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Thermo-Optic Switch with High Tuning Efficiency Based on Nanobeam Cavity and Hydrogen-Doped Indium Oxide Microheater

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Abstract: We propose and experimentally demonstrate an efficient on-chip thermo-optic (TO) switch based on a photonic crystal nanobeam cavity (PCNC) and a hydrogen-doped indium oxide (IHO) microheater. The small mode volume of the PCNC and the close-range heating through the transparent conductive oxide IHO greatly enhance the coupling between the thermal field and the optical field, increasing the TO tuning efficiency. The experimental results show that the TO tuning efficiency can reach 1.326 nm/mW. And the rise time and fall time are measured to be 3.90 and 2.65 µs, respectively. In addition, compared with the conventional metal microheater, the measured extinction ratios of the switches are close (25.8 dB and 27.6 dB, respectively), indicating that the IHO microheater does not introduce obvious insertion loss. Our demonstration showcases the immense potential of this TO switch as a unit device for on-chip large-scale integrated arrays.

Keywords: silicon photonics; nanobeam cavity; optical switch; hydrogen-doped indium oxide

1. Introduction

With its low power consumption, high integration, and compatibility with complementary metal–oxide–semiconductor (CMOS) processes, silicon photonics provides an ideal platform for on-chip applications [1], such as optical phased array [2–4], quantum information processing [5–7], optical neural networks [8–10], arbitrary waveform generation [11–13], and so on. Thermo-optic (TO) tuning devices have become the indispensable basic unit of these large-scale photonic networks due to their small footprint, simple structure, and low cost. In these devices, TO tuning is typically achieved through metal microheaters, which are usually made of titanium (Ti), chromium (Cr), or alloys. By utilizing the high TO coefficient of silicon (~1.84 × 10⁻⁴ K⁻¹ [14]), different waveguide structures are heated through microheaters to change the refractive index of silicon, thereby achieving the tuning of transmitted light. Therefore, in order to achieve better performance in TO tuning, there are generally two optimization schemes, namely the selection of the microheater material and the design of the waveguide structure. However, to avoid the metal absorption losses, it is usually necessary to add a thick layer of silicon dioxide between the metal microheater and the silicon waveguide as an optical isolation layer, which significantly reduces the TO tuning efficiency and slows down the tuning time due to the low thermal conductivity of silicon dioxide. Two-dimensional materials such as graphene [15,16], phosphorene [17,18], etc., have been proposed to directly cover silicon waveguides for TO tuning, but their complex preparation and transfer processes limit their application in large-scale photonic networks. Transparent conductive oxides such as indium tin oxide [19] and hydrogen-doped indium oxide (IHO) [20], as conductive materials that can be film-grown by magnetron sputtering, have become a new alternative for microheaters. In particular, IHO film, due to its high near-infrared transparency and high conductivity, as well as its...
room-temperature growth, is advantageous for achieving low-loss and high-efficiency TO tuning and large-scale integration on silicon photonics platforms.

When it comes to the design of waveguide structures, so far, Mach–Zehnder interferometers (MZIs) [21–23] and micro-ring resonators (MRRs) [24,25] are commonly used structures for creating TO switches. However, due to the insufficient interaction between light and matter, the tuning efficiency of these devices is limited. Although many studies have used folded waveguide structures [26–28] to increase the coupling length between waveguides and thermal fields to fully utilize heat, the oversized dimensions of individual devices are a burden for large-scale photonic networks. In the photonic crystal nanobeam cavities (PCNCs), photons are strongly confined within a small area, resulting in ultra-small mode volumes, highly enhancing the interaction between light and matter [29,30]. Therefore, compared with previous device structures, a PCNC may be an effective solution for achieving low-power TO switches.

In this paper, we propose and experimentally demonstrate an efficient on-chip TO switch based on a PCNC and an IHO microheater, and demonstrate the use of a conventional metal nickel–chromium (NiCr) alloy microheater as a contrast. The small mode volume of the PCNC and the close-range heating through the IHO microheater greatly enhance the coupling between the thermal field and the optical field. While improving the TO tuning efficiency and increasing the tuning speed, there is no deterioration of the switching extinction ratio (ER) caused by the microheater. The TO tuning efficiency of the switch we proposed is as high as 1.326 nm/mW, which is a 46% improvement compared to the conventional metal NiCr microheater with a tuning efficiency of 0.907 nm/mW. The measured rise time and fall time of the switch we proposed are 3.90 and 2.65 µs, respectively, showing a TO tuning speed that is significantly faster than the conventional metal NiCr microheater with a rise/fall time of 6.75/4.70 µs. The switching ER of the switch we proposed is 25.8 dB, close to the 27.6 dB of the conventional metal NiCr microheater.

2. Methods

A top-view schematic diagram of the proposed PCNC is shown in Figure 1a. The PCNC is formed by a waveguide etched with 40 air holes. These air holes are centrally symmetrically distributed, forming the central gradient region and two side-reflector sections. The 13 holes in each side-reflector section are designed the same, forming a strong photonic bandgap that confines the resonant light to the central gradient region. The central gradient region is optimized to reduce the scattering loss from reflections and to provide high phase matching between the PCNC mode and the strip waveguide mode. To achieve a relatively large ER, the widths of the nanobeam waveguide and the coupled waveguide are optimized to be 500 and 380 nm, respectively. The minimum gap between them is 225 nm. Figure 1b shows the simulated electric field distribution of the PCNC structure at the resonant wavelength based on the finite difference time domain (FDTD) method. It can be seen that the optical power is mainly distributed in the ultra-small area of the 14 holes in the central gradient region, and the effective length of the TO tuning is only ~4 µm. Figure 1c presents a scanning electron microscope (SEM) image of the coupled waveguide and the central gradient region of the PCNC. Figure 1d shows the cross-sectional diagrams of a TO switch with a conventional metal microheater and a TO switch with an IHO microheater for comparison. In our design, a 100 nm thick NiCr alloy is used as a representative of the conventional metal microheater, with a 1 µm thick silicon dioxide layer as an isolation layer to avoid optical loss caused by metal absorption. The thickness of the IHO microheater is 70 nm, and due to the high near-infrared transmittance of the IHO film, the absorption loss caused by the IHO film is very low [20]. Therefore, we greatly reduce the thickness of the silicon dioxide isolation layer to 200 nm to improve the efficiency and rate of heat conduction, at the same time avoiding affecting the optical resonance in the PCNC.
Figure 1. (a) Schematic diagram of the PCNC. (b) Simulated electric field distribution of the PCNC at the resonance wavelength. (c) SEM image of the PCNC. (d) Simplified cross-sectional diagram of the TO switches (not to scale). WG—waveguide. H = 1 µm; h = 200 nm.

Figure 2a,b present the microscope images of the TO switches with the NiCr micro-heater and the IHO microheater, respectively. Since they are all fabricated on a silicon-on-insulator (SOI) chip with a top silicon thickness of 220 nm, the 200 nm thick silicon dioxide isolation layer under the IHO microheater is achieved by locally etching 800 nm deep after growing a 1 µm thick silicon dioxide layer on the entire chip. Thus, Figure 2b shows an additional rectangular window of a different color in the coupling region compared to Figure 2a, and it can also be seen that the gold pad in the inset clearly passes through a stepped structure. Then, the IHO microheater is patterned on the PCNC through ultraviolet lithography and the magnetron sputtering process. The dimensions of the IHO microheater and the NiCr microheater are the same. The part covering the PCNC is a rectangle with a length of 22 µm and a width of 2.6 µm. On both sides are rectangles with a length of 4 µm and a width of 6 µm, increasing the contact area with the gold pads.
1.326 nm/mW. Compared to conventional metal microheaters, the IHO microheater has a wavelength of 1551.49 nm (corresponding to the resonant wavelength of PCNC at 0 mW). The duty cycle of the modulation signal is 50%, the frequency is 50 kHz, and the power of 5.60 mW (corresponding to an applied voltage of 1.0 V). Figure 3b shows a linear fit of the redshift of the resonant wavelength and the applied power. It can be seen that the TO tuning efficiency of the PCNC with the NiCr microheater can reach 0.907 nm/mW. Figure 3c presents the measured transmission spectra when different driving powers are applied to the NiCr microheater. The measured transmission spectra are normalized to the reference strip waveguide to exclude the coupling loss of the grating couplers. The spectra in Figure 3a indicate that the resonance wavelength has a significant red shift by 5.09 nm under the applied power of 5.60 mW (corresponding to an applied voltage of 1.0 V). Figure 3b shows a linear fit of the redshift of the resonant wavelength and the applied power. It can be seen that the TO tuning efficiency of the PCNC with the NiCr microheater can reach 0.907 nm/mW. Figure 3c presents the measured transmission spectra when different driving powers are applied to the IHO microheater. The resonance wavelength can reach a redshift of 4.00 nm at an applied power of 2.86 mW (corresponding to an applied voltage of 2.6 V). Figure 3d shows that the TO tuning efficiency of the PCNC with the IHO microheater can reach 1.326 nm/mW. Compared to conventional metal microheaters, the IHO microheater has a 46% improved TO tuning efficiency, due to the fact that it reduces the thickness of the silicon dioxide isolation layer.

Then, we replace the input light source from the ASE source to a tunable laser (Alnair Labs, TLG-200), replace the DC power supply with an arbitrary waveform generator (AWG, RIGOL, DG4202), and convert the modulated light output from the chip into electrical signal through a photodiode (Discovery, DSC40S), which is received by an oscilloscope (RIGOL, DG4022). We measured the dynamic response performance of the TO switches. Figure 4a presents the switching state of the TO switch with the NiCr microheater at a wavelength of 1551.49 nm (corresponding to the resonant wavelength of PCNC at 0 mW heating power in Figure 3a). The switching ER reached 27.6 dB and the corresponding switching voltage is 1.0 V. As shown in Figure 4b, we measured the response time of the TO switch with the NiCr microheater by applying a square wave modulation signal through AWG. The duty cycle of the modulation signal is 50%, the frequency is 50 kHz, and the amplitude is 1.0 V. The measured rise time from 10% to 90% of the response signal is 6.75 µs, and the fall time from 90% to 10% is 4.70 µs. Figure 4c presents the switching state of the TO switch with the IHO microheater at a wavelength of 1550.97 nm (corresponding to the resonant wavelength of PCNC at 0 mW heating power in Figure 3c), which shows a
switching ER of 25.8 dB and a switching voltage of 2.6 V. Similarly, as shown in Figure 4d, we experimentally measured a rise time of 3.90 µs and a fall time of 2.65 µs through a square wave modulation signal with an amplitude of 2.6 V. As a comparison, under a 50 kHz square wave modulation signal, the output signal waveform of the TO switch with the conventional metal NiCr microheater deforms into a triangle wave, while the output of the TO switch with the IHO microheater is still an edge-smoothed square. This indicates that the IHO microheater, by reducing the thickness of the silicon dioxide isolation layer, can effectively improve the response speed and the 3 dB bandwidth of the device.

Figure 3. (a,b) Transmission spectra and resonance shifts of the TO switch with the NiCr microheater for different heating powers. (c,d) Transmission spectra and resonance shifts of the TO switch with the IHO microheater for different heating powers.

Figure 4. (a,b) The ON/OFF states and the dynamic response of the TO switch with the NiCr microheater. (c,d) The ON/OFF states and the dynamic response of the TO switch with the IHO microheater.
4. Discussion

Table 1 lists the performance summary of previously reported on-chip TO switches based on different structures and microheaters, providing a comparison of the presented devices with the state-of-the-art work. None of the schemes listed in the table use a complicated undercut process. Our work combines IHO thin film materials with PCNC structures for the first time. The TO switch based on PCNCs and IHO microheaters that we proposed exhibits a switching power of 2.86 mW, a TO tuning efficiency of 1.326 nm/mW, a switching ER of 25.8 dB, and a response time of 3.90/2.65 μs. It can be seen that compared to the MZI [16,20,21] and the MRR [15,24,25] structure, the PCNC structure can significantly improve the TO tuning efficiency. In particular, compared with the MRR structure, the PCNC structure with the NiCr microheater can increase the TO tuning efficiency by 8 folds, and even by 12 folds when the microheater is replaced by an IHO microheater. In contrast to the research into the graphene microheater in the table [15,16,29], the excess loss caused by the transfer process of graphene will significantly reduce the ER of the devices, typically deteriorating from 20–30 dB to below 10 dB, while the IHO microheater does not have such a problem. The ER of the devices before and after covering the IHO will not change significantly, in a similar manner to conventional metal microheaters. Compared with the research based on PCNCs in recent years [29,30], our switching ER shows a significant advantage compared to the work using the graphene microheater, and our TO tuning efficiency and switching ER are both superior to the work using the Ti microheater. Therefore, given the high TO tuning efficiency, high ER, and high response rate of the TO switch based on PCNCs and the IHO microheater, it is expected to replace structures such as MRR as the fundamental building block of on-chip large-scale optical networks in future research.

Table 1. Comparison of TO switches with different structures and different microheaters.

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<tbody>
<tr>
<td>MZI</td>
<td>PhCW a + graphene</td>
<td>[16]</td>
<td>3.99</td>
<td>1.07</td>
<td>~8</td>
<td>0.750/0.525</td>
<td>2017</td>
</tr>
<tr>
<td></td>
<td>strip WG + IHO</td>
<td>[20]</td>
<td>9.6</td>
<td>0.0472</td>
<td>~20</td>
<td>0.970/0.980</td>
<td>2023</td>
</tr>
<tr>
<td></td>
<td>adiabatic bend + doped silicon</td>
<td>[21]</td>
<td>12.7</td>
<td>\</td>
<td>~25</td>
<td>1.2/2.4</td>
<td>2013</td>
</tr>
<tr>
<td>MRR</td>
<td>rib WG + graphene</td>
<td>[15]</td>
<td>28</td>
<td>0.104</td>
<td>7</td>
<td>0.700/0.800</td>
<td>2015</td>
</tr>
<tr>
<td></td>
<td>rib WG + doped silicon</td>
<td>[24]</td>
<td>3.33</td>
<td>0.1</td>
<td>~8</td>
<td>3.56/3.70</td>
<td>2021</td>
</tr>
<tr>
<td></td>
<td>strip WG + MoS\textsubscript{2}</td>
<td>[25]</td>
<td>7.5</td>
<td>0.1</td>
<td>~25</td>
<td>26/24</td>
<td>2023</td>
</tr>
<tr>
<td>PCNC</td>
<td>strip WG + graphene</td>
<td>[29]</td>
<td>\</td>
<td>1.5</td>
<td>8</td>
<td>1.11/1.47</td>
<td>2017</td>
</tr>
<tr>
<td></td>
<td>strip WG + Ti</td>
<td>[30]</td>
<td>0.16</td>
<td>1.23</td>
<td>15</td>
<td>3.1/4.5</td>
<td>2017</td>
</tr>
<tr>
<td></td>
<td>strip WG + TiCr</td>
<td>this work</td>
<td>5.60</td>
<td>0.907</td>
<td>27.6</td>
<td>6.75/4.70</td>
<td>2017</td>
</tr>
<tr>
<td></td>
<td>strip WG + IHO</td>
<td>this work</td>
<td>2.86</td>
<td>1.326</td>
<td>25.8</td>
<td>3.90/2.65</td>
<td>2017</td>
</tr>
</tbody>
</table>

a PhCW—photonic crystal waveguide.

5. Conclusions

In conclusion, we experimentally demonstrate an on-chip thermo-optic switch based on a PCNC structure and an IHO microheater. It exhibits a high TO tuning efficiency of 1.326 nm/mW, with a rise and fall time of 3.90 and 2.65 μs, respectively. Compared with the conventional MRR structures and metal microheaters, its TO tuning efficiency is significantly improved, demonstrating its enormous potential as a unit device for on-chip large-scale integrated arrays.

Author Contributions: Data curation, W.T.; funding acquisition, J.D. and B.H.; methodology, W.T., J.Z. and S.L.; writing—original draft preparation, W.T.; writing—review and editing, S.L., J.D., B.H. and X.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Science Foundation of China (U21A20511, 52192612, 62274071).

Institutional Review Board Statement: Not applicable.
Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

References


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