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Optical-force-induced bistability in nanomachined ring resonator systems

Y. F. Yu,^{1,2,3} J. B. Zhang,² T. Bourouina,³ and A. Q. Liu^{1,a)}

¹*School of Electrical & Electronic Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798*

²*Data Storage Institute, Agency for Science, Technology and Research (A*STAR), 5 Engineering Drive 1, Singapore 117510*

³*Ecole Supérieure d'Ingénieurs en Electronique et Electrotechnique (ESIEE), Paris-Est University, Paris 93162, France*

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This paper reports optical-force-induced bistability in a nanomachined ring resonator system. It consists of two ring resonators and a bus waveguide, whereby each ring resonator has a free-hanging arc that is perpendicularly deformable by an optical force and changes the effective refractive index of the system. Therefore, an optical bistability is induced into the nanomachined ring resonator system, in which the bistability band can reach 0.3 nm and 0.68 nm in the ring resonators 1 and 2, respectively. It has potential applications in optical signal processing area, such as all-optical switching and opto-mechanical memory. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.3690955>]

Optical bistability is a research topic in physics, which refers to the phenomenon that one input has two possible and stable outputs. It is one of the basics for light control in all-optical signal processing. The optical bistability is reported as early as in 1970s.^{1,2} In 2000s, a 5- μm -radius silicon ring resonator system demonstrated the optical bistability based on the thermal-optic non-linear effect.³ Due to the small thermo-optic coefficient ($\frac{\partial n}{\partial T} = 1.86 \times 10^{-4} \text{ K}^{-1}$) and high thermal conductivity of the silicon dioxide (SiO_2), the input optical power of the optical bistability ring resonator requires 1 mW. Thereafter, a free-standing silicon ring resonator is demonstrated and reduced the input power to 60 μW due to lower thermal conductivity.⁴ However, the transition time for the thermal effect is in the microsecond level, which is a limitation for high speed devices. The carrier-induced optical bistability is demonstrated subsequently by the silicon ring resonator,⁵ which is based on the free-carrier dispersion that can achieve a nanosecond level of the transition time with an input power of 10 mW. Both the thermo-optic effect and the free-carrier dispersion are based on the free electrons and holes generated by the two-photon absorption (TPA).⁶ In communication wavelength range ($\sim 1550 \text{ nm}$), the linear absorption of silicon is extremely weak (absorption coefficient $< 10^{-8} \text{ cm}^{-1}$). In addition, the TPA is a second-order process, which is several orders of magnitude weaker than linear absorption. Therefore, only a few photons from every one billion participate in TPA, which accounts for its low efficiency. Nano-opto-mechanical system is a hot research approach, whereby the nano-opto-mechanical nanostructures are driven by an optical force through the inelastic interaction between the photons and the nanostructures, and this induces the dispersion into the system.⁷⁻¹² The optical force induced dispersion is more efficient than the TPA induced dispersion. As a result, the optical-force-induced bistability is an important approach to achieve low input

power and short transition time for high-speed optical signal processing.

In this letter, an optical-force-induced bistability system is designed using a nanomachined ring resonator system. The system consists of two ring resonators and a bus waveguide as shown in Fig. 1. A vertical nano-gap (G) between the free-hanging arcs and the substrate is introduced in each ring resonator as shown in Fig. 1(b). The input lights are coupled into the ring resonators through the bus waveguide, which include the control light for optical force generation and the probe light for transmission detection. When the wavelength of the control light matches with the resonant wavelength of the ring resonators, the light intensity in the ring resonators is dramatically increased, and the evanescent

FIG. 1. (Color online) (a) The schematic illustration of the nanomachined ring resonator system and (b) cross-section view of the deformation of the free-hanging arcs in ring 1 and ring 2 caused by the optical gradient forces.

^{a)} Author to whom correspondence should be addressed. Electronic mail: eaqliu@ntu.edu.sg. Tel.: +65 6790 4336.

field of the free-hanging arc is enhanced. Therefore, two vertical optical gradient forces (F_1 and F_2) are produced by the evanescent field, and subsequently, the free-hanging arcs of the ring resonators are deformed by the optical gradient force shown in Fig. 1(b).

When the free-hanging arcs are deformed, the effective refractive indices are correspondingly changed due to the optical field redistribution. The effective refractive index N_{eff} is determined by the nano-gap G and the wavelength λ based on the dispersion properties; the optical force can be calculated based on the energy conservation law,¹⁰ which assumes that the change in mechanical energy is corresponding to the change in energy of each photon in the system. The optical force can be expressed as,¹³

$$F = \frac{1}{N_{eff}} \frac{\partial N_{eff}}{\partial G} U, \quad (1)$$

where U is the total energy, which can be expressed as

$$U = \frac{PL}{N_g C}, \quad (2)$$

where P is the optical power, L is the length of the free-hanging arc, and C is the light velocity in vacuum. $N_g = N_{eff} - \lambda \frac{\partial N_{eff}}{\partial \lambda}$ is the group velocity.¹⁴ The optical power is expressed as $P = BP_{in}$, where P_{in} is the input power and B is the build-up factor.¹⁵

The normalized optical force F_n ($F_n = \frac{F}{PL}$) on the free-hanging arc is calculated with the following parameters: the width of the bus waveguide and the ring resonator are 450 nm, the radius of the two rings are 30 μm , and the width of the release window is 10 μm . The numerical results are shown in Fig. 2. When the gap decreases, the maximum normalized optical force and the corresponding resonant wavelength are increased. When the nano-gap G or the wavelength λ decreases, the effective refractive index N_{eff} is increased.¹³ It can be seen that the maximum value of the normalized optical force occurs at the resonant wavelengths of the ring resonator (e.g., $\lambda_1 = 1545.7$ nm and $\lambda_2 = 1548.4$ nm for $G = 170$ nm).

FIG. 2. (Color online) The contour plot of the optical force in gap-wavelength domain.

FIG. 3. The SEM image of the fabricated nanomachined ring resonator system.

The nanomachined ring resonator system is fabricated on the SOI wafer using nano-photonic-silicon fabrication processes as shown in Fig. 3. The two waveguide-ring gaps are both 200 nm, the thickness of the silicon structure layer is 220 nm, and the one of the buried oxide layer is 2 μm . Except for the free-hanging arcs, the remaining parts of the system are deposited with a 2- μm thick SiO_2 cladding layer. The free-hanging arcs are released by a selective etching process, and the nano-gap G is controlled to be approximately 200 nm.

In the experiments, a pair of tapered fiber is used to guide light into the nano-waveguide and detect the output light. The probe light is a broadband light source with a central wavelength of 1550 nm and a bandwidth of 70 nm. With the probe light, each ring has two absorption modes within the spectrum range, i.e., ring resonator 1 with $\lambda_{11} = 1545.4$ nm and $\lambda_{21} = 1548.2$ nm while ring resonator 2 with $\lambda_{12} = 1545.6$ nm and $\lambda_{22} = 1548.4$ nm. Subsequently, a control light with a minimum output power of 160 μW and a tunable wavelength ranging from 1500 nm to 1600 nm with a tuning step of 0.01 nm is introduced into the system. When the control light has a constant output power of 160 μW operated at different wavelengths, the transmission spectra are distinctively different as shown in Fig. 4. When the control light has a wavelength of 1547.47 nm (off-resonant to both rings), the absorption peaks are identical to the one without the control light. When the wavelength of the control light (control

FIG. 4. (Color online) The transmission spectra with different control wavelengths and offset intensity of 10 dBm.

wavelength) is increased and close to the resonant peak λ_{21} of the ring resonator 1, both resonant peaks (λ_{11} and λ_{21}) of ring resonator 1 are red shifted. The two resonant peaks of the two rings at mode 1 (λ_{11} and λ_{12}) interfere constructively to form a high absorption peak when the control wavelength is increased to 1548.27 nm. Thereafter, the enhanced absorption peak red shifts continuously when the control wavelength increases from 1548.27 nm to 1548.77 nm. When the control wavelength is increased beyond 1548.77 nm, the resonant peaks of ring 1 are jumped back to the original position, which means that the control light is off-resonant to ring 1. The transparent band between the two peaks of mode 1 (λ_{11} and λ_{12}) is increased as compared to the original state. Similarly, when the control wavelength is increased beyond 1549.37 nm, the resonant peaks of ring 2 are also jumped back to the original position, and the control light becomes off-resonant to both ring resonators again.

The absorption peak of ring 2 at mode 1 (λ_{21}) in term of the control wavelength is plotted in Fig. 5(a). When the control wavelength is tuned from 1547 nm to 1548.27 nm, the absorption peak initially keeps constant at 1545.6 nm. When control wavelength is tuned from 1548.27 nm to 1549.37 nm, the absorption peak red shifts linearly to a maximum value of 1546.5 nm and jumps back to the original value at 1549.37 nm. Thereafter, it remains constant at 1545.6 nm. On the contrary, when the control wavelength is tuned from 1550 nm to 1548.69 nm, the absorption peak remains constant initially and red shifts instantly to 1545.9 nm at 1548.69 nm. Subsequently, it blue shifts linearly to the original value when control wavelength is from 1548.69 to 1548.27 nm. Thereafter, it remains constant again. It can be

observed that there is a hysteretic cycle on the absorption peak, and the each control wavelength corresponds to two possible and stable λ_{12} . Therefore, the optical bistability is induced in the ring 2 by the optical force, and the bistability band is 0.68 nm at mode 1. A hysteretic cycle on the curve of output intensity/absorption at a fixed wavelength of 1545.9 nm can be observed as shown in Fig. 5(b). Similarly, the optical bistability is also induced in the ring 1 at mode 1 (λ_{12}), and the optical bistability band is 0.3 nm. The optical bistability is caused by the nonlinearity of the optical force, which is affected by the confined energy in the ring 1 and ring 2. When the nano-gap G is reduced through the deformation of the free-hanging arc by the optical force, the effective refractive index is changed. Subsequently, the resonant wavelengths of the ring resonator are shifted, and the confined energy is varied. Finally, a balance between the optical force and the mechanical force is achieved by the deformation of the free-hanging arc.

In order to verify this phenomenon is induced by the optical force but not the thermal optic effect, different release times of the free hanging arcs are experimented. When the etching time is longer than 15 min (etching rate: 10 nm/min), the parts of the free-hanging arcs are completely released and can be deformed by the optical force, in which the optical-force-induced bistability is observed in all cases. On the contrary, when the etching time is shorter than 15 min, the part of the free-hanging arcs is not released from the SiO₂ substrate, and the optical bistability is not observed. Therefore, it is verified that this bistability is induced by the optical force. In addition, the simulation results are in good agreement with the experimental results with the first order Eigen frequency of 1.414 MHz. Therefore, the transition time is estimated at micro-second level. Furthermore, it is possible to reduce the transition time to nano-second through the structure optimization.¹⁶

In summary, the optical-force-induced-bistability is observed in a nanomachined ring resonator system. The optical bistability occurs at the input power of 160 μ W with the bistability band of the ring 1 and ring 2 at mode 1 is 0.3 nm and 0.68 nm, respectively. The bistability is obtained by a small range from 1547 nm to 1550 nm in the control wavelength, which avoids large tuning power and increases the system stability. It has potential applications in optical signal processing area, such as all-optical switching, opto-mechanical memory, etc.

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FIG. 5. (Color online) The variation of (a) the absorption peak of ring 2 (mode 1) and (b) the output intensity/absorption (at fixed wavelength of 1545.9 nm) versus the wavelength of control laser.

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