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Nano-opto-electro-mechanical switch based on a four-waveguide directional coupler

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Abstract: Optical switches connect optical circuits, and route optical signals in networks. Nano-electromechanical systems can in principle enable compact and power-effective switches that can be integrated in photonic circuits. We proposed an optical switch based on four coupled waveguides arranged in three-dimensional configuration. The switching operation is controlled by a cantilever displacement of only 55 nm. Simulations show that our proposed device requires a low switching voltage down to 3V and can operate at frequencies in the MHz range. Our results also pave the way towards novel optical components that electromechanically manipulate light in both the horizontal and the vertical direction in photonic circuits.

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1. Introduction

Compact, fast and power-effective integrated optical switches are needed in next-generation communication systems. The performance of switches highly depends on the switching method they employ. The approaches reported in the literature rely on different physical mechanisms, e.g. gain tuning [1–4], thermal tuning [5–7], electro-optical tuning [8–10], acousto-optic deflection [10,11], micro/nano mechanical actuation [12–16]. However, each of these approaches has some shortcomings. Switches based on gain or thermal tuning usually consume significant power (tens or hundreds of milliwatt) [1-7] and cause a heat dissipation problem, when densely packed. Electro-optical switches can be very fast (sub-nanosecond switching time) but usually require relatively large footprint (a few millimeters) [8–10], due to the small tuning range of refractive index by electro-optics. Acousto-optic switches also have limited scalability since they require a large propagation distance for the acoustic wave to deflect light [11,17]. Micro-electromechanical optical switches are mostly based on mechanically displaceable mirrors [12,15], which are power-efficient but are difficult to integrate and therefore difficult to scale. Recently, micro-/nano- electromechanical optical switches based on movable waveguides have been reported [16,18–22], which are more compact and can be integrated in photonic integrated circuits. However, most designs require a displacement of several hundreds of nanometers for switching operation, resulting in a high actuation voltage [16,18–22], which limits their practical application.

In this paper, we propose a switch design based on a coupled-waveguide nano-optoelectro-mechanical system (NOEMS). It requires only a 55 nm displacement tuning range for switching operation, which is one order of magnitude smaller than current designs. This gives

our device the advantage of small actuating voltage, while retaining a high resonant frequency. The switching operation is based on four modes interference, induced by a mix of vertical and horizontal coupling in a three-dimensional four-waveguide directional coupler [23]. The concept can be implemented within the silicon photonics or the Indium-Phosphide Membrane on Silicon (IMOS) [24] platforms.

2. Structure and principle

Figure 1 shows the 3D view and cross-sectional view of the proposed NOEMS 2×2 switch. The structure is composed of two input/output waveguides and two movable waveguides suspended above them. For the calculations in this paper we assume Si on SiO₂ as bottom waveguide layer and poly-Si for the movable waveguides. A process similar to [18] could be used to fabricate the device. Three lithography steps are needed, for the bottom waveguides, sacrificial layer and top waveguides respectively. The two movable waveguides are controlled by two cantilevers, which can be electrostatically actuated separately, in the vertical direction.



Fig. 1. A simplified illustration of NOEMS switch based on double-membrane waveguide. Bus (ON) and Cross (OFF) states are indicated by the blue and the red arrow respectively. (a) 3-D view. The layers indicated in yellow are the metallic contacts. (b) Switch in cross-state (c) Switch in bus-state(cantilevers are omitted in b and c)

It is well known that there exist two supermodes, i.e., symmetric and anti-symmetric mode, in a coupled two-waveguides system [25]. When both supermodes are excited, light can be completely transferred from one waveguide to the other, due to the interference of the two supermodes. One can control this transfer simply by tuning the coupling rate between the waveguides (e.g. by varying their distance), which is the principle of most micro/nano electromechanical switches based on directional couplers [18–21]. From the optical point of view, as most waveguides have a height/width aspect ratio lower than one, vertical actuation is more efficient because of larger mode overlap, compared to horizontal one. From electromechanical point of view, vertical actuation is also more efficient because a larger capacitor surface area can be easily obtained, compared to horizontal actuation. However, in a vertical directional coupler, it is challenging to bring the upper input/output waveguides to the same layer as the bottom waveguide, as needed for cascadability. One way to address this problem is building a horizontal directional coupler and using vertical actuation [18], which requires displacement as large as 1 um to switch between cross (coupled) state and bus (uncoupled) state. In our proposed design, switching between the two channels is obtained not by changing their separation (i.e. coupling), but by breaking the symmetry and introducing a phase mismatch between the two channels. This can be realized by a perturbation of the effective refractive index (ERI) of one channel. To build this ERI-tunable system, we utilize four waveguides, each two of them forms one 'super-waveguide', whose ERI can be tuned by actuating the suspended waveguide vertically. We show below that switching be achieved by a small ratio of displacement to gap in this system.

To reduce the insertion loss, we want all the output power couples back to the bottom waveguide, therefore the beating length between the bottom and top waveguides needs to be considered. In order to demonstrate that it is theoretically possible to avoid the insertion loss of top waveguides, we made a simplified four-waveguides model and describe it by coupledmode theory [23]. Figure 2(a) shows the schematic diagram of the model. The rectangles represent the modes of each waveguides. Arrows represent the coupling between them. For simplicity we assume that all waveguides share the same propagation constant β . The coupling rate between a_1 and b_1 is noted by κ_{v_1} , while the coupling rate between a_2 and b_2 is noted by κ_{v_2} . κ_{v_1} and κ_{v_2} can be tuned independently by the actuators. To further simplify the model, we assume that the coupling rate between a_1 and a_2 , has the same value as that between b_1 and b_2 , which is denoted by κ_h . κ_h remains constant when κ_{v1} and κ_{v2} are tuned in a relatively small range. For example, if the horizontal distance (center to center) between two waveguides are 644 nm and the maximum vertical offset is 50 nm, then the real distance change induced by this offset is only 1.9 nm. So the change of coupling rate can be neglected in the range of vertical offsets investigated in the following. The diagonal coupling is neglected in this theory model to make it analytically solvable. Further numerical analysis and FDTD simulations verify that the influence of diagonal coupling becomes noticeable only when the interactive length is far longer than the device length.



Fig. 2. (a) Diagram of a four-waveguide model, the field distribution of the symmetric and anti-symmetric modes in the horizontal and vertical directions are schematically depicted. (b) The simulated E_x field distribution of the four supermodes in non-displaced and displaced structure.

The coupled-mode equations for such a system are described as follows:

$$\frac{d}{dx} \begin{bmatrix} b_{1}(x) \\ b_{2}(x) \\ a_{1}(x) \\ a_{2}(x) \end{bmatrix} = -i \begin{bmatrix} \beta & \kappa_{h} & \kappa_{v1} & 0 \\ \kappa_{h} & \beta & 0 & \kappa_{v2} \\ \kappa_{v1} & 0 & \beta & \kappa_{h} \\ 0 & \kappa_{v2} & \kappa_{h} & \beta \end{bmatrix} \begin{bmatrix} b_{1}(x) \\ b_{2}(x) \\ a_{1}(x) \\ a_{2}(x) \end{bmatrix}$$
(1)

Assuming b_1 is the input, the initial conditions are:

$$b_1(0) = 1, b_2(0) = 0, a_1(0) = 0, a_2(0) = 0$$
 (2)

The solution of Eq. (1) under condition Eq. (2) is:

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$$\begin{bmatrix} b_{1}(x) \\ b_{1}(x) \\ b_{1}(x) \\ b_{1}(x) \\ b_{1}(x) \end{bmatrix} = e^{-i\beta x} \begin{bmatrix} -\cos(s_{v}x)\cos(s_{h}x) + \frac{\kappa_{v1} - \kappa_{v2}}{2s_{h}}\sin(s_{v}x)\sin(s_{h}x) \\ i\frac{\kappa_{h}}{s_{h}}\cos(s_{v}x)\sin(s_{h}x) \\ i\sin(s_{v}x)\cos(s_{h}x) + i\frac{\kappa_{v1} - \kappa_{v2}}{2s_{h}}\cos(s_{v}x)\sin(s_{h}x) \\ \frac{\kappa_{h}}{s_{h}}\sin(s_{v}x)\sin(s_{h}x) \end{bmatrix}$$
(3)

Where

$$s_{h} = \sqrt{\kappa_{h}^{2} + \frac{(\kappa_{v1} - \kappa_{v2})^{2}}{4}}$$
(4)

$$s_{\nu} = \frac{K_{\nu 1} + K_{\nu 2}}{2}$$
(5)

Note that if $\kappa_{v1} = \kappa_{v2}$, then $s_h = \kappa_h$, $s_v = \kappa_{v1} = \kappa_{v2}$, and Eq. (3) becomes:

$$\begin{bmatrix} b_{1}(x) \\ b_{1}(x) \\ b_{1}(x) \\ b_{1}(x) \end{bmatrix} = e^{-i\beta x} \begin{bmatrix} -\cos(\kappa_{v}x)\cos(\kappa_{h}x) \\ i\cos(\kappa_{v}x)\sin(\kappa_{h}x) \\ i\sin(\kappa_{v}x)\cos(\kappa_{h}x) \\ \sin(\kappa_{v}x)\sin(\kappa_{h}x) \end{bmatrix}$$
(6)

which clearly indicates a combination of vertical and horizontal beating. The system can also be described through the eigenvectors of the matrix in Eq. (3), which in the limit of $\kappa_{v1} = \kappa_{v2}$ become {1,1,1,1}, {1,-1,1,-1}, {-1,-1,1,1} and {-1,1,1,-1}, as plotted in Fig. 2(b). These supermodes can be seen as the superposition of vertical and horizontal symmetric/antisymmetric modes. Simulations by Comsol verify that these are the only four modes given the assumption of quasi-TE polarization (Fig. 2(b)). This solution Eq. (3) is therefore the result of interference of 4 supermodes, which are all excited by an input from b₁.

For the cross-state (all power switched to target waveguide), the following conditions are necessary:

$$|b_2(L)|^2 = 1, |a_2(L)|^2 = |a_2(L)|^2 = |b_1(L)|^2 = 0$$
(7)

where L is the length of coupling region.

By putting the solution into Eq. (7), we get:

$$\begin{cases} \kappa_{v1} = \kappa_{v1} = 2l\kappa_h & l = 1, 2, 3... \\ L = (2m+1)\frac{\pi}{2\kappa_h} & m = 0, 1, 2... \end{cases}$$
(8)

The first equation in Eq. (8) indicates that for the cross-state we need a symmetric setup and the vertical separations between the waveguides have to be matched with the horizontal separations. The second equation defines the device length, and the term $\frac{\pi}{2\kappa_h}$ represents the

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beating length of the two horizontal-coupled waveguides. Since we want our device to be as compact as possible, we choose m = 0 so that the device length will just be $L = \frac{\pi}{2\kappa_k}$.

For bus-state (all power coupled back into input waveguide), the following conditions have to be satisfied when $L = \frac{\pi}{2\kappa}$:

$$|b_1(\mathbf{L})|^2 = 1, |a_1(\mathbf{L})|^2 = |a_1(\mathbf{L})|^2 = |b_2(\mathbf{L})|^2 = 0$$
 (9)

There are two solutions that can satisfy Eq. (9):

$$\begin{cases} \kappa_{v1} = \left(2p \pm \sqrt{4(2n-1)^2 - 1}\right) \kappa_h \\ \kappa_{v2} = \left(2p \mp \sqrt{4(2n-1)^2 - 1}\right) \kappa_h \end{cases} \quad p = 2, 3, 4...; n = 1, 2, 3... \tag{10}$$

Or

$$\begin{cases} \kappa_{v1} = \left(2p \pm \sqrt{16n^2 - 1}\right) \kappa_h \\ \kappa_{v2} = \left(2p \mp \sqrt{16n^2 - 1}\right) \kappa_h \end{cases} \qquad p = 3, 4, 5...; n = 1, 2, 3... \tag{11}$$

Equations (10) and (11) indicate we need to tune move both waveguides to get a complete switching from cross-state to bus-state, because κ_{v1} or κ_{v2} in Eq. (10) or Eq. (11) cannot take the same value as that in Eq. (8). In our design we choose $\kappa_{v1} = \kappa_{v2} = 6\kappa_h$ for the cross-state. κ_{v1} and κ_{v2} have to be larger in bus-state since we cannot produce repulsive actuation. Here we choose $\kappa_{v1} = (8 - \sqrt{3})\kappa_h$, $\kappa_{v2} = (8 + \sqrt{3})\kappa_h$ for the bus-state. Note that $8 + \sqrt{3}$ is only slightly larger than 6, which means that one waveguide only needs a tiny displacement (5 nm in the implementation discussed in the next section) while the other one needs a larger displacement (55 nm). Although any κ_{v1} and κ_{v2} values satisfying Eqs. (8) and (10) or Eq. (11) can be chosen in principle, smaller κ_{v1} and κ_{v2} are less effective, because $\kappa_v = Ae^{-\alpha d}$ [26], so $\frac{\partial \kappa_v}{\partial d} = -\alpha \kappa_v$, where *d* is the vertical distance between two waveguides. This means larger displacement is required for a given $\Delta \kappa_v$. On the other hand, larger κ_{v1} and κ_{v2} require too small vertical gap between waveguides, which make it unpractical in fabrication. Figure 3 shows the normalized power distribution in each waveguide predicted by our theory model. In the cross-state, the power transfers between the bottom and suspended waveguides

periodically, but gradually moves from the input to the target waveguide, so that all the power is eventually transferred to the bottom cross port; In bus-state, the spatial beating between bottom and suspended waveguides is similar, but as the vertical beating is not synchronized in the input and output waveguides, in the end all the power moves back to the input waveguide.



Fig. 3. Normalized power in each waveguide for the cross-state(a) and bus-state(b)as predicted by the coupled-mode model.

3. Simulation

In order to investigate the performance of the proposed switch, we build a simulation model using the finite-difference time-domain method (FDTD) [27]. We first choose geometry parameters that have been demonstrated feasible for waveguides [28], then determine the other parameters from the condition described in the previous section. The width of the waveguides is w = 370 nm. The thickness of the suspended waveguides is $h_1 = 235$ nm. The thickness of the bottom waveguide is $h_2 = 220$ nm, slightly smaller than h_1 to compensate for the higher refractive index of the substrate. The length of the suspended waveguides is 24.6 μ m. The horizontal distance between the waveguides is g = 274 nm. The initial zero-bias gap between suspended waveguides and bottom ones is 220 nm, which is relatively small compared to most MEMS switches in the literature. However, we have demonstrated experimentally several generations of devices based on similar gap scale, which work successfully and reproducibly [26,29,30]. In the symmetric case, the structure is symmetric and works in the cross-state. When a voltage bias is added to the actuator, the electrostatic forces pull the suspended waveguide to a lower position, breaking the symmetry of structure. The switch can be turned into the bus state by a 55 nm vertical displacement of right suspended waveguide, and 5 nm of the left one. Figure 4(a) shows the electric field magnitude distributions in cross-state and bus-state. Although one can get an almost complete switching by displacement of right suspended waveguide alone, the optimized switching ratio requires also a tiny displacement of the one, as explained in the previous section.



Fig. 4. (a) The electric field magnitude distribution (|E|) of cross-state and bus-state. The plot surface is through the mid-plane of bottom waveguides. The input is the fundamental TE mode. (b) Simulated transmission characteristics as a function of the displacement of right suspended waveguide, with the displacement of left one fixed at 5 nm. Inset is the range where the crosstalk is below -20 dB for the bus-state. (c) Simulated spectral response of bus and cross waveguide (WG) in the cross-state. (d) Simulated spectral response in the bus-state.

The transmission characteristics as a function of displacement of one suspended waveguide are plotted in Fig. 4(b), with the displacement of the other waveguide fixed at 5 nm. The insertion loss of both states is below 0.3dB. This loss is mainly due to the scattering at the two ends of the suspended waveguides. The output turns to the bus port gradually as displacement increases and reaches its maximum when displacement comes to 55 nm. Note that the transmission of the cross port at zero displacement in a symmetric system is slightly higher than that in Fig. 4(b). However, we can also optimize the parameters so that the transmission maximum of bus port and cross port has the same value when the displacement of the other waveguide is fixed at 0 nm. The spectral response of the cross- and bus-state are shown in Figs. 4(c) and 4(d). The maximum extinction ratio of both states exceeds 30dB. The bandwidth (extinction ratio > 10dB) of the device is around 50 nm. This 55 nm displacement requirement for switching is well below the pull-in limit (one third of the original distance [31]), and can be made even smaller by adjusting the horizontal gap and device length, but with a loss of bandwidth. The hinges showed in Fig. 1(a) are not included in the FDTD model. The extra loss induced by those hinges is estimated to be around 4dB/mm from preliminary experimental results on a similar structure, which means around 0.2dB for one device.

We now analyze the effect of fabrication and operation tolerances on the predicted performance. For crosstalk below -20 dB, the displacement tolerance is -3 nm /+4 nm and the corresponding voltage tolerance is -6 mV/+7 mV, according to the simulations discussed below. The performance under geometrical parameter variations are also simulated and showed in Table 1. Most performances deteriorate in an acceptable range under reasonable geometry variation. The most critical dependence is the one of the center wavelength versus

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width of the waveguide, which can be expected in any resonant device, and it can be mitigated using pre-bias of the device and larger waveguide widths.

Parameter	Variation	Extinction (cross/bus)	Insertion loss (cross/bus)	Bandwidth	Optimal wavelength drift
L	+ 100nm	-37dB/-32dB	0.2dB/0.2dB	52nm	<1nm
	-100nm	-37dB/-33dB	0.2dB/0.2dB	52nm	+ 1nm
h ₁	+ 10nm	-37dB/-33dB	0.2dB/0.3dB	44nm	+ 7nm
	-10nm	-36dB/-27dB	1.3dB/0.6dB	53nm	-11nm
h ₂	+ 10nm	-32dB/-21dB	0.4dB/0.4dB	60nm	+ 12nm
	-10nm	-35dB/-38dB	1.5dB/0.8dB	34nm	-16nm
w	+ 10nm	-35dB/-32dB	0.5dB/0.5dB	43nm	+ 20nm
	-10nm	-35dB/-29dB	0.4dB/0.4dB	41nm	-27nm

Tahla 1	The simulated	nerformance under	geometry	narameters variations
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Apart from a high switch ratio, an ideal NOEMS switch should also have a high switching speed and low actuation voltage. The switching speed is limited by the natural mechanical $1 \sqrt{k}$

resonant frequency of the cantilever, which can be written as $f_m = \frac{1}{2\pi} \sqrt{\frac{k}{m_e}}$, where m_e is the

effective mass of the cantilever. To make the discussion more general we utilize a simple point-mass model in which we assume the dynamic spring constant is equal to the static one, by adopting an effective mass. We assume for now that the effective mass is proportional to the real mass of the whole cantilever (including waveguide and other suspended parts), i.e.

 $m_e = C \cdot m$ where C is a constant. Then we have $fm = \frac{1}{2\pi} \sqrt{\frac{k}{C\rho Ah}}$, where A and h are the

surface area and thickness of the cantilever and \mathbf{P} is the material density. When using capacitive actuation, according to Hooke's law and Coulomb's law, the actuation voltage V_s

for a displacement z can be written as $V_s = (d-z)\sqrt{\frac{2kz}{A\varepsilon_0}}$ where d is the initial distance

between suspended and bottom waveguides, and ε_0 is vacuum permittivity. Note that one can always reduce the required actuation voltage by increasing the surface area of actuators, or reducing the stiffness (e.g, by etching holes on the cantilever). However, this comes at the

cost of a switching speed, since both $f_{\rm m}$ and $V_{\rm s}$ have the same coefficient $\sqrt{\frac{k}{A}}$ in their

expression. Their ratio $\frac{f_m}{V_s} = \frac{1}{2\pi(d-z)} \sqrt{\frac{\varepsilon_0}{2C\rho hz}}$ is instead independent of area and stiffness

of the cantilever. The proposed switch has a switching actuation displacement of only 55 nm, which is one order of magnitude smaller than the previous designs [16,18–20]. For crosstalk below -20 dB, the displacement tolerance is -3 nm /+4 nm and the corresponding voltage tolerance is -6 mV/+7 mV, according to the simulations. We calculate the resonant frequency and actuation voltage of our design using the finite-element method (Comsol Multiphysics), assuming a Young's modulus of 127 GPa and a Poisson's ratio of 0.278. Figure 5 shows the simulation results of resonant frequency and actuate on voltage as a function of the length of cantilever. As expected from the reasoning above, they both decrease as length of cantilever grows, but their ratio remains at 397 kHz/V, which confirms our theory in the above discussion. Table 2 lists the performance of reported micro-/nano- electromechanical optical switches. The actuation voltage of our design can be as low as 3.25V, which is the smallest in the list. The product of actuation voltage and interaction-length (V_s·L), also listed in the table,

is also by far the smallest, which shows that the low actuation voltage of proposed switch is not based on a compromise with the length. We note that actuation voltages of 3V have already been shown to be sufficient to produce displacements in the 60 nm range in similar double-membrane structures [32], which shows that the proposed design and predicted switching performance are realistic. At the same time, the resonant frequency of proposed switch is 1.29 MHz, which is also the highest among reported designs, to the best of our knowledge, and sufficient for optical routing applications [33]. The energy spent in one

switching operation is $E_s = \frac{\varepsilon_0 A V_s^2}{d-z}$, which is 85 fJ in our case, while the static dissipated

power is expected to be very low (in the nW range) as no current is needed to keep the switch in a given state. Additionally, the proposed switch can be turned into a digital switch using "beam stoppers" which define the bottom position of the waveguides, similarly to the approach demonstrated in [16]. In this case, the operation will be much less sensitive to fluctuations in the driving voltage and any ambient parameter.



Fig. 5. Simulated performance with different lengths of actuator. The black line indicates the natural mechanical resonant frequency of the actuator, the red line indicates the actuation oltage needed for a switch operation. The inset shows the structure of one cantilever and its displacement distribution (indicated by the colors, red for larger displacement, blue for smaller one) under actuation voltage.

 Table 2. The performance of reported micro/nano electromechanical optical switches.

 When available, the theoretical values (t) have been used to provide a fair comparison with our proposal, in other cases experimental values (e) are shown.

	Required displacement (nm)	Actuation voltage V _s (V)	V _s ·L (V·µm)	Resonant frequency (kHz)
E. Bulgan, et al [22]	400(t)	48(t)	480(e)	109(e)
Y. Akihama, et al [20]	110(t)	25.3(e)	253(e)	214(e)
S. Abe and K. Hane [19].	900(e)	35(e)	350(e)	200(t)
S. Han, et al. [18]	1000(t)	14(e)	168(e)	179(t)
T. J. Seok, et al. [16]	675(t)	42(e)	1260(e)	710(e)
This work	55(t)	3.25(t)	80(t)	1290(t)

4. Conclusion

We proposed a novel NOEMS optical switch design based on coupled waveguides. According to the theory and simulation results, the insertion loss and extinction ratio of our design are comparable to the best micro-/nano- electromechanical optical switches reported so far. The most outstanding advantage of our design is the very small required displacement (55 nm), and the correspondingly low actuation voltage (in the few V range), together with its low power consumption and compact footprint (less than 50 µm), which make it very

competitive among other optical switches. The switching speed cannot be compared with electro-optical switches but is higher than previous electromechanical optical switches, and suitable for applications with strict requirements on power and voltage, but low demand on switching speed, such as optical routing. The new mechanism of three-dimensional multi-mode interference provides a new way to manipulate the light flow in the plane using vertical actuation in photonic integrated circuits.

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