Light switching via thermo-optic effect of micromachined silicon prism

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This letter presents an optical switch using total internal reflection (TIR) via thermo-optic effect (TOE). The switching function is obtained by changing the refractive index of silicon prism via TOE to switch the light across the TIR state. The structure is fabricated by microelectromechanical systems technology. The switch measures a cross talk of $>30$ dB and an extinction ratio of $>40$ dB but exhibits high insertion losses of 31.67 and 18.95 dB in the TIR and transmission states, respectively. Compared with conventional micromechanical and light-tuned switches, this switch is unique in mechanism and free of mechanical instability. © 2006 American Institute of Physics.

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Miniaturized optical switch is widely used in network for routing, protecting, and switching the optical signal on physical layer.1 Therefore, various types of optical switches, as a major subgroup of microelectromechanical systems (MEMS) family, have attracted lots of interests of research.2–5 However, they are mostly based on mechanical movement of micromirrors, suffering from the problem of mechanical reliability and repeatability. Light-tuned optical switches have also been developed using the intensity-dependent nonlinear optic effects (such as two-photon absorption, Kerr effect, and cross phase modulation) to realize ultrafast switching,6–10 but the needs of high pumping power and costly short-pulse laser systems may limit their applications in optical networks. Based on these considerations, this letter presents an optical switch using a different mechanism to switch the incident light by total internal reflection (TIR).

In this switch, a silicon micromachined prism acts as the switching medium, while the thermo-optic effect (TOE) of silicon material is used to switch the light across the TIR state. As the TIR angle is sensitive to the refractive index change, a small amount of temperature change will be able to switch the light with high contrast. In the following parts, the design and simulation will be initially elaborated in terms of TOE of silicon and the prism parameters, followed by a brief description of the fabrication process. Finally, the experimental results will be presented and discussed.

The working principle of the proposed optical switch is illustrated in Fig. 1. In one state, the normally incident light is totally reflected to Output 1 [see Fig. 1(a)]. In the other state, the incident light passes through the prism to Output 2 [see Fig. 1(b)] by adjusting the refractive index of the prism across the critical TIR angle. To realize the switching function, two design issues should be addressed, i.e., the initial incident angle and the TOE of silicon material.

Assuming that the input light is normally incident onto the first surface of the prism and forms an incident angle $\alpha$ at the second interface, the refractive angle $\theta$ can be expressed as $n_0 \sin \alpha = n \sin \theta$,11 where $n_0$ and $n$ are the refractive indices of air and prism, respectively. In the condition of $\alpha > \alpha_c = \arcsin(n_0/n)$, the incident light is totally reflected to Output 1, corresponding to the TIR state. Otherwise, it is refracted out of the second interface to Output 2 (i.e., the transmission state). Here $\alpha_c$ is the critical angle. At room temperature and 1550 nm wavelength, $n=3.42$ (Ref. 12) and $n_0=1.0$, thus $\alpha_c=17.0^\circ$. The TOE of silicon material is given by the single oscillator model as $dn/dT=1.8 \times 10^{-4} + 3.47 \times 10^{-7} T - 1.98 \times 10^{-7} T^2(K^{-1})$.13

When the TOE is used to adjust the light to the critical TIR state, the required temperature change and refractive index change are theoretically analyzed for different original incident angles as shown in Fig. 2. It can be seen that the required temperature and refractive index changes are increased when the incident angle is away from the critical angle of 17.0°. For example, an angle discrepancy of 0.1° requires the changes of 109.1 K and 0.02 in temperature and refractive index, respectively. It is also observed that the two curves maintain good linearity when the original incident angle is changed over the range of 16.6°–17.4°.

This optical switch is fabricated by deep reactive ion etching (DRIE) process.14 The scanning electron micrographs are shown in Fig. 3, where (a) is the packaged device consisting of a silicon prism, three optic fibers, two rotational thermal actuators, and a high reflection mirror (to change the direction of the transmitted light for easily positioning Output 2), while (b) is the close-up view of the prism.

This optical switch is experimentally investigated at a wavelength of 1550 nm provided by a laser light source at a power of 4 dBm. Two photodetectors are employed to detect...
the powers at the two outputs. For temperature control, a
thermoelectric cooler (TEC) is stuck beneath the optical
switch by a thermal conductive tape. An infrared camera
(Hamamatsu C5332) is used to visualize the infrared power
distribution.

To realize the switching function, the optical switch can
be initially set at the TIR state and is then cooled down to
the transmission state, or initially at the transmission state
and then is heated up to the TIR state. In experiment, the former
is adopted. The bidirectional rotational actuator facilitates the
selection of the initial state simply by rotating the prism
relative to the fibers. As an experimental result, Fig. 4 shows
the snapshots of the switching from the initial TIR state to
the transmission state. At room temperature, when the inci-
dent angle is just over the critical angle, the incident light is
totally reflected to Output 1 as shown in Fig. 4a. The
switching is then obtained by reducing the prism temperature
in order to decrease the refractive index. The light is trans-
mitted through the prism to Output 2, obtaining the transmis-
sion state as shown in Fig. 4b. It can be observed that some
residual reflection is presented in Output 1 due to the Fresnel
reflection at the second interface.

The optical powers of the two outputs are detected as the
function of prism temperature as shown in Fig. 5. At room
temperature, the reflected power at Output 1 is −27.67 dBm
(insertion loss of 31.67 dB), while the received power at
Output 2 is negligibly small. The prism is then cooled down
to 10 °C. The power at Output 1 is decreased dramatically to
only −43.01 dBm while the power at Output 2 rises from
nearly no power to −14.95 dBm (insertion loss of 18.95 dB).
The switching from Output 1 to Output 2 has thus been achieved.

When the temperature is returned to room temperature,
the power at Output 1 does not rise as much as expected. It is
increased from −43.01 to only −33.01 dBm after keeping at
room temperature for 20 min. However, further heating up to
higher temperature (78.6 °C in this experiment) makes the
TIR coupling power rise back to −27.67 dBm. This power
remains unchanged even though the temperature of the
sample is later returned to room temperature, at which the
incident signal should be totally reflected. It shows that the
switching from Output 2 to Output 1 is obtained by increas-
ing the temperature.

In experiment, Output 1 obtains an extinction ratio of
greater than 15 dB between the two switching states, while
Output 2 has more than 40 dB extinction ratio. The measured
cross talk between the two outputs is more than 30 dB. As
the Brewster angle (16.3°) of the silicon-air interface is quite
close to the TIR angle, this optical switch exhibits strong
dependence on the polarization state. It is a drawback for
some applications but could be critically valuable in coherent
optical communication systems, in which the transmitted sig-

FIG. 3. Scanning electron micrographs of the fabricated optical switch (a)
Overview of the packaged switch and (b) close-up view of the prism.

FIG. 4. Output light of different outputs. (a) TIR state and (b) transmission
state.
The current prototype of optical switch measures quite high insertion losses (18.95 and 31.67 dB for the transmission and the TIR state, respectively), which can be attributed to several factors. The Fresnel reflection in the silicon-air and fiber-air interfaces introduces a loss of 3.41 dB. As the light is not collimated, the divergence of the signal causes 7.60 and 4.12 dB in the transmission and the TIR states, respectively. The surface roughness of the etched walls represents another main contributor, especially at the second surface. Due to the scalloping and roughness resulted from the DRIE, part of the incident light does not meet the critical angle of total internal reflection. It is estimated that a roughness of 20 nm will introduce additional losses of 1.98 and 10.10 dB to the transmission and the TIR state, respectively. Other losses may come from fiber misalignment, Fabry-Perot cavity effect (5.33 dB, only in the TIR state), and mirror surface scattering (0.34 dB, only in the transmission state). From the sources of losses, it can be seen that the insertion losses can be drastically reduced by optimizing the design and by improving the optical coupling.

In summary, a micromachined optical switch has been experimentally demonstrated based on the physical mechanisms of total internal reflection of prism and thermo-optical effect of silicon material. Such an optical switch exhibits its uniqueness and multifold advantages. Firstly, the switching mechanism is unique and the tuning of critical TIR angle is sensitive. Secondly, there is no mechanical instability issue as the switching is obtained by thermo-optic effect instead of mechanical movement. Lastly, the adjustment of initial angle by micromachined actuators makes it adaptive to various conditions such as variation of the refractive index of silicon substrate, environmental temperature change, different wavelength range, etc.

12http://www.ioffe.rssi.ru/SVA/NSM/Semicond/SiGe/optic.html