Nonvolatile silicon MEMS optical switch based on bistable mechanical beams

Qian MA
College of Optical Science and Engineering
Zhejiang University
Hangzhou, China
maqianopt@zju.edu.cn

Yinpeng HU
College of Optical Science and Engineering
Zhejiang University
Hangzhou, China
yinpenghu@zju.edu.cn

Ye LU
College of Optical Science and Engineering
Zhejiang University
Hangzhou, China
lu_ye@zju.edu.cn

Yunzhi LIU
College of Optical Science and Engineering
Zhejiang University
Hangzhou, China
3190106007@zju.edu.cn

Huan LI
College of Optical Science and Engineering
Zhejiang University
Hangzhou, China
lihuan20@zju.edu.cn

Daoxin DAI
College of Optical Science and Engineering
Zhejiang University
Hangzhou, China
dxdai@zju.edu.cn

***Abstract*—We have proposed and implemented a 2 × 2 nonvolatile silicon MEMS optical switch based on bistable mechanical beams driven by electrostatic comb actuators, which is fully compatible with standard silicon photonics foundry processes.**

Keywords—silicon photonics, MEMS, optical switch, nonvolatile, bistable mechanical beam

I. Introduction

The demand for high-performance interconnect networks in data center architectures has led to increasing interest in the use of optical switches. A variety of optical switches based on different principles and structures have been developed to meet the demand for large-scale optical routing. Among these, silicon MEMS optical switches have attracted significant attention due to their excellent performance, low power consumption, and ease of large-scale integration [1].

In 2008, E. Bulgan et al. developed an optical switch based on electrostatic comb actuators that control the position of movable waveguide segments to switch light [2]. In 2016, T. J. Seok et al. designed a 64 × 64 waveguide switching array that used vertical adiabatic coupler to switch light by applying voltage to the electrostatic actuator [3]. In 2019, H. Sattari et al. developed a nonvolatile bistable silicon MEMS optical switch using a vertically movable adiabatic coupler that displaced the movable waveguide out of plane upon release. The switch remains in the ON or OFF position without maintaining the drive voltage [4]. However, this switch requires the introduction of pre-stress for fabrication and uses a double-layer silicon structure that is not compatible with standard silicon photonics foundry processes. In 2021, A. Y. Takabayashi et al. designed a single-pole double-throw MEMS switch that enables optical coupling to the corresponding output waveguide by applying voltage at different electrodes to pull the input waveguide toward different directions [5].

In this paper, we propose a 2 × 2 nonvolatile silicon MEMS optical switch with a footprint of 140 μm × 300 μm (including electrode pads). Our switch is compatible with standard silicon photonics foundry processes and requires drive voltages of 20 V and 11 V for switching to ON and OFF states, respectively. The switch remains in the current state with nonvolatility when the voltage is removed. The optical performance of the switch was simulated using finite difference time domain (FDTD) software, with excess loss of up to 0.09 dB at the wavelength of 1550 nm. Due to fabrication nonidealities, the actual device has an excess loss of 14 dB, which, however, is expected to improve significantly with much more wide-band and fabrication-tolerant device designs based on adiabatic couplers.

II. Switch Design

A. Switch Structures

The proposed nonvolatile MEMS optical switch, referred to as the optical switch hereafter, is composed of movable directional couplers, an electrostatic comb actuator, and bistable mechanical beams, as illustrated in Fig. 1. The structure is suspended in the air once released. The bistable mechanical beams provide nonvolatility and is driven by the electrostatic comb driver to adjust the position of the movable directional couplers, which enables the optical switch to have two switching states, ON and OFF. Additionally, a fixed stopper is employed to restrict the displacement range of the structure.

B. Movable Directional Couplers

The movable directional couplers in the proposed optical switch has a waveguide width of 350 nm and thickness of 220 nm, optimized for the communication band. The waveguide gap of 0.2 μm and the straight waveguide length of 8.9 μm remain unchanged before and after switching for the left and

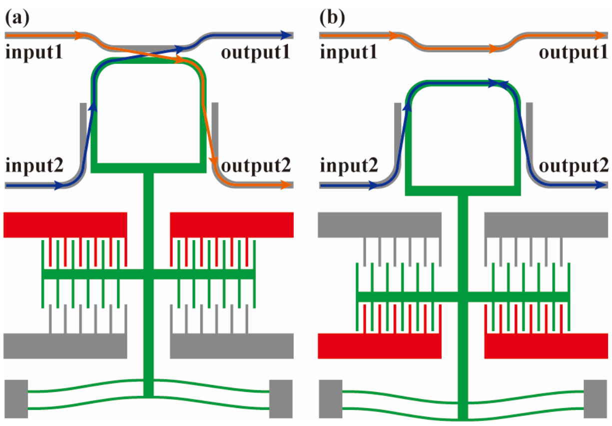

Fig. 1. The core structure of the optical switch. (a) The optical switch in ON state; (b) The optical switch in OFF state.

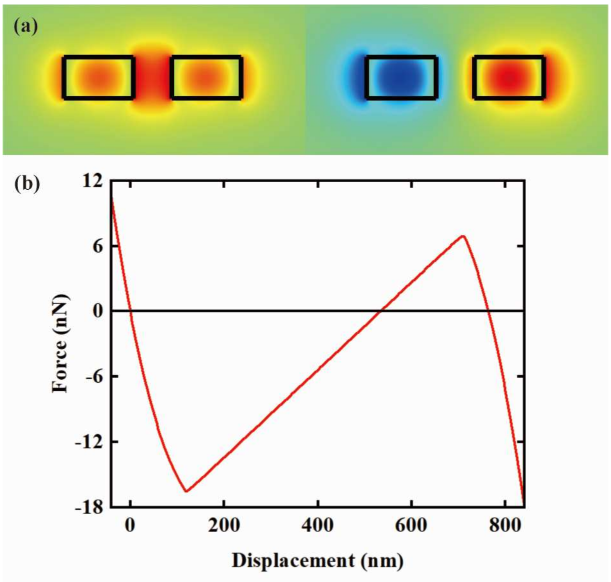

Fig. 2. (a) Symmetric and antisymmetric modes in couplers; (b) The force-displacement hysteresis relationship of the bistable beams.

right directional couplers. The upper directional coupler has a straight waveguide length of 9.2 µm in the coupling region, with a waveguide gap of 0.2 µm in the ON state and 0.96 µm in the OFF state. The symmetric and antisymmetric modes in the couplers are depicted in Fig. 2 (a).

C. Electrostatic Comb Actuator

The upper and lower fixed comb handles of the electrostatic comb actuators are connected to different electrodes. Upon application of a voltage to one of the electrodes, the suspended movable comb handle are attracted to the teeth of fixed comb handle through electrostatic force, causing translation. A total of 80 pairs of comb teeth are arranged periodically on different combs. The length and width of the comb teeth are 3.7 µm and 0.4 µm, respectively, while the gap between the teeth is 1 µm. The electrostatic force can be calculated using the following equation:

$$F_e = 1/2\ U^2\ \partial C/\partial y \tag{1}$$

Where U is the voltage and C is the capacitance between the comb teeth. Simulation by finite element analysis (FEA) software shows that each pair of comb teeth can provide about 6.8 nN of electrostatic force at 20 V.

D. Bistable Mechanical Beams

The mechanical properties of cosine-shaped bistable mechanical beams have been analyzed in detail by J. Qiu et al. in 2001 [6]. The bistable mechanical beams will switch from one steady state to the other when the deformation after the force in the y-direction exceeds a critical point, and the two steady states are approximately symmetric. In order to achieve better nonvolatility of the device, a total of four bistable mechanical beams are used in this design, with both ends fixed on nonsuspending fixed islands with length and width of 60 µm and 0.1 µm, respectively, and an amplitude of 0.4 µm. A displacement of 0.76 µm in the y-direction of the movable waveguide can be achieved when the optical switch is switched. The force-displacement hysteresis relationship of the bistable mechanical beams is shown in Fig. 2 (b) by simulation with FEA software.

III. Experimental Results

The optical switch was fabricated with electron-beam lithography (EBL) on an SOI substrate, consisting of a 220 nm thick silicon waveguide layer and a 2 µm thick buried oxide layer. The waveguide and MEMS structures were patterned using two etching steps, a partial etch at a depth of 70 nm and a full etch of the 220 nm SOI layer. Shallow etching was utilized to define the input and output ridge waveguides and grating couplers. The movable directional couplers, electrostatic comb actuators, bistable mechanical beams, and square silicon wafer were patterned using full etching by electron beam lithography. Electrode and pads were patterned using metal deposition and lift-off processes. Finally, the silicon dioxide was vapor etched with hydrofluoric acid to release the suspended structure. Fig. 3 depicts the optical switch in the ON and OFF states, with both the suspended and fixed parts visible.

The mechanical performance of the optical switch was tested. The drive voltages of 20 V and 11 V was required to switch the device to the ON and OFF states, respectively.

Fig. 4 shows the spectral responses of the four input-output cases at the wavelength of 1550 nm, and the test results of the extinction ratio are provided in Table 1. The maximum excess loss was found to be 14 dB, partly due to the narrow transmission bandwidth of the directional couplers. The large

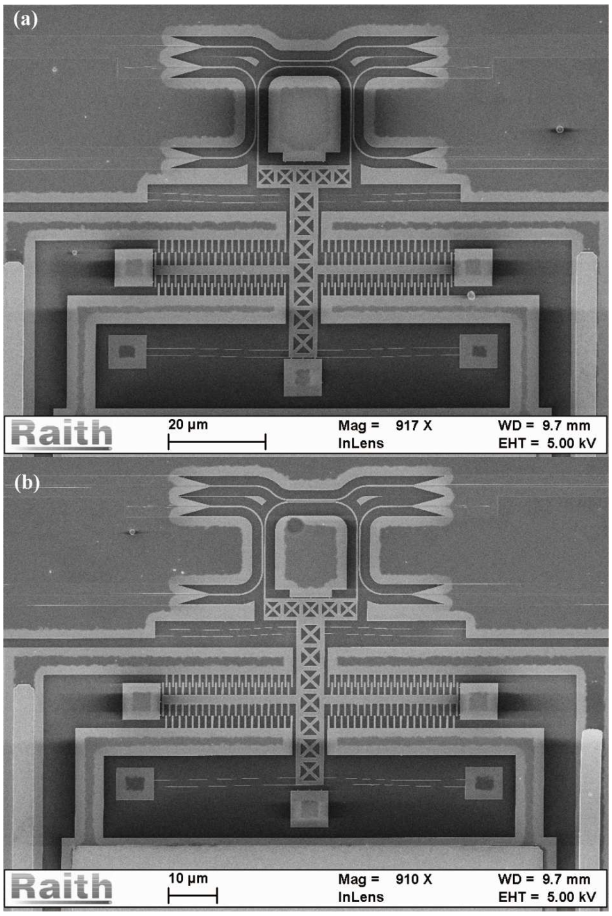

Fig. 3. Optical switch structure under SEM observation. (a) A optical switch in OFF state; (b) A optical switch in ON state.

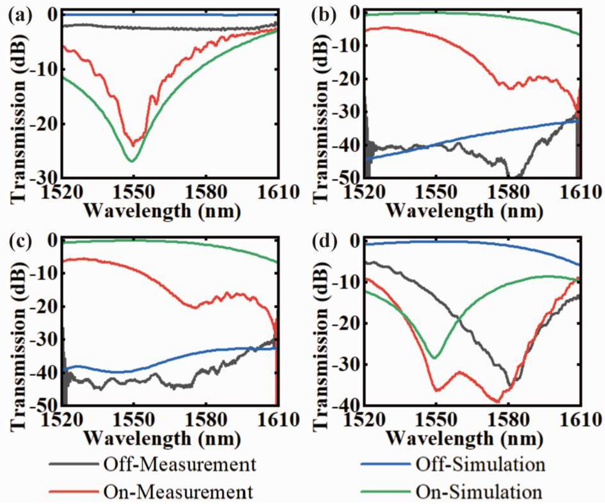

Fig. 4. Spectral response of the optical switch at the wavelength of 1550nm. (a) Input 1 to Output 1; (b) Input 1 to Output 2; (c) Input 2 to Output 1; (d) Input 2 to Output 2.

discrepancy between simulation and experiment results was attributed to fabrication nonidealities and structural deformation after stress release. The switching performance is expected to improve significantly with much more wide-band and fabrication-tolerant device designs based on adiabatic couplers, which is our future research effort.

IV. Summary and Discussion

We designed and fabricated a 2 × 2 silicon MEMS optical switch that utilizes bistable mechanical beams to achieve nonvolatile ON and OFF states. The design is compatible with standard silicon photonics foundry processes and does not require pre-stress. The feasibility of bistability has been experimentally verified, and switching to the ON and OFF states requires drive voltages of 20 V and 11 V, respectively. The switching performance is expected to improve significantly with much more wide-band and fabrication-tolerant device designs based on adiabatic couplers.

TABLE I. Extinction Ratio at the Wavelength of 1550 nm

Unit (dB)	Measurement		Simulation	
	Output 1	Output 2	Output 1	Output 2
Input 1	21.3	32.4	26.7	39.6
Input 2	33.2	22.1	39.2	28.1

Acknowledgment

This work is funded by Leading Innovative and Entrepreneur Team Introduction Program of Zhejiang (2021R01001), Zhejiang Provincial Major Research and Development Program (2021C01199), Natural Science Foundation of Zhejiang Province (LZ22F050006), and Startup Foundation for Hundred-Talent Program of Zhejiang University. The authors thank the ZJU Micro-Nano Fabrication Center and the Westlake Center for Micro/Nano Fabrication and Instrumentation for the facility support and technical assistance. The authors also acknowledge Tianjin H-Chip Technology Group Corporation for device fabrication.

References

[1] J S. Chen et al., "Technologies and applications of silicon-based micro-optical electromechanical systems: A brief review," Journal of Semiconductors, 2022, Vol. 43, Issue 8, Pages: 081301-1-081301-9, vol. 43, no. 8, pp. 081301–1, Aug. 2022.

[2] E. Bulgan et al., "Theoretical Analysis of Mechanical-Contact-Based Submicron-Si-Waveguide Optical Microswitch at Telecommunication Wavelengths," IEEJ Transactions on Sensors and Micromachines, vol. 128, no. 3, pp. 80–84, Mar. 2008.

[3] M. C. Wu, N. Quack, R. S. Muller, S. Han, and T. J. Seok, "Large-scale broadband digital silicon photonic switches with vertical adiabatic couplers," Optica, Vol. 3, Issue 1, pp. 64-70, vol. 3, no. 1, pp. 64–70, Jan. 2016.

[4] H. Sattari, A. Toros, T. Graziosi, N. Quack , "Bistable silicon photonic MEMS switches," MOEMS and Miniaturized Systems XVIII. vol. 10931, no. 4, pp. 97–104, Mar. 2019.

[5] A. Y. Takabayashi et al., "Broadband Compact Single-Pole Double-Throw Silicon Photonic MEMS Switch," Journal of Microelectromechanical Systems, vol. 30, no. 2, pp. 322–329, Apr. 2021.

[6] J. Qiu, J. H. Lang, and A. H. Slocμm, "A centrally-clamped parallel-beam bistable MEMS mechanism," Proceedings of the IEEE Micro Electro Mechanical Systems (MEMS), pp. 353–356, 2001.