A Theoretical Model of All-optical Switching Induced by a Soliton Pulse in Nano-waveguide Ring Resonator

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Abstract. We propose a theoretical model of 1×2 all-optical switching in a silicon nano-waveguide ring resonator induced by a soliton pulse. All-optical switches made by silicon fiber or silicon waveguide have attracted much attention, because the low-absorption wavelength windows of silicon material just match optical fiber communication. However, to achieve all-optical switching in silicon is challenging owing to its relatively weak nonlinear optical properties and require high switching power, which is much higher than the signal power. Such high power is inappropriate for effective on-chip integration. To overcome this limitation, we have used a highly confined nano-waveguide ring resonator structure with soliton pulse input to enhance the nonlinearity and this leads to enhance the effect of refractive index change on the transmission response. The refractive index is changed by controlling the free-carrier concentration through two-photon absorption (TPA) effect. The result indicates that a refractive index change as small as 6.4×10⁻³ can reduce the switching power to 2.38 ×10⁻⁶ W. The nano-waveguide ring resonator all-optical switching described here is achieved by using the concept of strong light confinement, and the switching power is approximately three orders of magnitude lower than the available silicon optical switches. Such controllable switch is desired for achieving high performance in nanometer-size planar structures.

1. Introduction

In recent years, efficient all-optical switching in silicon has been realized primarily in resonant devices for electro-optic modulator, wavelength conversion, ultra-high speed transmission, broadband generation, optical tweezers and chaotic signals generation [1-8]. One of the major challenges in realizing practical all-optical switching devices is the need for strong and fast material nonlinearity. All-optical switches have been demonstrated with III-IV compound semiconductors [9-10], but achieving the same in silicon is very difficult owing to its relatively weak nonlinear properties [11]. In silicon, all-optical switching has been demonstrated only by use of extremely high pumping powers and with large dimension and non-planar structure in which the pump light propagates out of the integration plane. Such silicon optical switches with high power, a large dimension and non-planar geometry are in appropriate for effective on-chip integration. The difficulty of silicon optical switches arises from the weak dependence of silicon’s refractive index and absorption coefficient on the free-carrier concentration [12-13].
To overwhelm this restriction, Li and Yupapin [14] have proposed an active double-coupler all-optical switch, in which half of the fiber ring is made by an erbium-doped fibre amplifier (EDFA). The switch can accumulate the nonlinear phase shift to $\pi$, and the switching power can be reduced to miliwatt. In this paper, we propose a theoretical model of 1x2 all-optical switching in a silicon nano-waveguide ring resonator induced by a soliton pulse. We have used a highly confined nano-waveguide ring resonator structure with soliton pulse input to enhance the nonlinearity and this leads to enhance the effect of refractive index change on the transmission response. The refractive index is changed by controlling the free-carrier concentration through two-photon absorption (TPA) effect. The result indicates that a refractive index change as small as $6.4 \times 10^{-3}$ can reduce the switching power to $2.38 \times 10^{-6}$ W. The nano-waveguide ring resonator all-optical switching described here is achieved by using the concept of strong light confinement, and the switching power is approximately three orders of magnitude lower than the available silicon optical switches. Such controllable switch is desired for achieving high performance in nanometer-size planar structures.

2. All-optical Switch Configuration

The configuration for all-optical switching is shown in Figure 1. This configuration is similar with the all-optical switch configuration proposed by Li [12, 13]. A silicon ring with a length of $L = l_1 + l_2$ and a nonlinear refractive-index coefficient is coupled with two straight waveguides through the couplers $C_1$ and $C_2$. A continuous-wave signal beam with power $P_{in}$ at 1550 nm and a soliton pulse pump beam with average power, $P_{avg}$ at 400 nm are simultaneously launched into the ring through a WDM, and then the signal power passes through couplers $C_1$ and $C_2$ successively and outputs from output port 1 or 2. Here we use two other WDMs to separate the pump beam from the signal beams at the two output ports [12, 13].

![Figure 1. Configuration of 1x2 all-optical switch based on a single silicon ring resonator.](image)

The relationships between the electrical field amplitudes $E_r, E_1, E_2, E_3, E_4$ and $E_{in}$ when neglecting the losses are [9, 10,12,13]

$$E_r = r_1 E_{in} + i t_1 E_4, \quad (1)$$
$$E_1 = i t_1 E_{in} + r_1 E_4, \quad (2)$$
$$E_2 = \exp(i\phi_1) E_1, \quad (3)$$
$$E_3 = r_2 E_2, \quad (4)$$
$$E_4 = i t_2 E_2, \quad (5)$$
$$E_4 = \exp(i\phi_2) E_3, \quad (6)$$

where $r_i$ and $t_i$ ($i=1,2$) are reflectivity and transmission of couplers $C_1$ and $C_2$, respectively, and $r_i^2 + t_i^2 = 1$ is satisfied, $\phi_1$ and $\phi_2$ are the phase shifts for two half rings. The phase shift in one cycle of
the ring is $\varphi=\varphi_0+\varphi_2$. Letting $r_1=r_2=r$, we obtain the reflection, $R$ and transmission, $T$ of the nanoring all-optical switch and the power ratios of $P_2$ and $P_4$ with $P_{in}$[9, 10,12,13]

$$
R = \frac{P_R}{P_{in}} = \frac{|E_R|^2}{|E_{in}|^2} = \frac{2r^2(1 - \cos \varphi)}{1 - 2r^2 \cos \varphi + r^4}, \quad (7)
$$

$$
T = \frac{P_T}{P_{in}} = \frac{|E_T|^2}{|E_{in}|^2} = \frac{1 - 2r^2 \cos \varphi + r^4}{(1 - r^2)^2}, \quad (8)
$$

$$
\frac{P_2}{P_{in}} = \frac{|E_2|^2}{|E_{in}|^2} = \frac{1 - 2r^2 \cos \varphi + r^4}{1 - r^2}, \quad (9)
$$

$$
\frac{P_4}{P_{in}} = \frac{|E_4|^2}{|E_{in}|^2} = \frac{r^2(1 - r^2)}{1 - 2r^2 \cos \varphi + r^4}. \quad (10)
$$

Here $r$ is coupler reflectivity, $\varphi$ is the phase shift in one circle of the ring, which can be divided into two parts: the linear part $\varphi_0$ and the nonlinear part $\Delta \varphi$, namely $\varphi = \varphi_0 + \Delta \varphi$. We suppose $r\to1$ in the following discussion. In the beginning without pump power and at resonance: $\varphi = \varphi_0 = 2m\pi$ ($m = 0, 1, 2, 3, \ldots$), from Eqs. (7) and (8), we obtain $R = 0$ and $T = 1$, the signal is output from port 1. When adding a pump power to lead a nonlinear phase shift $\Delta \varphi = \pi$, so that $\varphi = \varphi_0 + \Delta \varphi = (2m + 1/2)\pi$ ($m = 0, 1, 2, 3, \ldots$), then $R = 1$ and $T = 0$, the signal will be outputted from port 2. Therefore, as it is shown in Figure 2, the phase shift of $\Delta \varphi = \pi$ is necessary for switching in all-optical switch in nanowaveguide ring resonator.

![Reflection and transmittance response of a single silicon ring resonator with radius of 5 μm and $r_1=r_2=0.9$.](image)

**Figure 2.** Reflection and transmittance response of a single silicon ring resonator with radius of 5 μm and $r_1=r_2=0.9$.

3. All-optical Switch Configuration

The soliton source for the pump is produced by a tunable mode-locked Ti:sapphire femtosecond laser at a 90-MHz repetition rate, which induces TPA effect in the silicon material. This makes changes in the free carrier concentration including a change of electron concentration $\Delta N_e$ and a change of hole concentration $\Delta N_h$. By using Kramers-Kronig relationship, the refractive index changes $\Delta n$ can be obtained from the experimental spectrum of nonlinear absorption. The refractive index change at wavelength of 1.55 μm is given by [10-11]

$$
\Delta n = \Delta n_e + \Delta n_h = 8.8 \times 10^{-22} \Delta N_e + 8.5 \times 10^{-18} (\Delta N_h)^{0.8}. \quad (11)
$$
The nonlinear refractive-index change in the free carrier concentration is \( \Delta N = \Delta N_e = \Delta N_h \), then Eq.(11) becomes

\[
\Delta n = 8.8 \times 10^{-22} \Delta N + 8.5 \times 10^{-18} (\Delta N)^{0.8}.
\]  

(12)

The free-carrier concentration \( N \) is generated predominantly by TPA [12-13],

\[
\frac{dI}{dz} = \left( \frac{dN}{dt} \right) 2h\nu = -\beta I^2,
\]

(13)

and the generation rate of the free-carrier concentration is given by,

\[
\frac{dN}{dt} = \frac{\beta I^2}{2h\nu}.
\]

(14)

Here \( I \) is light intensity, \( h\nu \) is the photon energy, \( \beta \) is the TPA coefficient.

Presuppose that the light intensity of the incident temporal soliton is [15],

\[
I = \frac{P_0}{S} \text{sech}^2(\tau),
\]

(15)

where \( \tau = \frac{t}{T_0} \). \( t \) is the time and \( T_0 \) is the pulse width. The Eq.(15) becomes,

\[
I = \frac{P_0}{S} \text{sech}^2 \left( \frac{t}{T_0} \right).
\]

(16)

By substituting Eq.(16) into Eq.(14), then, the free-carrier-concentration change created by a single soliton pulse is given by

\[
\Delta N = \frac{\beta}{2h\nu} \int_{-\infty}^{\infty} \left( \frac{P_0}{S} \right)^2 \text{sech}^4 \left( \frac{t}{T_0} \right) dt = \frac{\beta}{2h\nu} \frac{P_0^2}{S^2} \left[ T_0 \sinh \left( \frac{t}{T_0} \right) \right]  \left[ 2 \cosh^2 \left( \frac{t}{T_0} \right) + 1 \right] \frac{3 \cosh^3 \left( \frac{t}{T_0} \right)}{S^2 T_0^2}.
\]

(17)

Here \( P \) is the peak power and \( S \) is the effective cross section area. For a stream of soliton pulses, the relationship between the peak power \( P_0 \) and the average power \( P_{\text{avg}} \) is

\[
\frac{P_0}{P_{\text{avg}}} = \frac{T_B}{T_0},
\]

(18)

where \( T_B \) is the pulse separation. Using Eq. (12), (17) and (18), the relationship between the refractive index change and the average power of the pump beam can be obtained as

\[
\Delta n = 8.8 \times 10^{-22} \frac{\beta}{2h\nu} \frac{P_{\text{avg}}^2 T_B^2}{S^2 T_0} \left[ \sinh \left( \frac{t}{T_0} \right) \right]  \left[ 2 \cosh^2 \left( \frac{t}{T_0} \right) + 1 \right] \frac{3 \cosh^3 \left( \frac{t}{T_0} \right)}{S^2 T_0^2}.
\]
\[ + 8.5 \times 10^{-18} \left( \frac{\beta}{2\hbar} \frac{P_{\text{avg}} T_R^2}{S^2 T_0} \left[ \sinh \left( \frac{t}{T_0} \right) \right] \left[ 2 \cosh^2 \left( \frac{t}{T_0} \right) + 1 \right] \right)^{0.8} \]  

Substitute the data for practical devices [10-13], the wavelength of pump light, \( \lambda = 400 \text{ nm} \), \( h\nu = 4.9696 \times 10^{-19} \text{ J} \), \( \beta = 7.9 \times 10^{-12} \text{ m/W} \), \( T_0 = 100 \text{ fs} \), \( T_B = 12.5 \text{ ns} \), \( t = T_0/2 \), \( r_1 = r_2 = 0.9 \), \( \varphi_0 = 0 \), \( D = 10 \text{ \( \mu \)m} \), \( S = 450 \times 250 \text{ nm}^2 \), and \( L = \pi D \) into phase shift equation,

\[ \Delta \varphi = \frac{2\pi n}{\lambda} \Delta n. \]  

Figure 3. represents the variation of effective phase shift against the wavelength area of pump light. The phase shift for the reflection and transmission has identical response as it enhanced interval resonance peaks.

![Figure 3. Phase shift in the ring resonator as a function of wavelength.](image)

We obtain the curves of the phase shift and reflection/transmission as a function of the average pump power as shown in Fig.4(a) and 4(b), respectively. Figure 4(a) indicates that the phase shift is a parabolic function of the average pump power. When the phase shift reaches \( \pi \), the average pump power or switching power is \( 2.38 \times 10^{-6} \text{ W} \). Refractive index change of \( 6.4 \times 10^{-3} \) is needed to achieve phase shift of \( \pi \). Figure 4(b) illustrates when the switching power reaches \( 2.38 \times 10^{-6} \text{ W} \), the output light will be switched from output port 1 to the output port 2.
Figure 4. (a) Phase shift in the ring resonator as a function of switching power under TPA effect induced by a soliton pulse. (b) Reflection and transmission in the ring resonator as a function of switching power under TPA effect induced by a soliton pulse.

From the result, the calculated switching power is approximately three orders of magnitude lower than the Gaussian pulse pump beam obtained by Li group as shown in Figure 5 [12-13]. The calculated switching power is also approximately two orders of magnitude lower than the theoretical model proposed by Yupapin. His active double-coupler all-optical switch, in which half of the fiber ring is made by an erbium-doped fibre amplifier (EDFA) can switch the input signal by using the power range of 15.0-28.6 mW [14].
Figure 5. (a) Phase shift in the ring resonator as a function of switching power under cross pumping and TPA effect by a Gaussian pulse. (b) Reflection and transmission in the ring resonator as a function of switching power under TPA effect by a Gaussian pulse [12, 13].

4. Conclusion
We have analyzed silicon nano-waveguide ring resonator all-optical switch based on silicon nano-waveguide ring resonator based on two-photon absorption (TPA) effect induced by a soliton pulse. The result indicates that a refractive index change as small as $6.4 \times 10^{-3}$ can reduce the switching power to $2.38 \times 10^{-6}$ W.

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