Micromachined optical well structure for thermo-optic switching

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(Received 26 August 2007; accepted 4 October 2007; published online 28 December 2007)

This letter demonstrates the thermo-optic switching function using an adjustable optical well structure, which is constructed by a thin air gap sandwiched between two micromachined hemicylindrical prisms. The device is etched on a silicon-on-insulator wafer within a footprint of $400 \times 400 \, \mu m^2$. In experiment, it measures an extinction ratio of 30.2 dB and a switching time of 2.2 $\mu s$. Compared with the other demonstrated switches that have optical barrier structures, this device is unique in the working principle and optical design, and shows various merits such as high extinction ratio, fast speed, low power consumption, and small size. © 2007 American Institute of Physics. [DOI: 10.1063/1.2825578]

Optical well structure refers to a thin layer of lower refractive index (RI) material sandwiched between two thick layers of higher RI materials, as shown in Fig. 1(a). Transmission of light is forbidden if the incident light hits the lower RI layer at an angle larger than the critical angle. To photons, such structure functions as an optical well (or optical wall), like the quantum well to the electrons. As seen in Fig. 1(a), the optical well has finite width in the central part (corresponding to the lower RI layer) and is extended infinitely to both sides (corresponding to the higher RI layers). In this simple structure, the barrier phenomenon can be easily understood by the total internal reflection (TIR) effect based on geometric optics. However, the quantum mechanical explanation presents a different angle and more importantly, it can treat more complicated cases such as two (or multiple) optical wells and the optical tunneling effect since there are many established analyses in the electron tunneling. Optical well structure has attracted broad interest for studying the fundamental physical property such as tunneling time and phase delay, but its application has not been equally emphasized. Similar idea has been found in the x-cross waveguide switches and the prism switches. The x-cross waveguide has two inputs and two outputs meeting up at an intersection region. The light is switched by heating half of the intersection region to reach the TIR state. In our previous study, a triangular silicon prism is used to switch the light at the silicon-air interface by heating up or cooling down the entire piece of prism. These two types of switches have higher RI on one side and lower RI on the other side, as illustrated in Fig. 1(b). The quantum equivalence is an optical barrier (like a step function) that extends infinitely to both sides. It can be observed straightforwardly from Fig. 1 that the main difference between the optical well and the optical barrier is that the former supports resonance in the well while the latter does not. For the switching function, the resonance is preferable since it improves the selectivity of light and thus the sensitivity to the RI change.

The design and working principle are illustrated in Fig. 2. The switch consists of a thin air gap sandwiched by two identical silicon hemicylindrical prisms (called double prisms hereafter), as shown in Fig. 2(a). This silicon-air-silicon structure functions effectively as an optical well, as illustrated in Fig. 2(c). In the initial state, the input light is chosen to make a subcritical angle $\phi_0$ (slightly less than the critical angle $\phi_c$) at the interface between the first prism and the air gap. This interface is named as the first prism-air interface hereafter. The light then penetrates the air gap into the second prism and eventually forms the output, corresponding to the on state. The corresponding quantum picture is illustrated in Fig. 2(c), the optical well has an equivalent potential $V_0=-n_2^2k_0^2$ while the incoming photon has an equivalent energy $E=-n_1^2k_0^2\sin^2 \phi_0$ by analogy to the quantum well. Here, $n_1$ and $n_2$ are the refractive indices of the first prism and the air, respectively, and $k_0$ is the wavenumber. Under the condition $\phi_0<\phi_c=\arcsin(n_2/n_1)$, the photon energy is higher than the barrier potential and thus can be transmitted. To realize the switching, a microheater patterned on top of the first prism is used to heat up a small part of the

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first prism sidewall where the light passes through (named as the working region), as shown in Fig. 2(b). Due to the thermo-optic effect, the RI of the work region is increased from \( n_1 \) to \( n_1 + \Delta n \). As a result, the photon energy is reduced to be \( E = (n_1 + \Delta n)^2 k_0^2 \sin^2 \theta \) and becomes smaller than the barrier potential, as shown in Fig. 2(d). Consequently, the incoming photons are reflected back by the optical well and leave nearly zero power to the output, corresponding to the off state.

In this design, the hemicylindrical shape of the prism plays important role to the switching performance. With proper parameters, the hemicylindrical prism can act as a focus lens in the horizontal plane to collimate the light from input fiber to an exactly plane wave when hitting the working region. This avoids the divergence of the light beam to cause power leakage from one state to the other (i.e., cross-talk), and thus ensures the desired abrupt power change during the switching (i.e., high extinction ratio and high isolation). In addition, due to structural symmetry, the double prisms focus the input light into the output fiber, resulting in a minimized coupling loss. These features are clear advantages of this design in comparison to the fixed x-cross switches and the triangular-prism switches.

In the on state, the optical well acts as a Fabry-Pérot resonant cavity. The transmission \( T \) can be expressed as

\[
T = 1 - |r|^2
\]

and

\[
r = \sum r_i = \frac{r_1 + r_3 e^{i\delta}}{1 + r_1 r_3 e^{i\delta}},
\]

where \( r \) is a complex representing the total reflected light field, \( r_1 \) and \( r_3 \) are the Fresnel reflection coefficients of the first prism-air interface and the second prism-air interface, respectively. The variable \( \delta = 4 \pi n_i d \cos \phi_2 / \lambda \) is the phase difference between consecutively reflected waves, \( d \) the width of air gap (i.e., the width of optical well), \( \phi_2 \) the refractive angle in the air gap, and \( \lambda \) the wavelength. The design parameters are \( n_i = 3.42 \) for the silicon material at \( \lambda = 1550 \text{ nm} \) and \( d / \lambda = 1.6 \). The switching states can be chosen based on Eq. (1). In the initial on state, the incident light is 0.10° below the critical angle (here, \( \phi_c = 17.0° \)). To reach the off state with a targeted extinction ratio of 25 dB, the RI is required to rise by \( \Delta n = 0.0076 \), corresponding to a temperature increase \( \Delta T = 35.4 \text{ K} \). Only s polarization is taken into consideration in this letter.

Figure 3 shows the design of MEMS structure for fine tuning. The first prism is supported by two flexures, each has a bidirectional parallel-plate actuator at every end. The rotation and translation of the first prism can be realized as shown in Figs. 3(a) and 3(b). The second prism is supported by a bistable beam and is designed to have a large separation from the first prism. The wide gap ensures a moderate etching rate and a good surface quality for the dry etching process, especially when the depth of prism is quite large (~75 μm). After fabrication, the second prism is flipped over to the first prism by pushing it using a probe [indicated by the force \( F \) in Fig. 3(a)]. In this way, a thin air gap of about one wavelength wide could be obtained. Various terminologies labeled in Fig. 3 are defined and designed as: \( l_0 = 374 \mu m \) for the length from the prism to the edge of the parallel-plate capacitance actuator, \( O \) the center of the prism, \( \rho = 176 \mu m \) for the hemicylindrical prism radius, and \( d_0 = 2.5 \mu m \) for the initial air gap (close to the standard of \( d / \lambda = 1.6 \)). The parallel-plate actuator aims at providing a displacement \( \Delta d \) of ±5 μm and consequently can rotate the first prism over \( \Delta \phi = \pm 0.2° \) in a controllable manner. The incident light has a Gaussian waist radius \( w_0 = 5.4 \mu m \). The fiber ends of the input and output are positioned away from the prism surfaces by an object distance \( s = 60 \mu m \). With these parameters, the Gaussian beam from the input fiber will be collimated to the working region by the hemicylindrical prisms.

The scanning electron micrograph of the overview of an integrated optical well device is shown in Fig. 4. The device consists of two silicon prisms, two bidirectional actuators, and four single mode fibers (one for input, one for reflection, one for transmission, and the additional one for alignment monitoring). The core part is within a footprint of \( 400 \times 400 \mu m^2 \). The MEMS structures are fabricated by deep
reactive ion etching on a silicon-on-insulator wafer, which has a 75 μm structural layer bonded on a 675-μm handling wafer through a 2 μm oxide layer. The microheater is formed by patterning a deposited aluminum layer (0.2 μm thick) into a serpentine shape. The large prisms are released by etching the handling wafer from the back side.

The static transmitted output as a function of the dc electrical heating power is plotted in Fig. 5(a). The optical power is normalized with respect to the input power. The incident light is at wavelength of 1550 nm from a laser light source (Ando AQ4321D) with an input power of 0 dBm. A polarization controller is used to adjust the input light to the s polarization. Following the design parameters, the incident angle is adjusted to be 0.1° below the critical angle. Further more, the air gap is adjusted to 1.6 μm. A dc current from a source measurement unit is applied to the microheater. As the local temperature and RI change are not easy to monitor directly in experiment, the electrical power is used as the control parameter. When no electrical current is applied, the transmission is at its maximum of −9.5 dB, representing the on state. With the increase of electrical heating power, the transmitted power decreases quickly. At the level of 119.2 mW, the optical output is dropped to only −39.7 dB, corresponding to the off state. The extinction ratio is 30.2 dB, larger than the initial target of 25 dB. The simulated curve in Fig. 5(a) is calculated by finite element method. It matches reasonably with the experimental curve except for the last part that has higher heating powers (>100 mW).

The measured dynamic switching is shown in Fig. 5(b). Here, a square current pulse of 1.8 mA (duration 2 μs) is used to drive the device. The rise and fall times are measured as 10–90% power transitions. The electrical pulse is also plotted in the same figure just for showing the time relationship. The fall time (on to off state) is measured to be 2.2 μs, and the rise time (off to on state) is 22.9 μs. The rise time is significantly larger than the fall time by approximately ten times. This phenomenon is due to the slow heat dissipation process in the bulky silicon in the absence of a heat sink.

In conclusion, this work utilizes an optical well structure to realize a sensitive thermo-optic switching through localized heating. In the static characterization, the device measures an extinction ratio of 30.2 dB under a heating power of 119.2 mW. The switch shows a fall time of 2.2 μs and a rise time of 22.9 μs when driven by a short current pulse. The device is advantageous over the previous optical-barrier-based switches in terms of high extinction ratio, low temperature change, high speed, and small size, making it promising for optical interconnecting in future optical networks.