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A nanomachined optical logic gate driven by gradient optical force

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In this letter, a nanomachined optical logic gate using optical gradient force is demonstrated. The device consists of a partially free-hanging silicon double-ring resonator developed by the nano-electro-mechanical system technology. The logic NOR gate function is demonstrated at 20 Mb/s with a high extinction ratio of about 21.3 dB. This proposed NOR gate has the advantages of low power consumption (~ 0.5 mW), highly compacted size ($40\text{ }\mu\text{m} \times 45\text{ }\mu\text{m}$), and easy batch fabrication which has potential applications in silicon-photonics integration for digital signal processing. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.3693610>]

An optical logic gate is an optical controlled physical device used to process optical signals and implement a Boolean function. It is a key element for simple optical-signal processing in telecommunication networks such as a gate used to modulate a continuous wave (CW) signal, or a pulse train that can function as a wavelength converter, or a part of an optical regenerator.^{1,2} Simple logic operation such as XOR is useful for routing functions and constructing other logic gates.³ Moreover, optical logic gates enable many advanced functions such as all-optical bit-pattern recognition,⁴ optical bit-error rating monitoring,⁵ and all-optical packet address and payload separation.⁶ In order to realize optical logic gates, various configurations have been proposed that utilize the nonlinear optical properties of semiconductor optical amplifier (SOA),^{2–6} laser diode chip,⁷ and optical fiber.^{8,9} In the literature, most SOA-based logic gates require interferometric structures, which complicate the systems and lead to the difficulty integrating with other silicon-photonics chips.² Even though some silicon-based optical logic gates have been demonstrated on centimeter-length waveguide,¹⁰ ring resonator,¹¹ and photonic crystal^{12,13} using two-photon absorption effect, their rather high power consumption or bulkiness hinder the progress of exploring their applications. In order to solve these limitations, a solution with low power consumption, compact size, and compatible with silicon-based integration is important and desired for optical logic gates applications.

Recently, the gradient optical force has been widely investigated in nano-structures, where its action on the suspended nano-structures can effectively result in nanometer or even micrometer displacement using milliwatt input power^{14,15} and manipulate the optical response of the photonic structures.^{16,17} These exploitations and demonstrations suggest an alternative approach enabling all-optical control in silicon photonic devices. Here, we present the experimental demonstration of an all-optical logic NOR operation on

silicon using the optical gradient force as a highly efficient, low power consumption, and all-optical control approach.

The proposed optical logic gate consists of a bus-waveguide and two ring resonators, R_1 and R_2 , respectively, as shown in Fig. 1(a). In the coupling region between the rings and the bus-waveguide, parts of the substrate underneath the ring resonators are removed, leaving the two rings and the bus waveguide to be free-hanging. Two control signals λ_a and λ_b , and the probe signal λ_c can be coupled into the two ring resonators through the bus-waveguide. As the

FIG. 1. (Color online) Schematic illustration of the proposed NOR gate. (a) Schematic illustration of the partially released double-ring system. (b) Cross-sectional view of the deflected ring after optical force loading.

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transmission of a ring resonator is highly sensitive to the signal wavelength, the two ring resonators are designed with different radii (r_1 and r_2) for their independent control using different wavelengths. When the control signal λ_a and λ_b (at the corresponding resonance of ring R_1 and ring R_2 , respectively) are coupled into the ring resonators R_1 and R_2 , respectively, the strong optical forces are induced by the evanescent fields of the resonant wavelengths. Thus, the free-hanging parts of the rings are bent downwards by the optical forces as shown in Fig. 1(b). The bending deformation can induce a change in the optical path length, leading to a red-shift in the resonant wavelength which affects all optical modes of the bent rings. Therefore, the output transmission of the probe light λ_c (tuned at another resonant wavelength) is modulated by the resonance shift.

During the resonance, the circulating power P_{ring} in the ring is determined as¹⁸

$$P_{ring} = |E_{ring}|^2 = \frac{\alpha^2(1 - |t|^2)}{1 + \alpha^2|t|^2 - 2\alpha|t|\cos(\theta + \varphi_t)} |E_{input}|^2, \quad (1)$$

where $|E_{input}|^2$ is the input optical power, α is the loss coefficient of the ring, $|t|$ represents the coupling losses, φ_t is the phase of the coupler, and θ is the round trip phase which is determined by the wavelength.¹⁸ Consequently, the amplitude of the optical force per unit length L (the total length of the free-hanging part) is dependent on both the input optical power and the wavelength, which is expressed as¹⁴

$$F = \frac{1}{n_{eff}} \frac{\partial n_{eff}}{\partial g} \frac{P_{ring}(\lambda) n_g}{c}, \quad (2)$$

where g is the separation between the ring and the substrate, n_{eff} is the effective refractive index of the deformation part of the ring, n_g is the group index of the mode in the ring, and c represents the speed of light in vacuum. Fig. 2 plots the contour map of the unified optical force. In the case where the initial g is ranging from 150 to 200 nm, the optical gradient force between the resonator and the substrate at “on-resonance” wavelength is sufficiently strong to bend the ring towards the substrate. As the gap is decreased, the optical force can be finally balanced by the mechanical elastic force

FIG. 2. (Color online) Calculated optical force between the ring and the SiO_2 substrate using the dispersion diagram method. The bright line marks the on/off resonance tuning process in the released movable ring system. Insert shows the ring resonator in its “on-resonance” state and “off-resonance” state.

TABLE I. Mechanical deformation states under optical force and binary truth table of the optical logic NOR function.

Mechanical states	A (λ_A)	B (λ_B)	C (λ_C)
	0	0	1
	1	0	0
	0	1	0
	1	1	0

induced by the ring bending, resulting in a stable resting state of “on-resonance”. On the other hand, the ring resonator is remained in its “off-resonance” state with off-resonant wavelength input, as shown in the insert. As a result, by tuning the input wavelength, the free-hanging ring has two stable resting states of “on-resonance” and “off-resonance”.

During the operation, the wavelength of the probe light, λ_c , is slightly detuned from the resonance wavelength of either one of the two rings. Its power is not strong enough to induce any nontrivial deformation, but it meets the resonance condition of any bent ring (at its “on-resonance” state), which is modulated by the control lights (λ_a and λ_b). The binary truth table of the proposed logic gate is shown in Table I. In the absence of the control signal of λ_a and λ_b , neither ring is bent (logic “0”). When the probe signal λ_c passes through the device with high-power optical transmission, the output is in logic “1”. Otherwise, with the presence of either of the control signals (at “on-resonance” wavelength), its correspondingly induced ring deformation results in the resonance of the probe signal, and the probe signal suffers resonance loss at the output. Therefore, the low-power transmission of the output is defined as logic “0”. Such logic operation satisfies the logic formula $A \text{ NOR } B = C$ as shown in Table I.

The scanning electron micrographs (SEMs) of the nanomachined optical logic NOR gate are shown in Fig. 3. The device with a footprint of $40 \mu\text{m} \times 45 \mu\text{m}$ is fabricated on a silicon-on-insulator (SOI) wafer with a Si structure layer of

FIG. 3. SEMs of the nanomachined optical logic NOR gate. Insert shows the close-up of the coupling part between waveguide and rings.

FIG. 4. (Color online) (a) Transmission spectrum when a wideband light source is injected into the system. (b) Transmission spectrum at different input states corresponding to the mechanical states of undeflected and deflected ring.

160 nm. The structures were patterned by deep UV lithography and etched by plasma dry etching. After plasma enhanced chemical vapor deposition (PECVD) of SiO₂ (2- μ m thick) as the upper cladding layer, a 50-nm amorphous silicon layer was deposited and patterned, which is used as the hard mask to protect those fixed structures. Then, the areas with the release window directly above the free-hanging features were etched away. Finally, HF-vapor was used to undercut the buried-oxide layer, forming the free-hanging structures and waveguides. The radii of ring R_1 and ring R_2 are 10 μ m and 10.5 μ m, respectively. The release window is 20 μ m $\times$ 6 μ m and the cross-section of the waveguide and the rings is 160 nm $\times$ 450 nm. Insert shows the zoomed view of the free-hanging part of the nano-machined optical logic gate. The gap between the bus waveguide and ring resonators is approximately 150 nm.

The transmission spectrum is shown in Fig. 4(a), with two resonances at the wavelength $\lambda_1 = 1592.51$ nm and $\lambda_2 = 1594.31$ nm, respectively. The transmission of the waveguide reduces by approximately 13 dB at both resonances. At the resonant wavelength around 1590 nm, their corresponding quality factors for the rings (R_1 and R_2) are $Q_1 = 2.63 \times 10^4$ and $Q_2 = 2.68 \times 10^4$, respectively. Fig. 4(b) shows the measured transmission spectra and the resonance dip frequency as a function of the control wavelength (λ_a or

λ_b). The black line shows the device transmission spectrum with only a broad-band light coupled to the device as the reference. When the control light ($\lambda_a = 1592.98$ nm or $\lambda_b = 1594.55$ nm) with the power of 1 mW is coupled into the rings by the waveguide, the resonant dip (λ_c) is shifted by 0.22 nm (e.g., from 1542.61 nm to 1542.83 nm). The expression using the logic function is as follows: when both control signals A and B ($\lambda_a = 1592.98$ nm and $\lambda_b = 1594.55$ nm) are low (logic “0”), the probe output power $\lambda_c = 1542.83$ nm is observed at high level (logic “1”). With the presence of one or both control signals, the output power level becomes low (logic “0”). This results in the NOR operations. In the experiment, two control lights (λ_a and λ_b) from two independent tunable lasers and a CW probe light (λ_c) are coupled into the device via the bus-waveguide. The device output waveforms of the probe light and the control signals are observed on the oscilloscope. Moreover, the device is tested with a bit rate of 20 Mbit/s. The optical power of the control signal (λ_a and λ_b) is fixed at 0.5 mW and the probe signal λ_c is fixed at 0.2 mW. The output shows exactly the Boolean NOR operation on the signal λ_a and the signal λ_b , with an extinction ratio of 21.3 dB.

In conclusions, a nanomachined all-optical logic NOR gate driven by the optical force has been designed, fabricated, and demonstrated. An extinction ratio of 21.3 dB is achieved with an average 0.5-mW optical power for each input control signal. It demonstrates the feasibility of a purely optical approach to process optical signals, where the mechanical element is driven by the optical force. Moreover, it has potential applications, such as optically multiplexed memory storage, optical computing, and reconfigurable all-optical networks.

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