A micromachined optical double well for thermo-optic switching via resonant tunneling effect

W. M. Zhu,1 X. M. Zhang,2 A. Q. Liu,1,a H. Cai,1 T. Jonathan,1 and T. Bourouina3
1School of Electrical and Electronic Engineering Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore
2Department of Mechanical Engineering, University of Maryland 2181 Martin Hall, College Park, Maryland 20742, USA
3Ecole Superieure d’ Ingenieurs en Electrotechnique et Electronique, School of Electrical and Electronic Engineering, 11 Science Park Road, 93162, Noisy-le-Grand Cedex, France

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This letter presents the thermo-optic switching characteristics of an optical double-well structure, which has a high-low-high refractive index construct formed by micromachined silicon prisms and air gaps. Analysis shows such structure features full transmission (i.e., on state) and requires low refractive index change for switching function. The device is fabricated on silicon-on-isolator wafer using deep etching process. In experiment, it measures a switching speed of 1 µs and an extinction ratio of 30 dB. Compared with the other micromachined switches, this device utilizes different physical principle and processes various merits such as fast switching speed and low power consumption. © 2008 American Institute of Physics. [DOI: 10.1063/1.2951621]

As an enabler of the optical networks, optical switch has attracted extensive interests of research and development. However, most of the available switches are based on the conventional methods such as free-space mirror reflection, waveguide interconnection, and some nonlinear effects.1,2 In a continuous effort in exploring the potential of the optical tunneling effect for switching function, we have demonstrated the thermo-optic switches using simple optical barrier structures.3–5 In this letter, we will investigate the resonant tunneling effect in the optical double-well structure (ODWS) and will further demonstrate the switching function using silicon micromachined devices.

Optical tunneling effect refers to the penetration of lightwave (or photons) through classically impenetrable barriers, which is an analogy of the quantum tunneling effect for the electrons to go through the quantum barriers.6,7 The application of single barrier structures to optical switching has been demonstrated in the x-cross switches8 and our previous work on micromachined switch.3,4 It requires a refractive index change Δn on order of 0.02 and a temperature change ΔT at the level of 100 °C for switching the transverse electric light. An improved optical barrier structure can be constructed by a three-layer construct with high/low/high refractive indices (named as the single well structure hereafter). It is the same as the frustrated (or attenuated) total internal reflection effect and has long been studied theoretically and experimentally for understanding the physical properties of electron tunneling such as spatial shift and time delay.3 In our recent work, the single well structure has been demonstrated for optical switching, which requires Δn of ~0.01 and a temperature change ΔT of ~50 °C for switching the TE light.5 Both the single barrier structure and the single well structure require considerable refractive index change of 0.01–0.02 and work only for the TE incidence. For transverse magnetic light (TM) polarized light, the required changes are about ten times larger and thus become impractical. To tackle these problems, a direct solution is to cascade two optical wells to form a resonant cavity for the tunneled waves, such as the quantum double wells for the electrons or the Fabry–Pérot cavity for the propagating lightwaves.9–12

The resonant optical tunneling effect not only improves the sensitivity but also works for both the TE and TM. A few studies have already verified this idea using the deposited multilayered GaAs/AlGaAs structures.11,12 We adopt a different approach to utilize the silicon and air as the high and low index materials and to switch the lightwave by thermo-optic effect of the central silicon layer. Our analysis shows that a refractive index change of 0.001 is large enough for switching both the TE and TM, ten times more sensitive than the previous work.3,5 The presence of the air gaps facilitates the fine position adjustment of silicon layers to accommodate the environment changes, and the thermo-optic switching ensures a fast switching speed.

The design and switching process of the thermo-optic switch is illustrated in Fig. 1. The double-well structure is consist of two hemicylindrical silicon prisms, two air gaps, and a silicon rib, and maintains symmetry in the horizontal direction, as shown in Fig. 1. The air gaps function as two optical wells as the refractive index of air is smaller than that of silicon. The corresponding optical potential diagrams are shown in Fig. 1. The rib region acts as a resonant cavity between the two optical wells. The resonance condition is highly dependent on the optical path length L=ng, where n is the refractive index of the rib and g is the physical length of the rib. A microheater is deposited on top of the rib region for adjusting the refractive index of the rib. In the initial state [Fig. 1(a)], the transmission reaches its maximum by choosing the proper parameters, corresponding to the off state. The switching process is achieved by heating up the rib region. The increase of the rib’s refractive index breaks the resonance condition and thus shut off the light transmission of the outputs [Fig. 1(b)], corresponding to the on state. The choice of the cylindrical shape of the prisms is for collimating the Gaussian waveform from the input fiber to the approximate plane waveform and converts the tunneled plane...
waveform into the output fiber as detailed in our previous work.5

To obtain a maximum transmission for the initial state, it is necessary to choose the proper parameters. Due to the symmetry, the double-well construct in Fig. 1 has only three independent parameters for setting the initial operation condition, i.e., the incident angle $\theta$, the normalized air gap width $d/\lambda$ and the normalized rib width $g/\lambda$. The wavelength $\lambda$ is not an independent variable since it can be normalized into $d$ and $g$. Due to the use of silicon material, the refractive index $n$ of the prisms and the rib is also fixed (here $n=3.42$ for silicon). As the transfer matrix method has been proven effective in studying the multilayered structures,13 it is adopted to analyze the double-well construct.11 Following this method, the characteristic matrix $M_{DW}$ of the ODWS can be expressed as

$$M_{DW} = M_{SW}NM_{SW} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix},$$

where $M_{SW}$ and $N$ are the characteristic matrices of the single well and the rib region, respectively. Then the reflection and transmission can be determined from the matrix elements $m_{ij}$ ($i,j=1$ or 2).13 In this paper, the incident angle $\theta$ is chosen to be $18^\circ$, greater than the critical angle $17^\circ$. So the transmission is only dependent on $d/\lambda$ and $g/\lambda$. Figure 2 shows the contour map for the TE wave. The bright region represents high transmission while the dark part means low transmission. It can be observed that a sharp peak appears in between $g/\lambda=11.54–11.56$ when it has $d/\lambda > 0.4$. Moreover, the peak narrows down with the increase of $d/\lambda$. The inset figure shows a larger range of the rib width. The peaks appear periodically with respect to the change of the rib width. This periodicity provides evidence on the existence of resonance between optical wells. The sharpness of the peaks implies that the transmission is very sensitive to the rib width change. Moreover, it should be equally sensitive to the rib’s refractive index change since the rib width and refractive index have the same contribution to the optical path length. This is the physical mechanism that facilitates the thermo-optic switching by heating up the rib. Based on the numerical analysis using Eq. (1), the designed parameters are chosen to be $g/\lambda=11.55$ and $d/\lambda=1.5$ which ensure the high transmission (ideally larger than 99%) in the initial state and low refractive index change ($\Delta n = 2.57 \times 10^{-4}$) required by the switching process. For $\lambda=1550$ nm, there are $g=17.9$ $\mu$m and $d=2.3$ $\mu$m.

After the design, the device is fabricated by deep reactive ion etching on a silicon-on-insulator wafer, which has a 75 $\mu$m structural layer bonded on a handling wafer through a 2 $\mu$m oxide layer. The overview of the fabricated thermo-optic switch is shown in Fig. 3 after the integration of three single mode fibers (one for input, one for reflection, and another for transmission). Each of the two silicon prisms is supported by a bidirectional actuator. The core part of the switch is within a footprint of $400 \times 400$ $\mu$m$^2$. The micro-heater is formed by patterning a serpentine-shaped aluminum wire (0.2 $\mu$m thick) on top of the rib. The fiber grooves are etched to ensure the incident angle of $18^\circ$. The bidirectional actuator provides a maximum displacement of 5 $\mu$m in any direction under a driving potential of 6.8 V. The air gaps between the rib and prisms can be finely adjusted by the tuning the driving voltage of the actuator for optimizing the initial working condition.

As there are always fabrication errors, the maximum transmission may not occur at the designed 1550 nm. Therefore the first step of experiment is to measure the transmission spectrum of the device. The result is shown in Fig. 4.
At room temperature, the peak transmission occurs at 1548.7 nm with a bandwidth of 0.8 nm. Correspondingly, the $Q$ factor is around $2 \times 10^3$. For comparison, the simulation result is also plotted in Fig. 4, which has a narrower bandwidth with the $Q$ factor on order of $10^4$. The discrepancy is mainly due to the lack of collimation in the vertical direction of the ODWS structure. When the rib region is heated up, the transmission spectrum would be changed. The inset of Fig. 4 shows that the peak wavelength is shifted by 2 nm when the microheater is under a static driving current of 75 mA.

The static and dynamic switching characteristics are plotted in Fig. 5. The optical power is normalized with respect to the maximum output power. The incident light is from a laser light source (Ando AQ4321D) with an input power of 0 dBm. The wavelength follows the peak wavelength of the transmission spectrum as measured above. A polarization controller is used to maintain the TE polarization. The electrical current generated by a source measurement unit is applied to the microheater via microprobes. Here the electric current is chosen as the control parameter because the actual temperature and refractive index change cannot be measured directly during the experiment. With the gradual increase of the heating current, the output power dropped dramatically, as shown in inset of Fig. 5. The measured extinction ratio is 31.7 dB, which roughly matches the predicted value of 35 dB given by the simulation. The dynamic switching process is shown in Fig. 5. Here a square voltage pulse of 10 V (duration 1 $\mu$s) from a waveform generator (HP 33120A) is applied to the microheater. The switching process is monitored by an oscilloscope (TDS360). The response time (on to off state) is measured to be 1 $\mu$s, which is the same as the duration of the driven signal. This suggests that the response time could be further decreased by a shorter driven voltage pulse. However the relaxation time (25 $\mu$s) of the optical switch is much longer than the response time due to the slow heat dissipation.

In conclusion, this work has demonstrated a fast thermo-optic switching process by the resonant tunneling effect of a silicon micromachined ODWS. In the static and dynamic experiment, the extinction ratio of larger than 30 dB and the switching speed of 1 $\mu$s are achieved. This thermo-optic switch design not only inherits the merits of the micromachining such as compact footprint, fine tuning structures, and easy integration with the external fiber optics but also distinguishes itself by its fast switching speed, low power consumption, and in-plane light modulation.

References: