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A nanoelectromechanical systems optical switch driven by optical gradient force

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A nanoelectromechanical systems (NEMS) optical switch driven by optical gradient force is demonstrated. The switch consists of a free-standing ring resonator and two bus waveguides. When the free-standing ring is bended by the optical gradient force, the output transmission signal is tuned from the on-state to the off-state of the switch. The NEMS optical switch shows a switching time of 43.5 ns and a switching contrast of more than 25 dB. With its chip-scale integrability, the optical switch has potential applications in signal processing and high-speed optical communication networks. © 2013 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4775674>]

Optical switch is a device that enables signals in optical fibers or integrated optical circuits to be selectively switched from one circuit to another. In the area of optical communications, a variety of network on chip architectures made on the silicon wafer technology enables electronic-optical-hybrid network change to an all-optical network.¹ In particular, optical switching is a key device for all-optical networks. Optical switches have multiple functions, including offering high speed provisioning and network management, network protection and restoration, helping to enhance the capabilities of the overall optic networks.² Various optical switches have been demonstrated by using different physics, such as thermo-optic effect,^{3,4} electro-optic effect,⁵ magneto-optic effect,⁶ electrostatics,⁷ photonic crystal,^{8,9} and nonlinear effects.¹⁰ Among them, microelectromechanical systems (MEMS) optical switches are one of the important approaches, with advantages of large interconnecting matrix integration, wavelength independence, and low cost.^{11–13} However, the micro-scale dimensions limit MEMS switching speed to microsecond level, which is hard to meet high speed switching request such as optical burst switching or optical packet switching applications, etc. Besides, the challenges of the traditional MEMS optical switch include high insertion loss and cross talk problem due to free-space interconnection, surface roughness of mirrors, etc. On the other hand, nanoelectromechanical systems (NEMS) can be used for optical switch applications: scaling down the dimensions and achieving low loss operation by waveguide structures. In addition, NEMS offer a different method of actuation for optical switches: optical gradient forces can realize nanoscale positioning, enabling optical signal manipulation.¹⁴

Optical gradient force with silicon nano-waveguide interaction has attracted considerable attention as for the ability to efficiently combine advances in the field of nano-mechanics and nanophotonics,^{14–16} resulting in the recent development

of the nanoscale optomechanical systems. It has also been shown that the optical force is increased by orders of magnitude in evanescently coupled waveguides due to the largely enhanced gradient of the optical field, especially in ring resonator cavities.^{17,18} The attractive characteristic of such ring resonator cavities is their resonant response, occurring only for wavelengths that are an integer fraction of the cavity's optical path length. Meanwhile, cavity enhancement provides strong interaction for optical routing with low input energy. It is therefore possible in principle to effectively achieve wavelength switching and routing by using a relatively weak optical force in the ring resonator.¹⁹ In this letter, an actively NEMS optical switch constructed with a free-standing ring resonator and waveguide structure is demonstrated, where the free-standing ring can be deformed by the optical gradient force, forming a nano-actuator to drive the switching operation. The NEMS switch is fabricated by using nano-photonic fabrication process. Through resonance enhancement of both optical field and mechanical motion, all-optical switching operation is presented.

Figure 1(a) shows the schematic of the proposed NEMS optical switch, which consists of a free-standing ring resonator, a control light nano-waveguide, and a signal light nano-waveguide. The control light is coupled into the ring cavity through the control waveguide, to excite its resonance and generate an optical force between the free-standing ring and the underneath oxide substrate. As a result, the free-standing ring is bent down to the substrate (z-direction), which is driven by the gradient optical force, as illustrated in Fig. 1(b). The actuator of the switch is designed as a free-standing ring supported by four spokes, which are anchored by a central pillar standing on the oxide-substrate. The spokes are geometrically designed such that two spokes in the y-direction is wider than the other two in the x-direction reducing the ring's radial and out-of-plane motions (e.g., y-z plane) in order to maintain a stable waveguide-ring optical coupling (see Fig. 1(a)). Therefore, the free-standing ring can be bent down to the substrate in the z-direction by the optical gradient force as shown in Fig. 1(b). Here, instead of using micro-disk

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FIG. 1. Schematic illustration of a nano-mechanical optical switch driven by optical gradient force. (b) Cross-sectional view of the free-standing ring resonator and (c) working principle of the switch, with schematic of the spectral response at different switching states.

geometry for the cavity design, the ring resonator with spokes is employed because of its lower mechanical stiffness. Meanwhile, a ring resonator design with a high optical quality factor helps to enhance the switching performance by increasing the extinction ratio. The principle of the switching operation is schematically illustrated in Fig. 1(c), showing the output signal as a function of the ring resonance. The control light (λ_c) and the signal light (λ_s) can be coupled into the free-standing ring resonator through the control and signal waveguides, respectively. Without the control light, the signal light cannot be detected at the output port due to its low transmission (i.e., λ_s aligns with the cavity resonance λ_r). On the contrary, when the control light is coupled to the cavity, the gradient force is generated by the induced evanescent optical field and applied on the free-standing ring, resulting in a downward-bending deformation of the free-standing ring, in which such motion leads to a cavity resonance wavelength shift from λ_r to λ_r' . Therefore, the signal light is switched from the “off-state” to “on-state” of the switch, which can be detected at the output port.

In Fig. 1(c), with the absence of a control light, there is no transmission of the signal light (at λ_s) to output 1 due to its overlapping with the ring resonance (e.g., λ_r , transmission “dip”). On the other hand, when a strong control light with the wavelength of λ_c (e.g., close to the ring resonance wavelength λ_r) is introduced, a gradient optical force is formed through the evanescent wave coupling between the ring resonator and the substrate. The magnitude of the optical force (F_{op}) can be expressed as²⁰

$$F_{op} = -\frac{1}{n_{eff}} g_{om} U, \quad (1)$$

where U is the optical energy coupled into the ring resonators, which is proportional to the optical power (control light) injected in the control waveguide. n_{eff} is the effective refractive index of the free-standing ring resonator, and $g_{om} = \partial n_{eff} / \partial g$ is the optomechanical tuning efficiency, with g representing the vertical gap between the free-standing ring and the substrate. The negative sign in Eq. (1) indicates that the force is attractive, leading to the gap to decrease due to the out-of-plane deformation of the free-standing ring (Fig. 2(a), z -direction). The simulated mode profile is illustrated in Fig. 2(a). The effective refractive index of the ring depends on the ring deformation: it increases as the ring bends down closely to the substrate due to a strong interaction between the optical field and the substrate. Fig. 2(b) plots the variation of the deformation of the ring with respect to the circumferential position θ , showing periodic peaks and valleys in the deformation versus the ring resonator circumference, due to the presence of the control light (λ_c). In particular, the peaks are located at the middle point between two neighboring wider spokes (e.g., connection point between the narrow spoke and the ring), indicating the largest deformation position of the ring, while the valleys correspond to the positions of the wider spokes connections. For instance, when the control light power is 10 mW, the

FIG. 2. (a) Simulated spatial displacement of the free-standing ring drive by the optical gradient force and (b) calculated displacement as a function of the ring circumferential position.

maximum deformation of 4.61 nm happens at the narrower spoke connection end, corresponding to a variation of the effective index (n_{eff}) of 6.36×10^{-4} . It further results in a red-shift of resonance wavelength λ_r , which can be estimated by $\Delta\lambda_r = g_{\text{om}}\Delta g$, where Δg is the deformation of the free-standing ring. Therefore, the transmission of the signal light is modulated. Combined with Hooke's law, the relationship between the resonance wavelength shift and the optical power coupled to the cavity can be determined by $\Delta\lambda \sim g_{\text{om}}^2 \cdot P_{\text{in}}/k$, where P_{in} is the control signal power and k is the beam stiffness of the free-standing ring. Apart from the tuning of power, it indicates that optomechanical tuning efficiency (g_{om}) and the beam stiffness (k) are the two important parameters, which can be engineered in order to achieve large optical wavelength shift. In addition, Fig. 2(b) compares the ring deformation at various power levels, showing different levels of deformations of the free-standing ring. As expected, a larger deformation can be obtained by increasing the control power level.

Figure 3(a) shows a scanning electron microscope (SEM) image of the NEMS optical switch with a free-standing ring and two nano-waveguides. It is fabricated on a standard silicon-on-insulator wafer, with a 340-nm thick silicon structure layer and a 2- μm buried oxide layer. The waveguides including the ring and straight sections have a width of 450 nm and a height of 340 nm. Meanwhile, the ring resonator is physically

(a)

(b)

FIG. 3. (a) Overview of SEM image of the free-standing ring resonator based switch and (b) close-up of the free-standing ring and nano-waveguide.

fixed to a 70-nm thick silicon slab layer and supported by four spokes, which are anchored by a central ring standing on the substrate. Except for the suspending parts (e.g., ring, spokes), all nano-waveguides have a silicon core surrounded by 2- μm SiO₂ cladding. The coupling gap between the ring and the nano-waveguide is 200 nm. During fabrication, a two-step lithography and plasma dry etching technique are used to form the ring, bus waveguide, and spoke beams, keeping the device with a stable optical coupling and improved mechanical properties. All nano-waveguides and other structures were first patterned by deep UV lithography, followed by plasma dry etching to transfer the photoresist pattern into the silicon structure layer (serves as the light guiding layer), leaving a 70-nm remaining silicon slab layer. The second lithography and dry etching defined the slab pattern. For low optical loss and symmetric waveguide geometry, a 2- μm PECVD SiO₂ layer was deposited as the upper cladding layer surrounding the Si waveguides. A 50-nm amorphous silicon layer for the release window protection was then deposited, patterned, and etched,

(a)

(b)

FIG. 4. (a) Experimental results of transmission spectral response of the switch without the control light launching into the ring resonator and (b) zoom-in view of wavelength shift corresponding to the control light in either off-state or on-state.

leaving the areas directly above the suspending features open for release process. Finally, HF-vapor selectively undercut the buried oxide layer, leaving the free-standing structures.

In the experiments of optical transmission measurement, a broadband lightwave is launched to the optical switch through the signal waveguide. The obtained transmission spectrum with typical resonance patterns is observed, with an average side-mode suppression ratio of more than 15 dB, as shown in the inset of Fig. 4(a). For the free-standing ring with a radius of 30 μm , the free spectral range of ~ 3.1 nm is measured. When the wavelength of the control light is slightly detuned from the cavity resonant wavelength (e.g., ~ 0.4 nm), the resonance conditions for the ring resonator will change in response to the modified effective refractive index. Correspondingly, a red shift of resonance wavelength in the optical transmission spectra can be detected. As shown in Fig. 4(a), the resonance shifts by 0.8 nm when the control light power is varied from 0 to 9.7 mW. It indicates also that the wavelength shift increases almost linearly with the increased control power. During such wavelength tuning, the wavelength of the control light is constantly maintained. Fig. 4(b) presents an example of the wavelength shift. The initial resonance wavelength is located at 1555.3 nm, with an extinction ratio of 15 dB. The typical full width at half-maximum (FWHM) is $\Delta\lambda_{\text{FWHM}} = 0.12$ nm and quality factor is $Q = 13\,000$. A signal light with the wavelength of 1555.3 nm (the ring's resonances frequency) is launched through the signal waveguide. Consequently, a control light with the wavelength of 1565.7 nm is coupled into the control waveguide. As a result, the resonance wavelength is shifted to 1555.59 nm, corresponding to a 0.29 nm wavelength shift, as shown in Fig. 4(b). Consequently, the signal light (at 1555.3 nm) is switched to the on-state that can be detected at the output port. Without the control light, a low transmission of the signal light is detected at the output port, corresponding to the off-state of the switch. In this case, the switching contrast of more than 25 dB is achieved between the on-state and off-state of the switch.

In the experiment of transient switching response measurement, a continuous wave (CW) from a tunable laser is modulated at 5 MHz. 10% of the modulated light is tapped off with a

coupler to be used as a reference for the switching response measurement. The other 90% of light is coupled into the control waveguide. The output light is coupled to the detection system through a tapered fiber, and the switching states are monitored with an oscilloscope for the switch response measurement. The applied modulated control signal causes a deflection of the ring resonator. The normalized switching response is shown in Fig. 5. A 10%–90% rise time and fall time are measured as 43.5 ns and 38.7 ns, respectively, and the settling time is approximately 75 ns. Therefore, the switching time is much faster than the traditional MEMS switches.³ It is observed also that there is no visible residual oscillation or overshoot in the switching response.

In conclusion, a NEMS optical switch driven by the gradient optical force by using a silicon free-standing ring resonator is demonstrated. The switching operation with an output extinction ratio of more than 25 dB is experimentally obtained, with the switching response of 43.5 ns (rise time). Compared with conventional MEMS optical switches, the NEMS optical switches offer their potential for the next generation of nano-scaled fast optical switches and other optical communication applications with fast switching speed, low power consumption, and easily integrated in large scale array without complex packaging techniques.

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FIG. 5. Switch dynamic response under a 5-MHz modulated light signal: waveforms of the control and output response signals of the switch.

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