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RESEARCH ARTICLE

Low-power 1×2 all-optical switching in a silicon double coupler microring resonator

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Abstract Low-power 1×2 optical switching in a double coupler ring resonator (DCRR) made by a silicon nanoscale waveguide b ased on two photon absorption (TPA) is analyzed theoretically. The TPA originates from a femtosecond pump light at 400 nm, which enters the DCRR together with a CW signal light at 1.55 μm through the input port. TPA makes the silicon free-carrier concentration change, which is proportional to the change of reflective index. Our numerical simulation shows that when average pump power reaches 2 mW, it will induce the 10^{-3} refractive-index change and the π-phase shift of signal light, after which 1×2 all-optical switching can be realized.

Keywords all-optical switching, double coupler ring resonator, two photon absorption, free-carrier concentration, nonlinear refractive index

1 Introduction

Silicon is a dominant material in the microelectronics industry and is increasingly being considered as a platform for photonic integrated circuits. All-optical switches have been demonstrated by employing III–V compound materials based on photon-excited free-carrier concentrations resulting from one- or two-photon absorption [1–3]. In silicon materials, all-optical switching has been demonstrated only by the use of extremely high pumping powers [4–9] and with a large dimension and non-planar structure in which the pumped light propagates out of the integration plane. Such silicon optical switches with high power, a large dimension, and non-planar geometry are inappropriate 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

To overcome the difficulty of a high-power requirement for silicon switching devices, Michal Lipson et al. presented an experiment of all-optical switches in a silicon microring resonator coupled to one straight waveguide [10,11]. In their experiment, the plane of a silicon ring resonator is pumped by a femtosecond pulsed beam at 400 nm in the perpendicular direction. Their experiment shows that to effect optical switching for the 1.55 μm-signal beam, a minimum average pump power of only 10 mW is required. This induces the material-refractive-index change $\Delta n = 10^{-3}$ and the signal-wavelength-peak shift $\Delta\lambda = 1.1$ nm. However, their switching device is a 1×1 intensity-type optical switch with one input port and one output port.

In this paper, a new all-optical switching system in a silicon microring resonator coupled with two straight waveguides, in which the combination of signal beam and pump beams is incident into the ring resonator, is analyzed theoretically. The pump beam induces the TPA-generated (two photon absorption) free-carrier concentration change of 10^{17} cm^{-3}. This results in the refractive-index change of 10^{-3} and the π-phase shift in one circle of the ring, so that 1×2 optical switching for signal beam between two output channels can be realized. The simulation shows that the threshold average pump power is only about 2.25 mW. Hopefully, such 1×2 all-optical switches can be used in future optical communication.

2 Reflectivity and transmission versus phase shift

The signal power P_{in} at 1.55 μm and the pump power P_{p} at 400 nm are launched together into the input port of a double coupler ring resonator (DCRR) as shown in Fig. 1. It can be proven that in the resonant case without pump power ($P_{\mathrm{p}} = 0$), the signal light comes from output port 2. However, when pump power P_{p} induces the nonlinear phase shift of signal light traveling in one circle φ to reach π due to a TPA-induced free-carrier-concentration change,

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the output signal light will be switched to output port 1 from output port 2. It can be supposed that the pump light is entirely absorbed by the silicon ring resonator.

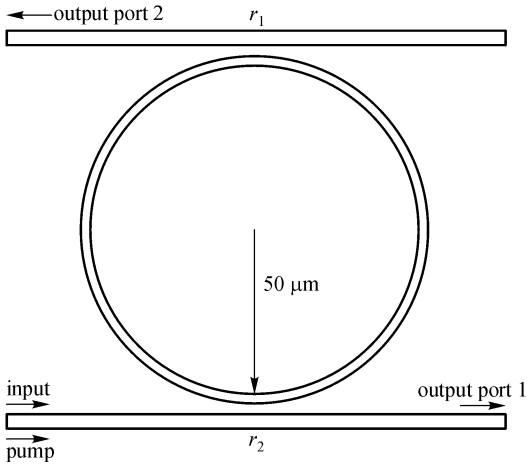

Fig. 1 Configuration of a ring resonator with two coupled straight waveguides by coupler 1 and coupler 2

We obtain the relationships among output power at reflection port P_r, output power at transmission port P_t and input power P_{in} from the coupling equations. R and T are reflectivity and transmission respectively:

$$R=\frac{P_r}{P_{in}}=\frac{|E_r|^2}{|E_{in}|^2}=\frac{r_1^2-2ar_1r_2\cos\varphi+a^2r_2^2}{1-2ar_1r_2\cos\varphi+a^2r_1^2r_2^2}, \quad (1)$$

$$T=\frac{P_t}{P_{in}}=\frac{|E_t|^2}{|E_{in}|^2}$$
$$=\frac{a^2}{\exp(-\alpha L/4)}\cdot\frac{(1-r_1^2)(1-r_2^2)}{1-2ar_1r_2\cos\varphi+a^2r_1^2r_2^2}, \quad (2)$$

where a is the loss rate in one circle, $a=\exp(-\alpha L/2)$. α is absorption coefficient; L is length of the ring; and r_1 and r_2 are reflectivity of coupler 1 and coupler 2, respectively. From Eqs. (1) and (2), assuming $r_1=r_2\rightarrow 1$, when the nonlinear phase shift $\varphi=2m\pi$ (m = 0, 1, 2, 3,...), we obtain $R=0$ and $T\approx 1$. However, when $\varphi=2m\pi+\pi$, we obtain $R\rightarrow 1$, $T\rightarrow 0$. Reflectivity and transmission as the function of phase shift are shown in Fig. 2.

3 Phase shift and refractive-index change versus pump power

In our device, femtosecond pump power mainly induces TPA in the silicon material of microring and straight waveguides. It will lead to the changes of free-carrier concentration, including the change of electron concentration ΔN_e and the change of hole concentration ΔN_h. By using the Kramers-Kronig relationship, the refractive-index changes in silicon material can be obtained from the experimental absorption spectra. Therefore, the refractive-index change, including contributions by electrons and holes, is given by [12]

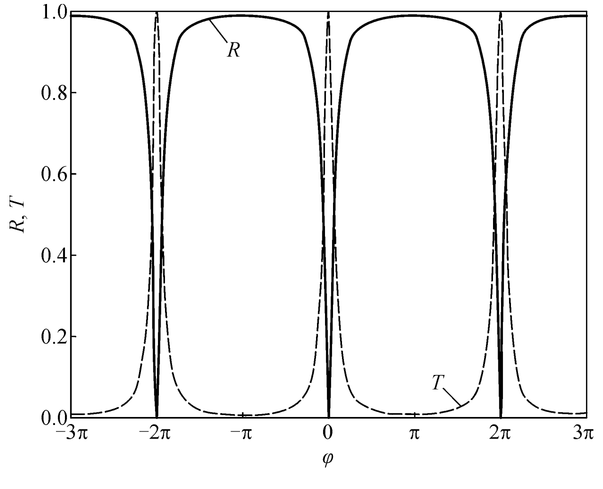

Fig. 2 Reflectivity R and transmission T as the function of the phase shift of φ

$$\Delta n=\Delta n_e+\Delta n_h$$
$$=-\left[8.8\times 10^{-22}\Delta N_e+8.5\times 10^{-22}(\Delta N_h)^{0.8}\right]. \quad (3)$$

The refractive-index change results in a phase shift change of the signal light at 1.55 μm in one circle of the ring:

$$\varphi=\frac{2\pi}{\lambda}\Delta nL, \quad (4)$$

where L is length of the ring and λ is wavelength of the signal light in vacuum.

The free-carrier concentration N is generated predominantly by TPA, so its rate of generation is given by [13]

$$\frac{dN}{dt}=\frac{\beta I^2}{2h\nu}, \quad (5)$$

where I is the light intensity, $h\nu$ is the photon energy, and β is the TPA coefficient. Assuming that the concentration change of electrons is equal to that of holes, $\Delta N=\Delta N_e=\Delta N_h$, and the laser pulse has a Gaussian time dependence, $I=(P/S)\exp(-2t^2/\tau^2)$, then the free-carrier concentration change created by a single pulse is given by

$$\Delta N=\frac{\beta}{2h\nu}\int_{-\infty}^{\infty}\left(\frac{P}{S}\right)^2\exp\left(\frac{-4t^2}{\tau^2}\right)dt=\frac{\beta\sqrt{\pi}\tau P^2}{4h\nu S^2}, \quad (6)$$

where P is the peak power, S is the effective cross-section of the waveguide and τ is the pulse width at half-peak power. It is considered that the full width at $1/e$ of the peak power is given by $\sqrt{2}\tau$. For Gaussian pulses, the relationship between the peak power P and the average power P_{avg} (with width of t_p) is [13]

$$\frac{P}{P_{\mathrm{avg}}} = \frac{\sqrt{2}t_{\mathrm{p}}}{\sqrt{\pi}\tau}. \tag{7}$$

Using Eqs. (3) and (6), the relationship between the refractive index and the average power of the pump light is obtained:

$$\begin{aligned}\Delta n &= \Delta n_{\mathrm{e}} + \Delta n_{\mathrm{h}} \\ &= -\left[8.8\times 10^{-22}\frac{\beta t_{\mathrm{p}}^2}{2h\nu\sqrt{\pi}\tau S^2}P_{\mathrm{avg}}^2 \right. \\ &\quad \left. + 8.5\times 10^{-22}\left(\frac{\beta t_{\mathrm{p}}^2}{2h\nu\sqrt{\pi}\tau S^2}P_{\mathrm{avg}}^2\right)^{0.8}\right].\end{aligned} \tag{8}$$

Substituting the following data $\beta = 7.9\times 10^{-10}$ cm/W, $\lambda_{\mathrm{p}} = 400$ nm (wavelength of pump light), $\tau = 100$ fs, $h\nu = 49.725\times 10^{-20}$ J, $t_{\mathrm{p}} = 12.5$ ns and $\alpha = 7\times 10^{-5}$ m^{-1}, $r_1 = r_2 = 0.9$, $d = 100$ μm (diameter of the ring resonator), and $S = 450$ nm × 250 nm into Eqs. (1)–(8), the curves of refractive-index change are obtained and the phase shift in the ring resonator is described as a function of average pump power as shown in Fig. 3. It can be shown that when the phase shift approaches π, the refractive-index change is -2.5×10^{-3}, and the average pump power required for switching is only 2.254 mW.

Figure 4 shows reflectivity and transmission as a function of average pump power. It shows that when the average pump power approaches 2.254 mW, the output signal light will be switching from the transmission port to the reflected port. Because the nonlinear refractive index in the TPA case is proportional to the square of the pump power, switching power is reduced dramatically.

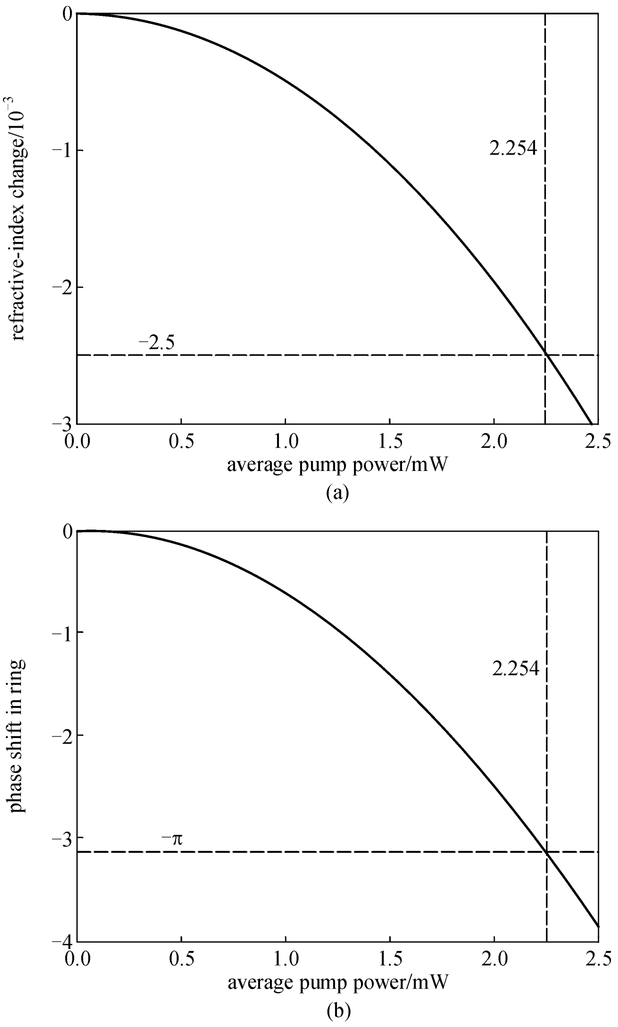

Fig. 3 Function of average pump power. (a) Refractive-index change; (b) phase shift in the ring

4 Discussion

The nonlinear effect we propose in this paper is different from the Kerr effect. To compare the TPA effect with the Kerr effect, the refractive-index change caused by the latter is $\Delta n = n_2 P/S$, which is proportional to pump power P. However, the refractive-index change caused by the TPA effect is proportional to the square of pump power P according to Eq. (8). In the same DCRR device, the pump power required for switching is in the order of a few Watts for the Kerr effect, which is larger than that for the TPA effect 10^3 times. The switching speed was influenced by the photon lifetime in ring cavity as well as the carrier recombination lifetime.

The absorption loss estimated is significantly lower than the scattering loss in the ring. The low absorption loss indicates that the switching is due only to the refractive-index change. The thermal effects can be neglected, because the pump light used is a femtosecond laser. Since all of the losses

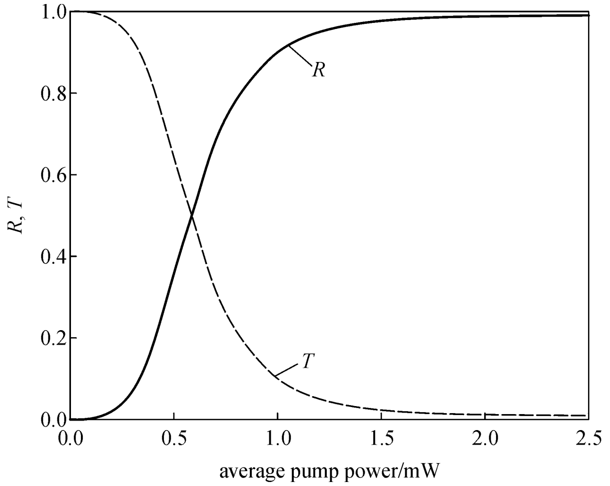

Fig. 4 Reflectivity and transmission as a function of average pump power

can be neglected, the switching power should be higher than the theoretical number.

5 Conclusion

In this paper, an all-optical switch in a double-coupler ring resonator as a 1×2 optical switch is proposed. Pump power is channeled into the waveguide together with the signal. The switching is realized by changing the refractive index to make the π-phase shift in one ring trip. The refractive-index change is based on a free-carrier (electron and hole) concentration change by the pump power-induced TPA effect. The minimum average power of pump power required for switching is only about 2.254 mW.

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