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A 2 × 3 Photonic Switch in SiGe for 1.55μm Operation*

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Abstract: A silicon-based photonic switch is proposed and simulated based on the multimode interference (MMI) principle and the free-carrier plasma dispersion effect in silicon-germanium. The proposed switch, designed for 1.55μm window operation, is useful for DWDM optical networks. The switch consists of two input single-mode ridge waveguide ports, a MMI section, and three output single-mode ridge waveguide ports. In the MMI section, two index-modulation regions are placed to divert input optical signals from the two input ports to each of the three output ports. Switching characteristics are demonstrated theoretically by a beam propagation method for 1.55μm operation. The simulated results show that the insertion loss of the switch is less than 1.43dB, and the crosstalk is between -18 and -32.8dB.

Key words: integrated optics; photonic switch; multimode interference

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1 Introduction

The rapid growth of optical networks has generated great interest in optical waveguide components. Optical switches are important components due to their role in switching and routing signals in the optical domain. During the past few years, a variety of switches based on the thermal-effect[1,2], electro-optical effect[3], plasma dispersion effect[4], and mechanical principle[5,6] have been developed. However, the reported switches have two input and two output ports and are fabricated for single wavelength applications. As the required number of input-output ports and the density of channels are increasing in DWDM networks, it is crucial to develop optical components, particularly switches, to address such issues. Therefore, one objective of this work is to propose an improved multi-wavelength photonic switch with a scalable number of ports beyond 2 × 2. Another objective is to design a multi-port photonic switch that can be produced by existing low cost technology and can be monolithically integrated with conventional Si-based optoelectronic devices and circuits.

2 Simulation and discussion

Figure 1 shows a schematic structure of the proposed 2 × 3 switch. Figure 1(a) shows a top view, and Figure 1(b) shows a cross-section of the index-modulation region. Figure 1(a) illustrates that the switch consists of three sections: an input section, a central section, and an output section. The input section consists of input waveguides A and B, while the output section consists of output waveguides 1, 2, and 3. All the input and output waveguides are single-mode waveguides. The central section consists of a multimode interference (MMI) waveguide with electronically controlled index-modulation regions Ⅰ and Ⅱ. Each index-modulation region is designed as a p-n junction, as shown in Fig. 1(b). When a forward bias voltage is applied to any of the p-n junctions, the refractive

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index in the index-modulation regions Ⅰ and Ⅱ decreases due to the plasma dispersion effect, leading to a variation in the propagation constant of the optical waveguide[7,8]. Therefore, the input optical signals are switched to any one of the three output ports.

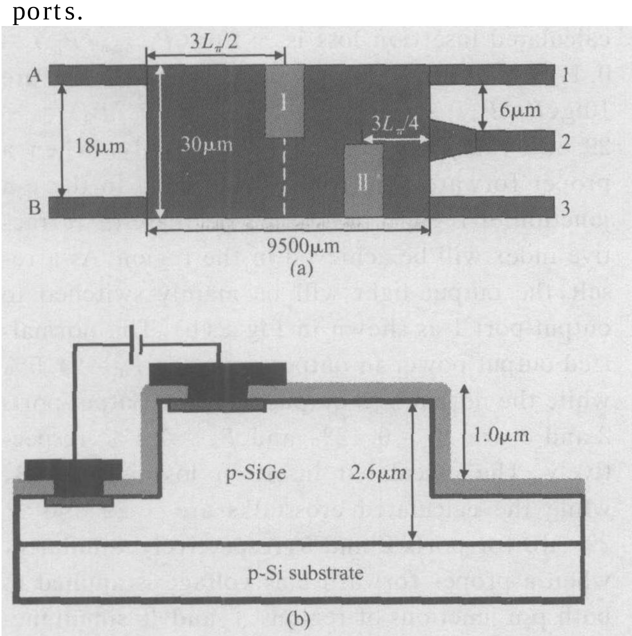

Fig. 1　Schematic structure of the proposed 2 ×3 photonic switch　(a) Top view of the photonic switch; (b) Cross-section of the index-modulation regions

Three basic parameters are considered in the design of the proposed 2 ×3 switch. They are (1) thickness of the ridge waveguide, (2) width of the single mode waveguides (A, B, 1, 2, and 3), and (3) width and length of the MMI section. With reference to our previous experimental work[9], we used a 2.6μm p-SiGe ridge waveguide with a Ge content of 4 % on p-Si substrate. The ridge height is chosen to be 1.0μm for all waveguides. To facilitate the butt coupling of optical signals between the ridge waveguides and single mode fibers, all the input and output single mode waveguides are set to 6μm in width.

The MMI section shown in Fig. 1 (a) is designed to support a large number of modes. According to self-imaging theory[10,11], when an input light is coupled into the multimode section from the input single-mode waveguides A or B, interfering optical fields will be produced in single or multiple images at periodic intervals along the direction of propagation of the multimode waveguide. The separation between the peaks of two images is half of the effective width of the MMI section, W_e. Taking into account the Goos-Hähnchen shift, W_e can be expressed as

$$W_e = W_M + \frac{\lambda_0}{\pi} \times \left(\frac{n_c}{n_r}\right)^{2\sigma}\left(n_r^2 - n_c^2\right)^{-1/2} \qquad (1)$$

where W_M is the width of the MMI waveguide, $\sigma = 0$ for the TE mode and $\sigma = 1$ for the TM mode, λ_0 is a free-space wavelength, and n_r and n_c are the effective refractive indices of the ridge waveguide layer and the cladding layer, respectively. Defining the beat length of the two lowest-order modes, the image of the input light field will be obtained at

$$L = p \times 3L_\pi, \quad p = 0, 1, 2, \cdots \qquad (2)$$

where the beat length of the two lowest-order modes, L_π, is

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} \approx \frac{4 n_r W_e^2}{3\lambda_0} \qquad (3)$$

where β_0 and β_1 are the propagation constants of the fundamental mode and first-order lateral mode, respectively.

When the width of the input and output waveguides is set to 6μm in this design, the width of the MMI is chosen to be 30μm with a 6μm spacing between output port waveguides. By Eqs. (1～3), the minimum length of the MMI section is calculated to be 9500μm with $L_\pi = 3166.67$μm at $\lambda_0 = 1.55$μm and $n_r = 3.502$.

To achieve the switching function by carrier injection, two index-modulation regions Ⅰ and Ⅱ are designed as shown in Fig. 1(a). For this type of symmetrical switching structure, region Ⅰ must be placed at a coupling length one-half (1/2) from the left side of the MMI section. The width of the first region is designed to be 15μm, which is the half width of the MMI section. Similarly, the second region is placed at the coupling length of three-fourths (3/4) from the right side of the MMI section with a width of 15μm. For a wavelength of 1.55μm, the refractive index of Si is 3.5 while that of SiGe with a Ge content of $x = 4\%$ is $n_{SiGe} = n_{Si} + 0.18x = 3.507$. To introduce a π phase difference by carrier injection, the refractive index should be decreased by 0～0.7 %. In this design, we choose a 0.3 % ～ 0.4 % decrease in refractive index. A length of about 300μm is obtained for the two index-modulation regions according to $(2\pi/\lambda) \times (\Delta n \times l) = \pi$.

To calculate the forward bias voltage (V_A) to be applied to the p-n junctions of regions Ⅰ and

II, the change of refractive index for $\lambda = 1.55\mu m$ can be expressed as[12]

$$\Delta n = -[8.8\times10^{-22}\times\Delta N_e + 8.5\times10^{-18}\times(\Delta N_h)^{0.8}] \quad (4)$$

where ΔN_e and ΔN_h are the concentration changes of electrons and holes, respectively. For an index change of 0.3%~0.4%, the calculated carrier concentration change is $\Delta N = \Delta N_e (\approx \Delta N_h) = (1 \sim 1.4)\times10^{18} cm^{-3}$. The change of refractive index ΔN can also be specified by

$$\Delta N = N_i \exp(qV_A/2kT) \quad (5)$$

where N_i is the intrinsic carrier concentration of Si, q is the electron charge, and V_A is the forward bias voltage applied to the two p-n junctions. By Eq. (5), V_A is calculated to be 0.95~1.0V under $N_i = 1.5\times10^{10} cm^{-3}$ and $kT = 0.026eV$ at room temperature. Furthermore, a current density of 26~36kA/cm^2 is estimated for this device[13] by

$$J = \frac{2qDN_i}{H}\exp\left(\frac{qV_A}{2kT}\right) \quad (6)$$

where H is the thickness of the SiGe waveguide layer and $D = 13cm^2/s$ is the diffusion coefficient of the carriers.

The fundamental characteristics of the 2×3 switch are simulated theoretically using the beam propagation method (BPM). All input lights are assumed to have the same wavelength, i.e. 1.55μm, and to retain their original phase, amplitude, and polarization.

When 1.55μm light is coupled into input waveguide A without applying a forward bias voltage to both p-n junctions I and II, the refractive index of the index-modulation regions I and II remains unchanged. In this case, the input optical signal will be output mainly from output port 3 as shown in Fig. 2(a) since the length of the MMI section is $L = 3L_\pi$. The normalized output power in output port 3 is $P_3 = 96\%$, while the normalized output powers in output ports 1 and 2 are $P_1 = 0.05\%$ and $P_2 = 0.1\%$, respectively. The calculated insertion loss is $-10\lg(P_{total-out}/P_{in}) = 0.17dB$ while the calculated crosstalks are $10\lg(P_1/P_3) = -32.8dB$ and $10\lg(P_2/P_3) = -29.8dB$ for ports 1 and 2, respectively. When a proper forward bias voltage is applied to the p-n junction of region I, a 0.3% decrease of refractive index will be achieved in the region. As a result, the output light will be mainly switched to output port 1 as shown in Fig. 2(b). The normalized output power in output port 1 is $P_1 = 94.5\%$ while the normalized output power in output ports 2 and 3 are $P_2 = 0.12\%$ and $P_3 = 0.1\%$, respectively. The calculated insertion loss is 0.24dB, while the calculated crosstalks are -29 and -29.8dB for ports 2 and 3, respectively. Similarly, when a proper forward bias voltage is applied to both p-n junctions of regions I and II simultaneously, the output light will be switched to output port 2, as shown in Fig. 2(c). The normalized output power in output port 2 is 75% while the normalized output powers in output ports 1 and 3 are 1.2% and 1%, respectively. The calculated insertion loss is 1.12dB, while the calculated crosstalks are -18 and -18.8dB for ports 1 and 3, respectively.

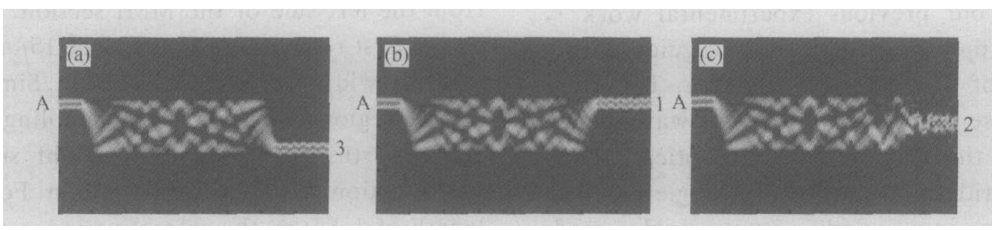

Fig. 2 Simulated switching states of the photonic switch when an input light is coupled into input waveguide A
(a) Switched to output 3; (b) Switched to output 1; (c) Switched to output 2

When the 1.55μm optical signal is coupled into input waveguide B without applying a forward bias voltage to both p-n junctions of regions I and II, the refractive indices of both the regions remain unchanged. In this case, the input optical signal will be output from output port 1 as shown in Fig. 3 (a). The normalized output power in output port 1 is 96% while the normalized output power in output ports 2 and 3 are 0.1% and 0.05%, respectively. The calculated insertion loss is 0.17dB, while the calculated crosstalks are -29.8 and -32.8dB for ports 2 and 3, respectively. Second, when a proper forward bias voltage is applied to the p-n junction of region I, the output light will be switched to output port 3, as shown in Fig. 3(b). The normalized output power in output port 3 is 95.5% while the normalized output powers in output ports 1 and 2 are 0.08% and 0.12%, respectively. The calculated insertion loss is 0.19dB while the calculated crosstalks are -30.8 and -29dB for ports 1 and 2, respectively. Third, when a proper forward bias voltage is applied to both p-n junctions of regions Ⅰ and Ⅱ simultaneously, the output light will be switched to output port 2, as shown in Fig. 3(c). The normalized output power in output port 2 is 76% while the normalized output powers in output ports 1 and 3 are 1.2% and 0.8%, respectively. The calculated insertion loss is 1.08dB, while the calculated crosstalks are -18 and -19.8dB for ports 1 and 3, respectively.

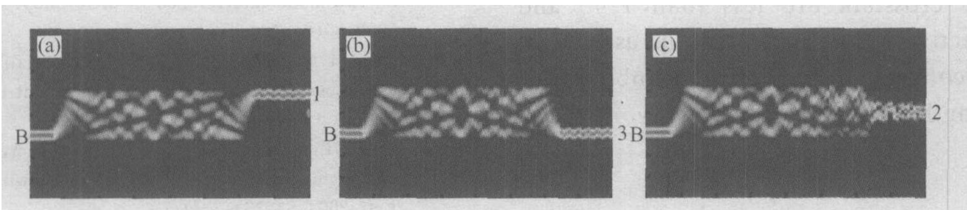

Fig. 3　Simulated switching states of the photonic switch when an input light is coupled into input waveguide B (a) Switched to output 1; (b) Switched to output 3; (c) Switched to output 2

When two 1.55μm optical signals with the same original phase, amplitude, and polarization are coupled into input ports A and B without applying a forward bias voltage to both p-n junctions of regions Ⅰ and Ⅱ, the input signal coupled from input port A will be switched to output port 3, and the input light coupled from input port B will be switched to output port 1. In this case, the switch is at cross-state and functions as an optical cross-connection as shown in Fig. 4(a). The normalized output powers in output ports 1, 2, and 3 are 48%, 0.05%, and 48%, respectively. The calculated insertion loss and crosstalk are 0.18 and -29.8dB, respectively. Second, when two 1.55μm light signals with same original phase, amplitude, and polarization are coupled into input ports A and B with a properly applied forward bias voltage to the p-n junction of region Ⅰ, the input light coupled from input port A will be switched to output port 1 and the input light coupled from input port B will be switched to output port 3. In this case, the switch is in the bar-state and also functions as an optical cross-connection, as shown in Fig. 4(b). The normalized output power in output ports 1, 2, and 3 are 48.3%, 0.12%, and 43.8%, respectively. The calculated insertion loss and crosstalk are 0.35dB and -26dB, respectively. Similarly, when the two 1.55μm signals are coupled into input ports A and B with a properly applied forward bias voltage to the p-n junctions of regions Ⅰ and Ⅱ simultaneously, the input signals coupled from input ports A and B are combined and will be output from output port 2. In this case, the switch functions as an optical power combiner as shown in Fig. 4(c). The normalized output power in output ports 1, 2, and 3 are 0.9%, 70%, and 1.0%, respectively. The calculated insertion loss and crosstalk are 1.43 and -19dB, respectively.

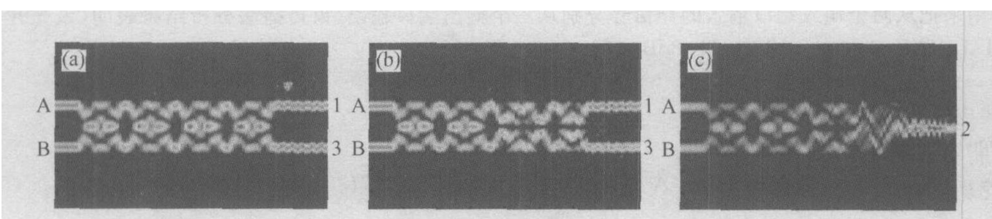

Fig. 4　Simulated switching states of the photonic switch when input lights are coupled into A and B simultaneously　(a) Cross-state; (b) Bar-state; (c) Combined-state

3 Conclusion

In summary, a multimode interference 2 ×3 photonic switch has been proposed and simulated based on the MMI principle and free-carrier plasma dispersion effect with Si-based material for 1.55μm window operation. The performance of the photonic switch has been analyzed by the beam propagation method. The calculated insertion loss and crosstalk are less than 1.43 and -18dB, respectively. The switch can be used as an optical cross-connect or an optical combiner for multi-wavelength signals in optical networks.

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1.55μm SiGe 2 ×3 光开关*

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摘要: 利用多模干涉效应和自由载流子等离子体色散效应设计和模拟了基于 1.55μm 波长的 2 ×3 SiGe 光开关. 该光开关由两个单模输入端口、一个多模干涉区和三个单模输出端口构成. 在多模干涉区, 设有两个折射率调制区, 可以利用来把从两个输入端口输入的光信号分别从三个输出端口输出. 束传播法分析结果表明, 该光开关的传输损耗小于 1.43dB, 串扰在 -18～-32.8dB 之间.

关键词: 集成光学; 光开关; 多模干涉

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