

# Experimental Demonstration of Optical Switch Using Gradient Optical Force

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**Abstract:** A novel optical switch driven by gradient optical force is demonstrated, allowing weak light to switch a strong one. The proposed optically controlled switch achieves an extinction ratio of 28 dB with ~ns switching speed.

**OCIS codes:** (220.4880) Optomechanics; (230.7390) Waveguides, planar; (130.3120) Integrated optics devices

## 1. Introduction

The development of optical communications enables its major change from the current electronic-optical-hybrid network to all-optical network, especially in the backbone [1]. In particular, active optical switching plays a vital role in turning all-optical network into reality. Nowadays, a multitude of photonic switching technologies are candidates for highly integrated optical communication networks, such as electro-optic switches, thermo-optic switches, micro-optoelectromechanical systems based switches, and so on [2-3]. While all these advances do have their virtues, the obvious advantages of waveguide-based devices could be of the economy of scale and easy integration. Furthermore, it is highly desirable to use silicon as the platform to achieve high speed switching.

Optical forces have attracted significant interest, especially in the areas of nano-particle trapping and manipulation [4-5] and opto-mechanically driven nanostructures [6-7] for potential applications such as all optical signal processing. One type of optical force, named as the transverse gradient force, has recently been reported and demonstrated in nanophotonic waveguide systems [8-10], including enabling mechanical displacement of integrated nanophotonic structures. It has also been shown that the gradient optical force is increased by orders of magnitude in evanescently coupled waveguides due to the largely enhanced gradient of the optical field.

In this work, we demonstrate a novel optical switch utilizing the gradient optical force arising from the strong evanescent coupling between two parallel suspended waveguides. The proof-of-concept optical switch obtains a switching contrast of more than 28 dB with a response time of ~20 ns.

## 2. Switch Design

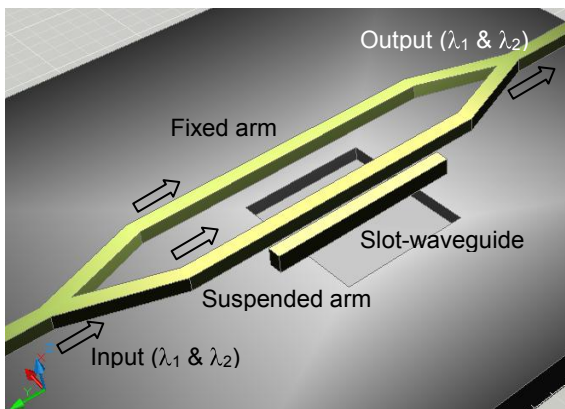


Fig. 1 Schematic of the optical switch, where  $\lambda_1$  is the input signal light and  $\lambda_2$  is the control light.

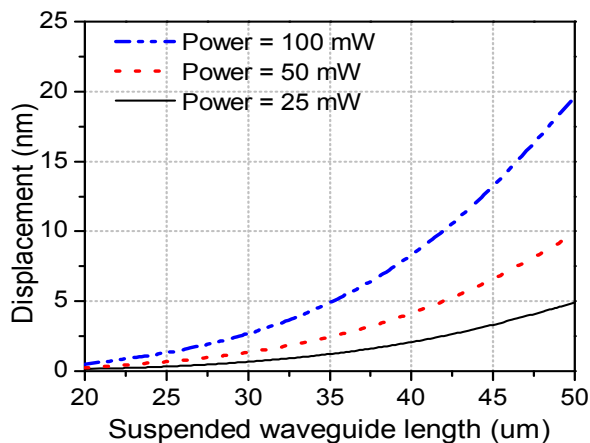


Fig. 2 The displacement of the suspended slot-waveguide versus the suspended length, at different power levels.

The schematic of the proposed optical switch is illustrated in Fig. 1. It consists of suspended waveguide structures in Mach-Zehnder interferometer (MZI) configuration. One of the MZI arms is arranged as a slot-waveguide, which consists of two parallel suspended waveguides with a narrow gap in-between, forming a doubly-clamped suspension arm; while the other is completely fixed. During the operation, the signal light ( $\lambda_1$ ) propagates along the MZI, while another control light ( $\lambda_2$ ) with the power of ( $P$ ) is injected and coupled to the slot-waveguide. As a result, the gradient electromagnetic field within the slot-waveguide produces a strong attractive optical force ( $F_{opt}$ ) evenly distributed over the waveguide length  $L$ , which can be expressed as:

$$\frac{F_{opt}}{L} = -\frac{P}{v_g \omega} \frac{d\omega}{ds} \Big|_k \quad (1)$$

where  $\omega$  is the optical input frequency, corresponding to  $\lambda_2$ ,  $v_g$  is the group velocity,  $L$  is the suspension length of the slot-waveguide, and  $s$  is the width of the gap of the slot waveguide. Due to the optical force, a corresponding mechanical displacement ( $D$ ) of the suspension arm is introduced, and can be expressed as:

$$D = -\frac{PL^4}{32Eha^3 v_g \omega} \times \frac{d\omega}{ds} \Big|_k \quad (2)$$

where  $E$  is the waveguide Young's modulus,  $h$  and  $a$  are the waveguide height and width, respectively. It indicates that  $D$  varies proportionally to the power of the control light. Based on the above equations, we calculate the displacement  $D$  varying with the optical power, as plotted in Fig. 2. As expected, the displacement increases as the power is strong. Meanwhile, for the same optical input power, the displacement increases when the suspension part becomes longer. However, a longer suspended waveguide may be less robust and less resistant to the effects of external mechanical shock, placing a practical limit on the increase in large displacement obtainable by increasing  $L$ .

Due to this displacement, the gap within the slot-waveguide is changed. Therefore, the effective refractive index is changed ( $\Delta n_{eff}$ ), leading to a further phase shift ( $\Delta\phi_{WG}$ ) of the signal light. As a result, the output of MZI is switched. In this case, the phase shift induced by the waveguide displacement is given by:

$$\Delta\phi_{WG} = \frac{2\pi}{\lambda} \int_{-L/2}^{L/2} \Delta n_{eff}(x) dx + \Delta\phi_L \quad (3)$$

### 3. Fabrication and Experimental Results

Based on the theoretical analysis presented in the previous section, the optical force driven switch is designed and fabricated on an SOI-wafer. The scanning electron micrograph (SEM) of the switch is shown in Fig. 3, where a slot-waveguide is suspended from the substrate. The switch has a footprint of  $500 \mu\text{m} \times 150 \mu\text{m}$ . The suspended beam has a length of  $30 \mu\text{m}$  and a cross-section of  $300 \text{ nm} \times 340 \text{ nm}$ , which allows the single-mode light propagation at low loss. Except for the suspended part, all the waveguides have a silicon core surrounded by  $2 \mu\text{m}$   $\text{SiO}_2$  cladding. During fabrication, the device is patterned by deep UV lithography, Si etched by plasma, and  $\text{SiO}_2$  deposited to cover Si core as cladding. After that, a thin  $\text{Si}_3\text{N}_4$  layer (100 nm) is used to protect the parts not to be released. Then a wet-etching process is carried to remove the buried-oxide layer underneath the suspended slot-waveguide with precisely time control. Finally, supercritical carbon-dioxide process is used to clean the wafer and alleviate the stiction problem induced by surface tension of water.

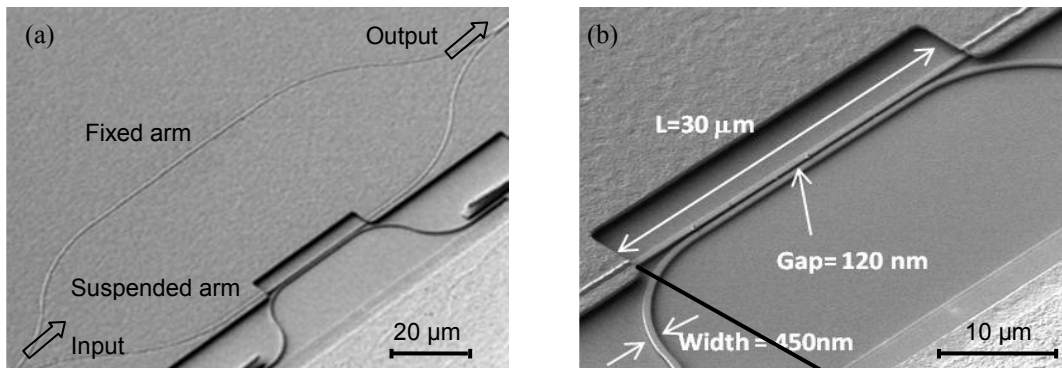


Fig. 3 Scanning electron micrograph (SEM) of optical switch (a) overview. (b) Zoom view of the suspended slot-waveguide, with the coupling gap is 120 nm.

Using the TE-polarized input signal light at 1550 nm and a control light at 1567.6 nm, measurements are conducted to monitor the static performance as well as quantify the response time of the proposed switch. As the magnitude of the optical force varies proportionally to the power of the control light, sufficient control power is needed for a better extinction ratio, as shown in Fig. 4. Therefore, an Erbium doped fiber amplifier (EDFA) is used to amplify the control light. According to the experiment, the extinction ratio of 28 dB is obtained. The switching time is measured by applying a pulse control signal to the switch and monitoring the output power simultaneously using an oscilloscope. The results are shown in Fig. 5, with the rise and fall time are 20.66 ns and 25.55 ns, respectively.

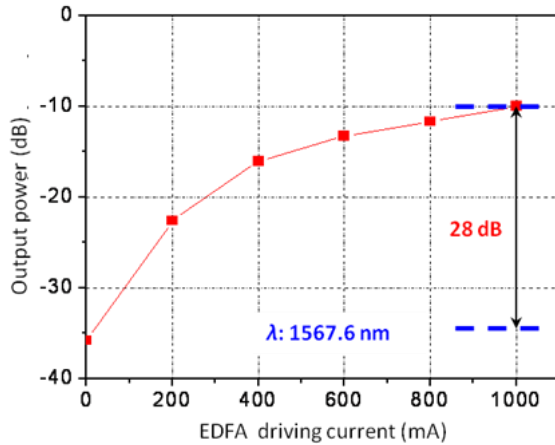


Fig. 4 Measured output power versus EDFA current (for control signal power amplification).

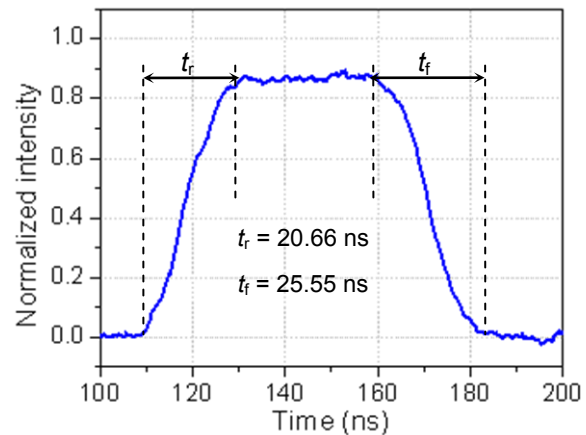


Fig. 5 Measured switching response, in term of normalized output power, when a pulse is applied.

#### 4. Conclusions

We have experimentally demonstrated a novel optical switch driven by gradient optical force. Through a suspended slot-waveguide and optical force driving, the switch obtains a switching contrast of 28 dB with a response time of  $\sim 20$  ns. Such optical force tuning approach may provide considerable room for device performance improvement, as well as open up more applications in future.

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