MEMS OPTICAL TUNNELING STRUCTURE FOR THERMO-OPTIC SWITCHING

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ABSTRACT

This paper presents a thermo-optic switch based on the optical tunneling effect of a double optical barriers system [1]. By introducing a new physical mechanism of the optical tunneling effect into Micro-electro-mechanical Systems (MEMS) technology, a switching contrast of more than 30 dB with a response time of less than 3 μs are obtained. Compared with the previously reported thermo-optic switches [2], this design requires very small change in refractive index for switching (Δn ≈ 10⁻⁴), which is only 1/10 of the typical requirement. It has fast tuning speed and low power consumption.

1. INTRODUCTION

Optical switch is one of the key components in integrated optical circuits. Compared to traditional optical switches, MEMS-based optical switches have greater advantages in an integration process due to their micro-scale size. However, the traditional MEMS optical switches, operated by mechanical means [3-4], usually fail to meet the application requirements of high speed and high stability in optical fiber and home communications.

Recent study in silicon photonics shows that the optical switches can be realized by varying the refractive index of the silicon material [5-7]. Although the refractive index of the silicon material can be changed by many methods such as light luminance [8], thermo process [9] and pressure [10], the maximum change to the refractive index is limited by the lattice structure of the silicon crystal. Micro-cavities designs provide one solution for the low tunability of the silicon material [11-13]. Light localization enhances light-material interaction which results in further tuning of the refractive index of the silicon. Ultra-high Q factors (above the order of 10⁵) of these micro-cavities also ensure that transmission states can be switched between an on-resonance state and an off-resonance state by small variation of the refractive index [14]. The micro-cavities have indeed been proven to be useful in realizing the optical switch in the silicon material. However sub-wavelength scaled cavities and extremely high Q factors introduce great challenges in fabrication processes.

In this paper, an alternative method is provided to realize the silicon based optical switch. The double optical barriers structure based on MEMS technology requires very small change in the refractive index, around the same order of the micro-cavities [15-16], to realize the switching function of the light transmission via tunneling.

Section 2 presents the theoretical analysis and the MEMS optical switch design. Section 3 shows the experimental results and some discussions. Section 4 concludes.

2. THEORY AND DESIGN

The design consists of three parts as shown in Fig. 1, two semi-cylindrical prisms and a central rib. The three components are separated by two air gaps that function as the optical double barriers. A micro-heater is located on the central rib for changing the refractive index. The incident light is input from the first prism at an angle greater than the critical angle while the output exits from the second prism. The incidence angle θ, the refractive index of each component (n₁, n₂ and n₃) and the gaps distances between two prisms and the rib (d₁, d₂ and d₃) are designed to achieve the total transmission condition of the two barriers system. The transmission states of the optical switch can be changed by adjusting the refractive index of the rib. The optical tunneling effect can be enhanced by resonance. For two optical barriers structures, total transmission state can be achieved by properly adjusting phase shift between the barriers. In this paper, the optical barriers are formed by frustrated total internal reflection (FTIR). The potential of the optical barrier (air gap between the interfaces) determines amplitude tuning when light is traveling through it while the distance between the barriers provides the phase shift. The transmission can be tuned by varying the optical length between the optical barriers.

![Figure 1: Schematic of the two barriers optical tunneling switch modulated by thermo effect.](image)

The transfer matrix method is applied for the numerical analysis of the optical switch. For single air gap, the reflection coefficient can be calculated as [17],

$$R = \frac{r_{10} + r_{2e}e^{i\delta}}{1 + r_{10}r_{2e}e^{i\delta}}$$

(1)
The phase term $\delta$ is given as,

$$
\delta = \left( \frac{4\pi d}{\lambda} \right) \sqrt{1 - n^2 \sin^2 \theta}
$$

(2)

where $d$ is the width of the air gap and $\lambda$ is the wavelength.

The phase shift of the light traveling through the air gap is imaginary because of the above critical angle. This results in the attenuation of the light amplitude. Therefore, the transmission coefficient $T$ can be written as,

$$
T = \frac{t_{10}t_{02}e^{i\Delta}}{1 + r_{02}r_{10}e^{i\delta}}
$$

(3)

where $r_{mn}$ and $t_{mn}$ ($m, n = 0, 1$ or $2$) are the reflection coefficient and transmission coefficient at different interfaces given by the Fresnel equations. [18].

The transfer matrix for two barriers structure can be expressed by $R$ and $T$. The simulation results are shown in Fig 2.

Figure 2: Transmission contour map of the double barriers optical tunneling.

The distance of the air gap and the rib depth are normalized with respect to the wavelength and the incidence angle which is chosen to be $18^\circ$. As it has been proven that total transmission condition can be obtained by the resonance enhancement between the two barriers which is similar to the two barrier systems of electrons. It can be seen (Fig 2) that the transmission states are highly sensitive to the variation of the central rib. Once the proper gaps distances ($d_1$, $d_2$ and $d_3$) are chosen according to the incidence angle $\theta$ and input wavelength $\lambda$, the transmission state can be easily controlled by changing the optical path length of the central rib.

In contrast to the traditional MEMS technology, the optical path length is modulated by changing the refractive index of the central rib via thermo effect. Compared with the mechanical actuators, thermo effect has higher tuning speed and stability.

Figure 3 shows the simulation results of transmission as a function of the change in the refractive index of the central rib.

![Figure 3: Analytical results of transmission as a function of refractive index change for TE and TM polarizations.](image)

At the initial state, both the TE and TM are fully transmitted. With the increase of $|\Delta n|$, the transmissions of both the TE and TM drop dramatically. At $|\Delta n| = 10 \times 10^{-4}$, the TE goes down to -41 dB while the TM goes to -25 dB. In this paper, TE polarization is chosen for the experiment for better sensitivity. In general, only a change in the refractive index of order $10^{-4}$ is required to achieve a contrast of transmission by 30 dB. For the silicon material, the refractive index change is approximately linear near the room temperature,

$$
\frac{dn}{dT} = -1.615 \times 10^{-10} T^2 + 3.156 \times 10^{-7} T + 8.919 \times 10^{-5}
$$

(4)

It can be derived from Eq. (4) that the refractive index change of the order $10^{-4}$ can be easily achieved by thermo effects. It should be noted that the change in the refractive index of the central rib is equivalent to the change in the width of the central rib since the resonance condition is determined by the optical path length, which is a multiplication of the refractive index and the width of the central rib.

3. RESULTS AND DISCUSSIONS

The optical switch is fabricated on a SOI wafer (Fig 4). The central rib is coated with aluminum which functions as the micro-heater. The semi-cylindrical prisms function as a fiber to chip couplers. A single mode fiber functions as the input and couple to the first prism which transfer Gaussian beam from the fiber to the plane wave. The other prism focuses the output light for better coupling of the output fiber. The air gap width can be finely adjusted by tuning the
voltage applied to the actuators that are linked to the semi-cylindrical prisms. Finite-difference time-domain method is used to get the optimized parameters for fabrication. The radii of the semi-cylindrical prism are chosen to be 270 µm and the rib width is 18 µm. They ensure plane wave condition. The best distinguish ratio can be achieved within the tuning range of the air gap width.

Figure 4: SEM graph of the fabricated thermo-optic switch.

The maximum transmission state is achieved, during the experiment, by adjusting the air gap width and the incidence angle (remained above the critical angle 17.2°) of the input light. Then, the central rib is heated by injecting electric current into the aluminum coating. The transmission at different heating power is plotted in Fig 5.

Figure 5: Measured transmission at different power applied to the micro-heater of the central rib.

More than 30 dB switching contrast is achieved within the heating power of 40 mW. Due to the difficulty to estimate the heating efficiency of the micro-heater and the micro scaled size, the exact amount of the temperature increasing of the central rib can not be calculated or directly measured.

Therefore, precise comparison between the experimental and simulation results is not applicable here. However, the experimental results and the simulation results demonstrate the similar tendency. Fig. 5 shows that when the best transmission state is achieved (the initial state when the transmission is the maxim) the transmission is highly sensitive to the change in the refractive index of the central rib. As the temperature goes higher, the drop of the transmission is less dramatic. Similar tendency is observed in Fig. 3. Further change in the refractive index does not have much effect on the transmission state of the optical switch. This can be explained by the contour map of the transmission (Fig. 2). When the air gap is above the incidence light wavelength, the high transmission state (bright region) can only be achieved by finely adjusting the optical path length of the rib. The transmission is highly sensitive to the change of the central rib at the high transmission region while in the low transmission region (dark region) the variation of the transmission is very slow. This ensures that the optical switch can be modulated within a small range of the change in refractive index. It should be pointed out that the heating power given here is the total power applied to the whole circuit which is certainly higher than the real power consumed by the micro-heater.

Figure 6: Time response of the switching process.

The time responds of the switching process is shown in Fig. 6. It can be seen from Fig. 6, that the response time of the optical switch is around 3 µs while the relax time is around 10 µs. This is because of the lack of cooling device in the experiment. The quick response time is due to the small change of the temperature. It should be noted that the duration of the current pulse (dashed line) is approximately the same as the measured response time.
(solid line) of the optical switch which means the real response time might be even smaller than the measured one due to insufficient resolution of the oscilloscope.

4. CONCLUSIONS

In this paper, a MEMS optical switch based on double barriers optical tunneling structures is demonstrated. A distinguish ratio of more than 30 dB and the response time of less than 3 µs are achieved in the experiments. The experimental results are well explained by numerical simulation. Compared with the traditional MEMS optical switch, the MEMS optical switch based on the tunneling structure is faster and more stable. Its fabrication process is easier compare to the sub-wavelength cavities.

5. REFERENCES