of two ring resonators and one mechanical arc. The resonating light inside the actuation ring generates optical gradient force on the mechanical arc and induces a displacement. The actuation ring is an integrated electro-optics modulator which tunes the Q-factor of the ring resonator. The nano-scale displacement is sensed by the integrated displacement sensor through opto-mechanical effects. By increasing the tuning voltage from 0 V to 3.5 V, the resonance wavelength of the sensing ring shifts 0.17 nm which corresponds to a 13-nm displacement of mechanical arc. With its chip-scale integratability, the optical actuator has potential applications in NEMS and nano-manipulation fields.

KEYWORDS
NEMS, optical actuator, optical gradient force, ring resonators

INTRODUCTION
With the development of nanotechnology, mechanical actuators with nanoscale precision are essential for active devices which are compatible for high density on-chip integration [1]. Conventional mechanical actuation mechanisms, such as capacitive, magnetomotive, and thermoelastic, which have been used to drive nanoscale devices, have the drawback of either being nonlinear in nature or requiring high power for operation [2, 3]. Currently, optical force, especially optical gradient force, is attracting more and more attention due to its capability to generate large force with nano-scale [4-6]. Optical gradient force with silicon nano-waveguide interaction efficiently combines advances in the field of nano-mechanics and nanophotonics, resulting in the recent development of the nanoscale optomechanical systems. Cavity enhancement provides strong interaction for optical routing with low input energy, which therefore in principle to effectively achieve actuation using optical force generated in the evanescent field of the ring resonator [6, 7]. Furthermore, WGM electro-optics ring modulator has developed fast these years due to the advantages of relatively high compactability, high tuning speeds (10-20 GHz) and low power consumption [8]. In this letter, a NEMS optical actuator is demonstrated, where the mechanical beam is actuated by optical gradient force. Through resonance enhancement of both optical field and mechanical motion, all-optical actuation operation of the nano-mechanical system is presented. The NEMS optical actuator has merits like small dimension, low power consumption and high capability for all optical integration.

DESIGN AND THEORY

Figure 1: (a) Schematic of the NEMS actuator. (b) Layout design of the actuator. (c) Schematic of the transmission spectrum upon actuation.
The actuator consists of three parts: the actuation ring, the sensing ring and the mechanical arc, as shown in Fig. 1(a). Light is transmitted through the input port and coupled to the actuation ring to generate optical gradient force, which pulls the mechanical arc toward the actuation ring. The motion of the mechanical arc is sensed by the sensing ring through its resonance wavelength shift. Part of the actuation ring is in-between two silicon pads which are N-doped and P-doped respectively, forming a p-i-n junction (Fig. 1(b)). Upon applying a voltage, injected current causes a non-linear effect of the ring which changes its refractive index and absorption coefficient [3]. Consequently, the Q-factor of actuation ring and the optical power are decreased. Decreased optical gradient force releases the arc towards the sensing ring, causing a red shift of sensing ring’s resonance wavelength. Therefore, the motion of the mechanical structure can be monitored by observing the transmitted signal of the sensing ring (Fig. 1(c)).

The actuation and sensing rings utilize opto-mechanical effects to drive or sense the deformation of the mechanical arc. A broad band light is pumped into the actuation ring. Light meeting the resonance condition accumulates inside the actuation ring. The power is known as $P_\text{in} = B \cdot P_\text{out}$, where $B$ is the building up factor and $P_\text{out}$ is the optical power inside the waveguide. The building up factor $B$ is defined as [9]

$$B = \frac{(1-t^2)a^2}{1-2at\cos \phi + t^2a^2},$$

where $k$ and $t$ are the coupling and transmission coefficient between waveguide and ring respectively, $a$ is the single pass amplitude transmission coefficient which is related with power attenuation coefficient ($\alpha$) as $a^2 = e^{-\alpha L}$, and $L$ is the perimeter of the actuation ring. The high power light accumulates in the actuation ring to generate an attractive optical gradient force. It can be simplified as [10]

$$F = -\frac{dU}{dg} = -\frac{1}{\omega} \frac{d \omega}{dg} U = -\frac{1}{\omega} \frac{d \omega}{dg} P_\alpha \cdot L_\text{couple} \cdot \frac{v_g}{\omega},$$

where $U$ is system energy, $g$ is the gap between the ring and the mechanical arc, $k$ is the wave factor, $P_\alpha$ is the optical power inside the ring, $L_\text{couple}$ is the coupling length and $v_g$ is the group velocity. It can be seen that the force is proportional to the accumulating power $P_\alpha$ inside the actuation ring. The normalized force is shown in Fig. 2(c), which increases exponentially as gap decreasing.

The optical force is controlled by tuning the Q-factor through attenuation tuning. The actuation ring integrated light modulator utilizes p-i-n junction to tune attenuation coefficient of propagating light, where the intrinsic zone is located in the waveguide core. Carriers are injected into the ring resonator by applying a voltage across the p-i-junction. Manipulating the carrier density in the ring results in a modulation of the absorption $\alpha$, which is related as [8]

$$\Delta \alpha = \Delta \alpha_0 + \Delta \alpha_i = -\left[8.5 \times 10^{-18} \cdot \Delta N + 6.0 \times 10^{-18} \cdot \Delta P \right],$$

where $\Delta N$ and $\Delta P$ are the injected electron and hole concentration respectively, which are linearly related with injection current. Therefore, majority carriers are forced into the core by forward biasing the diode, strongly affecting the absorption coefficient $\alpha$ and round trip gain $a$. The Q-factor of ring resonator is dominated by coupling coefficient (external loss) and intrinsic loss. When injecting more carriers, the Q-factor decreases. The Q-factor of resonance light is related with the round trip gain $a$ as [9]

$$Q = \frac{\omega}{\Delta \omega_{\text{FWHM}}} = \frac{\pi n_{\text{eff}} L \sqrt{1/a}}{\lambda (1-\alpha)},$$

where $\omega$ is the resonance frequency, $n_{\text{eff}}$ is the effective refractive index, $L$ is effective perimeter of the actuation ring and $\lambda$ is the wavelength. Increasing the forward

![Figure 2](image-url)
voltage/current results in an increase in round trip loss, which reduces the Q-factor, building-up factor, the resonance light power and finally the optical force.

The mechanical arc deforms as an effect of the attractive optical force. Due to small displacement, it can be simplified as linear mechanical system, and the displacement $\Delta g$ is related with force as $F_{\text{normalized}} = K \cdot \Delta g$, where $K$ is the effective spring constant of the mechanical arc. Without light, the gap between the mechanical arc and the sensing ring is $g_0$. When the power inside the actuation ring is $P_0$, the force pulls the mechanical arc away from the sensing ring. Therefore, the gap is now $g_0 + \Delta g$. The displacement of the mechanical arc is linearly related with optical power, which is shown in Fig. 2(c).

The mechanical actuation measurement is also a challenging issue in nano-scale devices, where traditional capacitive sensing requires high operating voltage and large area. In this optical actuator, the nano scale displacement of mechanical arc is sensed by the effective index change of the sensing ring. As shown in Fig. 2(b), the effective refractive index of the sensing ring is quite sensitive to the gap between mechanical arc and sensing ring. The change of effective refractive index caused by the gap change is measured by the opto-mechanical coefficient $g_{\text{norm}}$, which is defined as $g_{\text{norm}} = \Delta n_{\text{eff}} / \Delta g$. Due to the linear relationship between effective refractive index and resonance wavelength, the resonance wavelength of the sensing ring is related with the displacement by $\Delta \lambda \propto g_{\text{norm}} \cdot \Delta g$. Therefore, the displacement of mechanical arc can be measured by observing the wavelength shift of sensing ring.

The device is fabricated on a standard silicon-on-insulator wafer, with a 220-nm silicon structure layer and a 2-µm buried oxide layer. Figure 3 shows a scanning electron microscope (SEM) image of a NEMS optical actuator which includes two ring resonators and the mechanical arc. All waveguide structures have a width of 450 nm and a height of 220 nm, which allows a single mode transmission. For high evanescence field coupling purpose, the mechanical arc is designed to have a width of 200 nm while the coupling gap between the ring and the mechanical arc is 100 nm.

During fabrication, a two-step lithography and plasma dry etching technique are used to form the rings, mechanical arc and bus waveguide, keeping the device with stable optical coupling and improved mechanical properties. The p-i-n junction has a 70-nm silicon slab layer for doping and metal via connection. A 2-µm SiO$_2$ layer is deposited above the structure layers to ensure a low optical loss. Finally, HF-vapor selectively undercuts the buried oxide layer to release the free-standing structures from the substrate.

**RESULTS AND DISCUSSIONS**

In experiment, a broad band laser is pumped into the input port through waveguide mode converter. Light with its wavelength equal to actuation ring’s resonance wavelength accumulates to generate the optical force. Fig. 4(a) shows the transmission spectrum of the actuation ring at different voltages. By increasing the voltage from 0 V to 3.5 V, the Q-factor drops from above 4000 to 2400 while the building-up factor drops from 8 to only 4. Figure 4(b) shows the transmission spectrum of the sensing ring. By increasing the voltage from 0 V to 3.5 V, the resonance...
wavelength shifts by 0.17 nm, i.e. from 1542.66 nm to 1542.83 nm. Through the opto-mechanical coefficient $g_{om}$, the mechanical displacement is around 13.6 nm as shown in Fig. 5. Therefore, increasing voltage reduces the Q-factor, building-up factor and the optical power, which induces a 0.17-nm displacement of the mechanical arc. Nano-scale actuation is thus realized via the voltage tuning.

CONCLUSIONS
In conclusion, a NEMS optical actuator is demonstrated, fabricated and experimentally tested. The actuator is driven by optical gradient force and controlled through electro-optics modulator. The motion is sensed by the integrated opto-mechanical displacement sensor. A 0.17-nm wavelength shift is observed with applied voltage equal to 2.5 V, which corresponds to a driving distance of 13.6 nm. The optical gradient force driven actuator shows potential applications for nano-manipulation, small displacement sensing and future all optical devices.

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