Low-voltage Optical Switching by a Four-waveguide Directional Coupler

Tianran LIU*, Francesco PAGLIANO, Andrea FIORE
Department of Applied Physics and Institute for Photonic Integration, Eindhoven University of Technology, P.O. Box 513, 5600MB Eindhoven, The Netherlands
** t.liu@tue.nl*

Optical switches base on electrostatic movable micro-mirrors have been developed since nineties of the last century for their low power consumption and high optical performance [1]. As nano-fabrication technology advances, it is recently possible to build optical switches with other optical devices on a single chip. To reach higher level of integration, moving waveguides rather than mirrors to steer light is a better option since it involves less free-space alignment. Several works have been done in this direction in the recent years [2-4]. However, most of these devices require a high actuation voltage from 14V to 50V and the switching frequency is below 1MHz, which limit their diversity in application.

We propose a nano-opto-electro-mechanical switch based on three-dimensional four-waveguide directional coupler. Compared to most mechanical actuating optical switches, the actuation voltage of this novel device is small (3V). Thanks to the compact footprint, the natural mechanical frequency is above 1MHz range, allowing a fast switching speed.

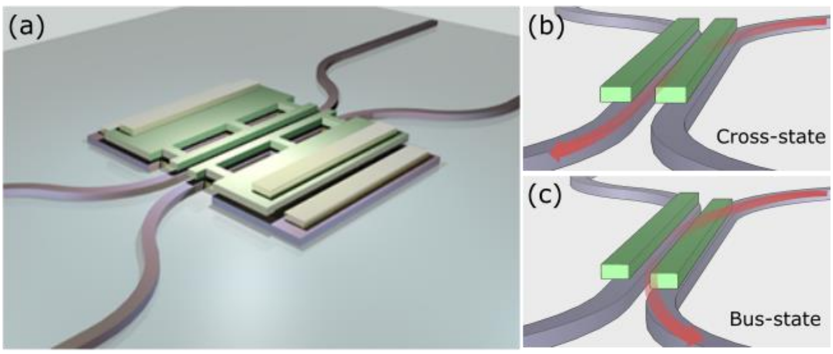

Fig. 1. (a) A simplified illustration of the switch. (b) Cross-state. (c) Bus-state.

The proposed switch is based on a directional coupler composed of four waveguides, with two of which are suspended. By inducing voltage bias, the two suspended waveguides can be actuated vertically, changing the state of switch between cross-state and bus-state, as showed in Fig.1(b) and (c).

The mechanism of our device can be depicted in the frame of coupled mode theory. Considering four identical waveguides arranged in the way described above, neglecting the diagonal coupling, the system can be depicted in Eq.1.

$$\frac{d}{dx}\begin{bmatrix} b_1(x) \\ b_2(x) \\ a_1(x) \\ a_2(x) \end{bmatrix} = -i\begin{bmatrix} \beta & \kappa_h & \kappa_{v1} & 0 \\ \kappa_h & \beta & 0 & \kappa_{v2} \\ \kappa_{v1} & 0 & \beta & \kappa_h \\ 0 & \kappa_{v2} & \kappa_h & \beta \end{bmatrix}\begin{bmatrix} b_1(x) \\ b_2(x) \\ a_1(x) \\ a_2(x) \end{bmatrix} \quad (1)$$

The solution of Eq.1 needs to satisfy $|b_2(L)|^2 = 1$ and $|a_1(L)|^2 = |a_2(L)|^2 = |b_1(L)|^2 = 0$ for the cross-state. By putting the solution into cross-state condition, we get Eq.2, which tells us the device length and coupling rates required by the state.

$$\begin{cases} \kappa_{v1} = \kappa_{v2} = 2l\kappa_h & l = 1,2,3 \ldots \\ L = (2m+1)\frac{\pi}{2\kappa_h} & m = 0,1,2 \ldots \end{cases} \tag{2}$$

The solution of Eq.1 needs to satisfy $|b_1(L)|^2 = 1$ and $|a_1(L)|^2 = |a_2(L)|^2 = |b_2(L)|^2 = 0$ for the bus-state. By putting the solution into this condition, we get Eq.3, which tells us the coupling rates required by the bus-state.

$$\begin{cases} \kappa_{v1} = \left(2p \pm \sqrt{4(2n-1)^2 - 1}\right)\kappa_h & p = 2,3,4 \ldots;\ n = 1,2,3 \ldots \\ \kappa_{v2} = \left(2p \mp \sqrt{4(2n-1)^2 - 1}\right)\kappa_h & p = 2,3,4 \ldots;\ n = 1,2,3 \ldots \end{cases} \tag{3}$$

The coupling rates can be related to vertical distances between waveguides after calibration. To demonstrate the concept, we build a FDTD model with following parameters. The length of the device is 25 µm. The width and thickness of the bottom waveguides are 370 nm and 220 nm. Initial vertical distance between waveguides is 220 nm. Suspended waveguides are 15 nm thicker to compensate the substrate effect. The material of waveguide is assumed to be silicon and the bottom waveguides sit on silica substrate.

Fig.2(a) shows the transmission evolution during actuating the device from cross-state to bus-state, given by FDTD simulations. The bandwidth of the switch is showed in Fig.2(b).

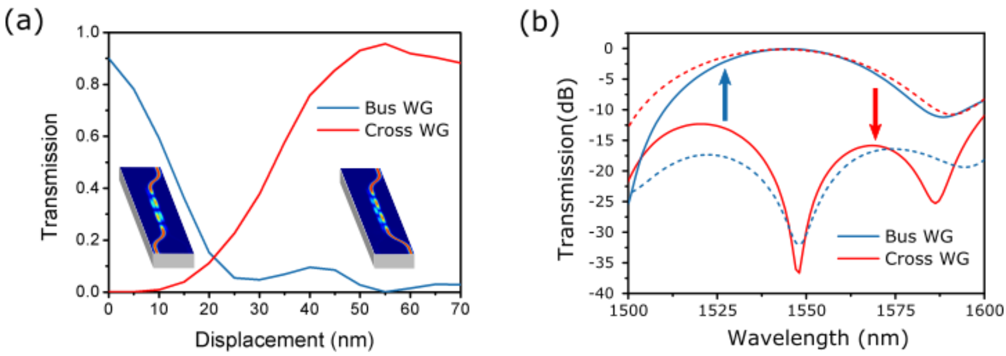

Fig. 2. (a) Simulated transmission characteristics as a function of the displacement of right suspended waveguide, with the displacement of left one fixed at 5 nm. (b) Simulated spectral response of Cross-state (solid line) and Bus-state (dashed line)

FEM simulations show that the actuation voltage of our design can be as low as 3.25V, thanks to the small displacement requirement compared to other designs [2-4]. The natural mechanical resonant frequency of the device is 1.29 MHz, which is also the highest among reported designs. The energy needed by each swithing operation is given by $E_s = \frac{\varepsilon_0 A V_s^2}{d-z}$, which is only 85 fJ here.

References

[1] Toshiyoshi, Hiroshi, and Hiroyuki Fujita. "Electrostatic micro torsion mirrors for an optical switch matrix." *Journal of Microelectromechanical Systems*, vol. 5, no. 4, pp. 231-237, 1996

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

[3] Han, S., Seok, T.J., Quack, N., Yoo, B.W. and Wu, M.C., "Large-scale silicon photonic switches with movable directional couplers." *Optica,* vol. 2, no. 4, pp. 370-375, 2015

[4] Abe, Syotaro, and Kazuhiro Hane. "Variable-gap silicon photonic waveguide coupler switch with a nanolatch mechanism." *IEEE Photonic Tech. L.* vol. 25, no. 7, pp. 675-677 , 2013