Theoretical Analysis of Mechanical-Contact-Based Submicron-Si-Waveguide Optical Microswitch at Telecommunication Wavelengths

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Keywords: optical switch, silicon waveguide, MEMS, finite difference time domain analysis, telecommunication

In this paper, we theoretically show optical characteristics of a novel mechanical-contact-based submicron-Si-waveguide optical microswitch with microelectrostatic actuator. The major optical design requirements are determined and studied with microfabrication considerations.

The switch, as seen in Fig. 1, consists of an input and identical output waveguide, and a movable waveguide driven by a miniature electrostatic comb actuator. When the comb actuator is energized, the movable waveguide closes the air gap between input and output waveguides. Due to the mechanical contact of waveguide tip surfaces, light propagates from the input waveguide to the output waveguide through the movable waveguide. When retracted, light propagation from the input to the output waveguide ends.

The switch uses a transverse-electric-like polarized single-mode light at 1.55 µm telecommunication wavelength as the incident light. Fabrication platform is assumed to be a silicon-on-insulator wafer for monolithic device integration.

Optical requirements from the optical switch for the best possible performance include single-mode light propagation in the submicron-Si-waveguide for less loss and higher controllability, minimum propagation loss towards cladding layers, minimum transmission leak through free-space between input and output waveguides, maximum output signal change between on and off states, minimum backreflection from the waveguide tips, and minimum leak from the movable waveguide towards the supporting beams at the on state.

As it can be seen from Fig. 2, theoretical calculations suggest that the optical switch with contact-tip waveguides at 45º tip angle can realize very sharp output signal change. As a result, 97.0 % transmission at the on state and 0.2 % transmission at the off state, corresponding to approximately 96.8 % optical output signal change between on and off states, are theoretically achieved by a displacement of 400 nm.

Possible fabrication imperfections, namely off-axis and axial gap issues, as illustrated in the inset of Fig. 3, are estimated and their effects on the optical performance are calculated. Calculation results emphasize the importance of mechanical-contact for the success of the optical microswitch. Enlargement of all contact-tip surfaces is understood to be a promising approach for the switch performance enhancement against possible fabrication imperfections.
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We present the theoretical analysis of a novel mechanical-contact-based submicron-Si-waveguide optical switch. The switch is composed of an identical input and output waveguides, and a movable waveguide driven by a miniature electrostatic comb actuator. The movable waveguide closes the gap between input and output waveguides. Due to mechanical-contact of submicron-Si-waveguides, input light propagates from input waveguide to output waveguide through the movable waveguide. The switch uses a transverse-electric-like polarized single-mode light at 1.55 µm telecommunication wavelength as the incident light. Theoretical calculations suggest that the optical switch with contact-tip waveguides at 45° tip angle can realize very sharp output signal change. As a result, 97.0 % transmission at the on state and 0.2 % transmission at the off state, corresponding to approximately 96.8 % optical output signal change between on and off states, are theoretically achieved by a displacement of 400 nm. Possible fabrication imperfections are estimated and their effects on the optical performance are calculated. Enlargement of all contact-tip surfaces is understood to be a promising approach for the switch performance enhancement against possible fabrication imperfections.

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1. Introduction

Utilization of optical fiber over long distances for geographically dispersed users and applications have increased the need for better optical telecommunication devices. Optical switches are the primary components for realization of more complex optical devices in the telecom field such as optical add-drop multiplexers, optical cross connects, etc. Several technologies are currently utilized for optical switching. Such techniques typically include one of refractive index change induced by exerting thermal energy(1), reflective surface creation by bubble formation(2), mechanically changing the orientation of a set of arrayed mirrors in free-space(3), relative motion of fiber optic cables(4), or inserting or retracting a mirrored vane between input and output waveguides for changing the optical path of the reflected light(5).

Microelectromechanical systems (MEMS) embedded optical microswitches have therefore been already utilized widely. In this case, generally size and, thus, the speed of the switch are determined by the necessary switching displacement, which for optical fibers, mirrored vane utilizing conventional silica-based waveguides, and free-space mirrors, has been in the range from several micrometers to tens of micrometers.

Due to its high refractive index, silicon, on the other hand, can confine light in very small regions. Sakai et al., for instance, have demonstrated that light at telecom wavelengths can propagate in a submicron Si-waveguide as small as 0.5 µm-bend-radius less than 1 dB bend loss, which suggests the potential for high-density monolithic lightwave circuits(6). In addition, ability to control of light in semiconductor-like periodic artificial bandgaps with the help of photonic crystal (PC) structures has attained significant research interest(7)(8). Lately, PC-based MEMS-actuated optical switches utilizing PC line-defect waveguides are studied and reported for slow to medium speed switching applications(9)(10).

Although, the former utilize out-of-plane, whereas, the latter does in-plane, use of PC structure in the switches remain unclear since standalone Si-waveguides can already confine the light successfully.

In this paper, we theoretically show that by utilizing submicron-Si-waveguides and their mechanical-contact, it is possible to achieve better switching with the actuation provided by an electrostatic comb drive. Fabrication platform is considered to be a silicon-on-insulator wafer for monolithic device integration.

2. Switch Structure and Principle

The switch, as seen in Fig. 1, consists of an input and identical output waveguide, and a movable waveguide driven by a miniature electrostatic comb actuator. When the comb actuator is energized, the movable waveguide closes the air gap between input and output waveguides. Due to the mechanical contact of waveguide tip surfaces, light propagates from the input waveguide to the output waveguide through the movable waveguide. When retracted, light propagation from the input to the output waveguide ends.

3. Theoretical Calculation

Optical requirements from the optical switch for the best possible performance include single-mode light propagation in the submicron-Si-waveguide for less loss and higher controllability, minimum propagation loss towards cladding layers, minimum transmission leak through free-space between input and output waveguides, maximum output signal change between on and off
states, minimum backreflection from the waveguide tips, and minimum leak from the movable waveguide towards the supporting beams at the on state.

In order to satisfy single-mode transverse electric (TE)-like polarized light propagation at 1.55 µm wavelength, Si waveguides are designed as to be 500 nm-wide and 260 nm-thick. TE polarization refers to the state in which electric field of the propagating light is perpendicular to the device layer.

Bottom cladding of the waveguides must at least be 1 µm-thick so as to keep optical propagation loss in the waveguides towards bottom cladding layer less than 0.001 dB/cm\(^{-1}\)). Bottom cladding SiO\(_2\), buried-oxide, layer is designed as 2 µm-thick. Side and upper cladding materials are all air, and upper cladding in the theoretical calculation is considered to be 4 µm-thick.

The scattering loss from Si/SiO\(_2\) waveguide interface sidewalls has already been presented\(^{12}\). Both experimental and theoretical results have shown that propagation loss due to scattering loss through the sidewalls increase with the square of the standard deviation of the sidewall roughness. Hence, during fabrication the most precise etching method and recipe for the switch geometry pattern trench creation should be considered.

Optical property of the switch is studied by three dimensional Finite Difference Time Domain (FDTD) Analysis (OptiFDTD, Optiwave Co.). For reliable calculation, the mesh size must be smaller than one tenth of the smallest feature size in the model, 50 nm in our case. All simulations reported herein are performed using an isotropic mesh size in the range from 22 nm to 30 nm.

TE-like polarized continuous single-mode at 1.55 µm wavelength is defined as the incident light into the input waveguide. Results in OptiFDTD are available in the form of a single precision floating-point numerals represented by four bytes, corresponding to a total of seven decimal digits, composed of two digits before and five digits after the decimal point. For most MEMS switching applications, optical output signal change is up to 60 dB. Therefore, use of at least one digit after the decimal point is necessary. This requirement is satisfied and, indeed, far exceeded by the provided five digits after the decimal point by OptiFDTD.

Effect of contact-tip geometry on optical properties is studied on three different submicron-Si-waveguide contact-tip geometries, as shown in Fig. 2, namely, abrupt, half-tapered with 45\(^{\circ}\) tip angle, and tapered with 26\(^{\circ}\) tip angle geometries. In general, these three are considered as first to be thought among many other possible contact-tip geometries. The tapered geometry has a tip angle of 26\(^{\circ}\) particularly in order to ensure maximum transmission, 96.7\%, at its on state.

First of all, required minimum spacing to be met between the input and output waveguides in order to limit direct free-space transmission leak from the input propagate towards the output waveguide within an acceptable level is considered. The minimum spacing must be satisfied so as to enforce incident light propagate from the input waveguide to the output through the movable waveguide so that switching can be realized. This study is conducted for all contact-tip geometries. Result of the study, as depicted in Fig. 3, reveals that a spacing of 1.6 µm or greater is able to constrain direct free-space transmission leak to within 1 % for all of the studied contact-tip geometries.

Second, for the three tip geometries defined, optical transmission between a single contact-pair is theoretically studied. Owing to cascade double contact-pairs use, the results obtained from the study are squared. Final results are illustrated in Fig. 4. The study indicates that tapered tip geometry depicts the fastest decay in transmission, smallest amount of loss during switching,
Table 1. Evaluation of studied submicron-Si-waveguide contact-tip geometries

<table>
<thead>
<tr>
<th>Contact-tip geometry</th>
<th>Optimum tip angle</th>
<th>Minimum spacing*</th>
<th>Transmission at air gaps &lt; 50 nm</th>
<th>Backreflection at off state</th>
<th>Switching loss</th>
<th>Minimum airgap**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acute</td>
<td>50°</td>
<td>1.6 μm</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>400 nm</td>
</tr>
<tr>
<td>Half-tapered</td>
<td>45°</td>
<td>1.6 μm</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>400 nm</td>
</tr>
<tr>
<td>Tapered</td>
<td>28°</td>
<td>1.6 μm</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>400 nm</td>
</tr>
</tbody>
</table>

* For transmission lost to be less than 1 %
** For off-state transmission to be less than 1 % after cascaded double contact-tip pairs.

Effect of tip angle on transmission and backreflection in half-tapered tip geometry is simulated with 30º, 45º, 60º and 90º tip angles. As seen in Fig. 5, the smaller the tip angle, the narrower evanescent region, thus, the sharper the change in transmission becomes. Nevertheless, when the tip angle is 45º, transmission is highest at air gaps corresponding to surface roughness values, approximately below 40 nm. It is also observed that backreflection at the on state stays in the range from 1.09 % to 1.67 % for studied four tip angles. Therefore, effect of the tip angle on backreflection at on state can be assumed to be negligible.

The theory, as shown in Fig. 5, suggests that with the half-tapered contact-tip geometry at 45º tip angle, by a motion of 400 nm, it is possible to have an approximately 96.8 % output signal transmission change from 97.0 % transmission at on state to 0.2 % that at off state, while backreflection increases from 1.0 % to 20.2 %, respectively.

Since the proposed microswitch structure employs a movable waveguide suspended in air, mechanical support is unavoidable. Therefore, a low loss elliptical intersection reported by Fukazawa et al.(13) is adapted to minimize leak from the movable waveguide towards mechanical supports. The adapted elliptical intersection geometry is as depicted in Fig. 6(a). The field remains as single-mode while the input light experiences mode expansion as the elliptical region enlarges from 500 nm to 1500 nm waveguide-width. Because the field is already expanded in the region, further expansion offered by the 500 nm-wide supporting beams can only attract the field slightly, which, in return, causes low insertion loss. Calculated distribution of electrical field in x direction, E_x, as depicted in Fig. 6(b), confirms already reported results of leak towards supporting beams and backreflection in the elliptical intersection to be approximately 5 % and 1 %, respectively.

4. Imperfect Waveguide-tip Contact Case Studies

Submicron-Si-waveguide contact-tips are only 500 nm-wide. Therefore, in the patterning process, pattern degradation can be expected. Besides, side-instability(14) during actuation tests may also take place. Hence, each waveguide tip, as shown in the inset in Fig. 7, may complete its full stroke in a way that they stay at an off-axis distance from the central axis of both input and output waveguides, or stay perfectly on the axis but have an air gap along the axis among them, or, in general, a combination of both cases.
We have explicitly studied the effect of each so-called off-axis and axial gap on the optical transmission. Figure 7 shows the effect of both off-axis and axial gap cases on the transmission through the switch. As it can be seen in Fig. 7, propagation loss caused by an axial gap is remarkably greater than that by an off-axis case. This particular result, thus, approves the indispensability of the mechanical-contact phenomena even when contact occurs by a distance far from the ideal location.

Once the importance of contact is understood, a more reliable switch can be realized by enlargement of the contact-tip surface areas such that mechanical-contact is enforced even when imperfections exist. Therefore, as illustrated in Fig. 8, three types of modified switch designs are investigated numerically. Modified designs include enlargement of input and output waveguide contact-tip surfaces alone, or enlargement of movable waveguide contact-tip surfaces alone, or enlargement of all contact-tip surfaces.

Figure 9 is a plot of transmission and backreflection results obtained for the three modified design cases. By enlargement of contact-tip surfaces in all three modified designs, once the movable waveguide completes its full stroke and contacts both to the input and output waveguides, possible happening of axial gap is eliminated. All that will be left is contacting waveguides with a distance from the axis, called as the off-axis distance.

As can be seen from Fig. 9, the least imperfection-sensitive design is achieved when all contact-tip surfaces are enlarged. When off-axis distance is zero, the transmission and backreflection are same as those calculated for the ideal case, as depicted in Fig. 5. Out of the ideal case, if off-axis distance is not zero, the larger the off-axis distance, the smaller the transmission and larger the backreflection becomes. For an off-axis distance of ±250 nm, for instance, transmission decreases approximately 30.06 % and backreflection does not show noticeable increase. In case of axial gap with the same size of ±250 nm, transmission would have decreased approximately 85.6 % while backreflection would have increased by 5.2 %, clearly proving an improved design with less fabrication-error sensitivity. In this modified design, however, the need for a larger displacement range is expected to be fulfilled in order to achieve a similar level of output signal change with respect to the previous design without enlarged contact-tip design.

5. Conclusion

In this paper, major optical design requirements of a novel submicron-Si-waveguide mechanical-contact-based optical microswitch are determined and studied with microfabrication considerations. The switch uses a TE-like polarized single-mode light at 1.55 µm telecommunication wavelength as the incident light. Three submicron-Si-waveguide contact-tip geometries are studied and evaluated based on their optical performance. 97.0 % transmission at the on state and 0.2 % transmission at the off state, corresponding to 96.8 % optical output signal change between on and off states, are theoretically achieved by a displacement of 400 nm. Possible fabrication imperfections are estimated and their
effects on the optical performance are calculated. Studies emphasize the importance of mechanical-contact for the success of the optical microswitch. Accordingly, enlargement of all contact-tip surfaces is obtained to be an enhancement factor to the switch’s optical performance in case such imperfections take place.

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References


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