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微环光开关的偏振相关损耗研究

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摘　要:提出一种可同时支持横电模和横磁模传输的微环光开关设计方法,可用于构建波长平面内的偏振无关交换芯片.为了实现微环光开关的偏振无关传输,横电模和横磁模应工作在同一谐振波长且在该波长处有相同的群折射率,据此采用 MODE Solutions 优化基于硅绝缘体波导结构的微环参数,建立 Interconnect 芯片仿真模型,考察微环光开关芯片的透射特性和传输特性.经过优化设计,微环光开关的偏振相关损耗低至 0.13 dB,光脉冲传输时延为 42.5 ps.研究表明,当微环长度偏离优化值约 5 nm 时,偏振相关损耗就会增加到 1 dB,其中热光效应可以用来弥补工艺偏差,温度每变化 1 K,则可弥补 2.2 nm的环长偏差.

关键词:微环谐振器;光开关;芯片仿真;偏振相关损耗;热光效应

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Research on Polarization Dependent Loss of Micro Ring Resonator Based Optical Switches

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Abstract: A design method of micro-ring resonator based optical switches capable of simultaneously providing the transmission of transverse electric and transverse magnetic modes was presented, which can be applied to the buildup of polarization-independent switch chips operating in a given wavelength plane. In order to realize polarization-independent transmission, transverse electric mode and transverse magnetic mode should both work at the same resonant peak and the group refractive index of these two modes are equal to each other in this resonant wavelength. The silicon-on-insulator based micro-ring parameters were optimized with MODE Solutions, the chip simulation model was then set up by Interconnect to investigate transmission and transfer characteristics of the optical switch chip. By optimum design, the resulting micro-ring resonator based optical switching chip had a very low polarization dependent loss of 0.13 dB, while the transmission delay was 42.5 ps. Simulation shows that the length variation of the micro-ring resonator should be smaller than about 10nm for the polarization dependent loss of 1 dB, in which the thermo-optic effect can be used to compensate for the fabrication error with the perimeter change of 2.2 nm/K.

Key words: Micro ring resonator; Optical switch; Chip simulation; Polarization dependent loss; Thermo-optic effect

OCIS Codes: 130.4815; 230.5750; 260.5430

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0 Introduction

More and more photonic integration technologies can be utilized to integrate many optical components, such as lasers, optical modulators, photoelectric diodes and optical switches, into a single chip, so-called Photonic Integrated Chip (PIC)[1]. Now, the development of PIC-based optical information processing devices has become one of the most popular researches in the fields of optical communications and interconnects[2]. Among several material platforms used for PICs[3-5], Silicon-On-Insulator (SOI) structure has a promising application potential due to its unique advantages, such as that of compatibility with the Complementary Metal Oxide Semiconductor (CMOS) process[6-7].

For the SOI-based PICs, the refractive index difference between the silicon core and the cladding layer should be large enough to restrict the guided optical waves. But, this will bring about the birefringence phenomenon or large polarization dependency[8]. In this case, the Transverse Electric (TE) and Transverse Magnetic (TM) modes have different effective refractive indices and group velocities[9]. In addition, the combination of SOI and resonant cavities such as Micro-Ring Resonator (SOI-MRR) can be used to fabricate the optical switches[10-13], and the on/off function is implemented through the transition between resonant and non-resonant states at the drop-off or throughout ports of the Micro-Ring Resonator (MRR) by use of the thermal or carrier dispersion effects[14-16]. However, the polarization dependency of the SOI waveguides will usually result in the separation of the resonant peaks or wavelengths of the TE and TM modes, and then degrade the switching performance.

In practice, polarization-independent transmission is realized by use of two identical polarization dependent PICs on a common substrate or different substrates, i.e., the input optical signal is divided into the TE and TM modes by a polarization beam splitter before launched into two PICs respectively, and then the optical modes output from the PICs are recombined together as the output optical signal. In this process the mode conversion is maybe needed[17]. But, this scheme is hardly applied to the optical switching nodes composed of SOI-MRR switch chips with large numbers of driver circuits since the driver circuits lack consistency, especially in synchronous switching, unless a more complicated control algorithm is available.

In this paper, we put forward a new design of MRR capable of providing the polarization-independent transmission of optical signals, in which the TE and TM modes have the same resonant peaks by optimizing the waveguide structure and the radius of the MRRs. The optimized MRR is mainly used in the construction of polarization independent optical switch systems, in this case, the number of the driver circuits required by the MRR switches can be reduced by 50%. The resulting MRR switches can operate in a given wavelength plane, which is desirable for the conventional buildup of switching nodes[18].

1 Design principle of MRR-based optical switches

The SOI-MRR optical switches based on the carrier dispersion effect are suitable for high-speed switching. The variation of the refractive index or absorption coefficient of the SOI waveguides depends on the carrier concentration in silicon material under control of the p-i-n electrodes[19]. The characteristics of the MRR-based optical switches are closely related to the resonant condition in terms of the resonant wavelength λ as follows[20]

$$2\pi R \cdot n_{\mathrm{eff}} = m\lambda \tag{1}$$

where n_{eff} is the effective refractive index for the mode number m and R is the MRR's radius. Obviously, the change of the effective refractive index will cause the drift of the resonant peaks or wavelengths.

In order to transmit the optical pulse signals in the on/off way, an optical MRR switch should satisfy the two conditions as follows:

i) The bandwidth of an optical signal B_{S} is not greater than the net passband bandwidth of the MRR switch, that is

$$B_{\mathrm{R}} \geqslant B_{\mathrm{S}} + \Delta B \tag{2}$$

where B_{R} is the passband bandwidth of MRR and ΔB is the spectral drift resulting from the drive circuits or chip temperature.

ii) The Free Spectral Range (FSR) of the optical MRR switch is not less than the sum of B_{R} and B_{S}

$$\mathrm{FSR} \geqslant B_{\mathrm{R}} + B_{\mathrm{S}} \tag{3}$$

where the MRR's FSR is defined as the difference between two adjacent resonant wavelengths,

$$\mathrm{FSR} = \frac{\lambda^2}{n_{\mathrm{g}} L} \tag{4}$$

in which n_{g} is the group index, $L = 2\pi R$ is the MRR's perimeter. Our experiments have showed that $\Delta B_{\mathrm{R}} \leqslant$ 0.2 nm. According to Eqs. (2) and (3), when the 3 dB-bandwidth of the optical signal at 1.55 μm is 50 GHz (0.4 nm), the MRR's passband bandwidth $B_{\mathrm{R}} \geqslant 0.6$ nm and FSR$\geqslant$1 nm. From Eqs. (1) and (4), for a given resonant wavelength, the MRR's radius and FSR are dependent on the mode number.

In a single micro-ring, it is also possible that the

TE and TM components of an optical pulse signal operate at the same resonant wavelengths for optical switching. From Eq. (1), the effective refractive indices of TE and TM modes, n_{eff}^{TE} and n_{eff}^{TM}, should satisfy:

$$n_{eff}^{TE}/n_{eff}^{TM}=m_{TE}/m_{TM} \tag{5}$$

where m_{TE} and m_{TM} are the TE and TM mode numbers. On the other hand, at the operating wavelength the free spectral ranges (or group refractive indices) for the TE and TM modes should be extremely close as possible for the realization of the polarization-independent switching.

For SOI rib waveguides, the thicker the rest of the silicon layer is after etching, the smaller are the group indices for the two modes (especially for the TE mode). In addition, the variation of the height or width of the ridge mainly affect the group refractive index for TM or TE mode, while another one remains about the same.

2 Optimization of MRR-based optical switches

According to the design principle of the MRR-based optical switched, now a specific design case is illustrated. It should be pointed out that the following particular example is used to show the whole design process, the specific parameters can be adjusted according to the processing technology and the design principle mentioned above. The operating wavelength of the optical switch is 1.55 μm and the design 3 dB bandwidth is 0.6 μm which has included the spectral drift resulting from the drive circuits or chip temperature. The design process contains three basic steps: 1) The waveguide structure should be determined based on the requirement of dispersion, group index or mode characteristics, then, the radius of MRR is calculated according to the effective index corresponding to the TE/TM mode. 2) The coupling gap is confirmed due to the consideration of 3 dB bandwidth. 3) Numerical solution is used to investigate the performance of the optimized MRR structure.

2.1 Waveguide structure and micro-ring parameters

The cross section of the designed MRR waveguide is approximately rectangular for the transmission of both fundamental TE and TM modes, in the absence of higher-order modes. The structure parameters of the SOI-MRR used here are as follows: the width and height of the SOI ridge are respectively 0.44 μm and 0.511 μm, and the etching depth is 0.421 μm, as shown in Fig. 1. In the case, the group refractive indices of the TE and TM modes are basically identical with n_g = 4.1055 and the corresponding effective refractive indices are respectively calculated to be n_{eff}^{TE} = 2.8507 and n_{eff}^{TM} = 2.9135 by the effective index method.

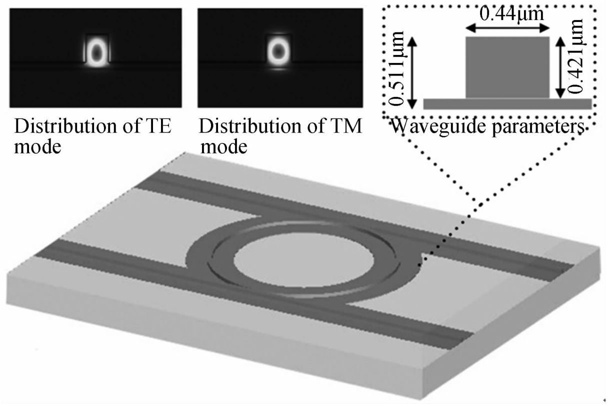

Fig. 1 The waveguide parameters of the simulated SOI-MRR structure with the fundamental TE and TM modes

Thus, at the operating wavelength of 1.55 μm, the MRR's radius can be determined as 7.875 μm with m_{TE}=91 and m_{TM}=93.

2.2 Design of the coupling gap

The gap between the straight waveguide and a single micro-ring can be deduced as follows[20]

$$B_R=\frac{FSR}{\pi}\cdot\frac{k^2}{\sqrt{1-k^2}} \tag{6}$$

where B_R is the 3 dB bandwidth of the optical MRR switch and k is the coupling coefficient between the straight waveguide and the micro-ring.

When B_R is 0.6 nm, k is 0.381 1. Unfortunately, for a given gap, the TE and TM modes have different coupling coefficients, as shown in Fig. 2. Thus, the gap width should be determined by the TE mode with lower coupling coefficient to satisfy the demand of the 3 dB bandwidth of 0.6 nm, that is, the gap width is 0.065 μm, corresponding to the 3 dB bandwidth of 1.718 9 nm for the TM mode.

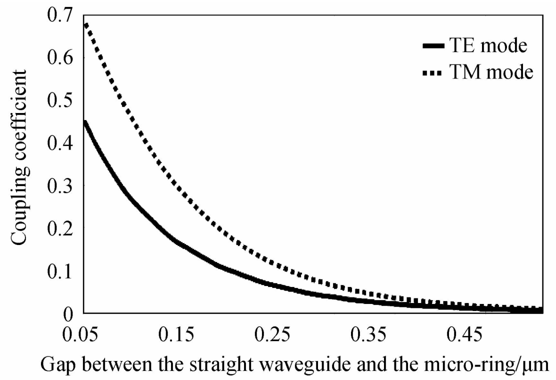

Fig. 2 The gap-dependent coupling coefficients between the straight waveguide and the micro-ring for the TE and TM modes

2.3 Simulate verification of polarization independent MRR-based optical switches

Then, the transmitted spectra of the two modes at the drop-off port can be calculated according to the transfer matrix method[21-22], as shown in Fig. 3. It is known from Fig. 3 that the TE and TM modes have the same resonance peak at the wavelength of 1.55 μm and the FSR is about 12 nm, which satisfy the design requirements above-mentioned.

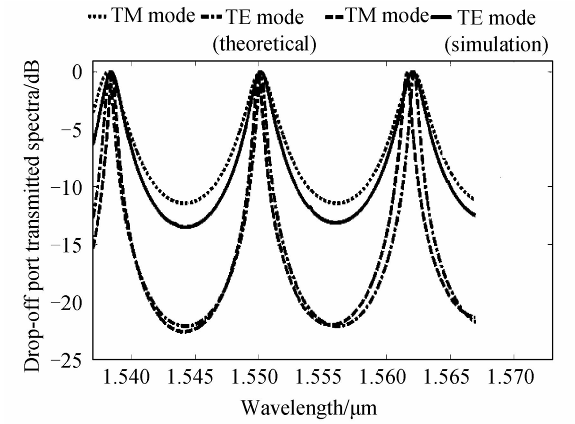

Fig. 3 The transmitted spectra of the TE and TM modes at the drop-off port

3 Simulation of MRR-based optical switch chip

According to the design parameters of the optical MRR switch, the corresponding simulation model of the SOI-MRR switch chip can be built up, in which the guided optical modes propagating in the MRR can be calculated by the simulation software for the transmission of the fundamental TE and TM modes, as plotted in Fig. 1. It should be pointed out that some simulation parameters may have a slight difference from the theoretical results, which is dependent on the detailed model of the MRR switch chip. Fig. 3 shows the transmitted spectra from the drop-off port when the MRR's radius is 7.83 μm, and the simulation results approach to the theoretical designs.

Then, the transmission characteristics of optical pulses, such as time delay and PDL, are investigated by software on condition that the S matrices of the TE and TM modes are derived from MODE Solutions, including the simulation results in time and frequency domains[23]. According to the operating mechanism of Interconnect, the TE and TM modes associated with two S matrix units (with 1×4 ports) are separately simulated in substance, as illustrated in Fig. 4. Therefore, the polarization beam splitter and combiner are used in the Interconnect simulation model of the MRR switch chip. The Interconnect simulation results are observed from optical or electrical spectrum and time-domain analyzers.

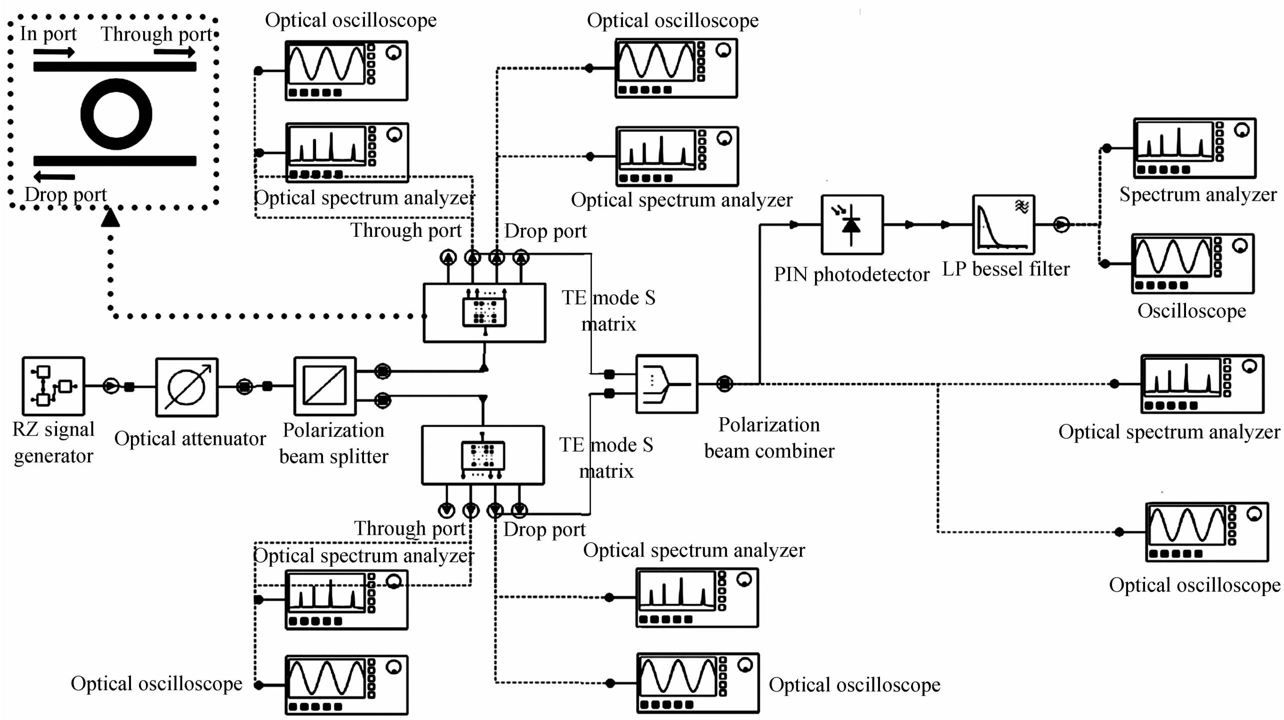

Fig. 4 The simulation model of the MRR switch chip

Fig. 5 shows the input and output (drop-off port) waveforms of the optical pulse signals at different polarization azimuths of incident linearly polarized light. The simulation results show that, the MRR switch gives rise to the time delay of 42.5 ps for the optical pulse sequence, the flatness of the pulse top means that the walk-off effect between the TE and TM pulses is negligible, and the fall time of the output optical pulses increases with the TE component, corresponding to the decrease of polarization azimuth.

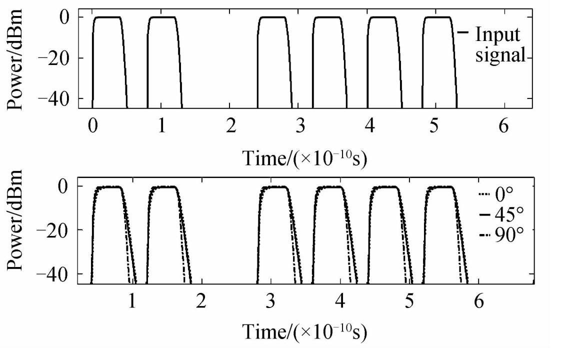

Fig. 5 The influence of polarization azimuth on the output optical pulse signal for the incident linearly polarized light

The polarization dependency of the optical pulse amplitude output from the MRR-based optical switch can be measured by the polarization dependent loss, which is defined as the peak power ratio of the TE to TM mode pulse components output from the MRR switch at the same input power. Then the PDL is obtained through the simulation and the calculation.

Fig. 6 shows that the simulation results fit well with the theoretical results which derive from matrix transmission method, in addition, under the optimized condition, the MRR-based optical switch has a minimal PDL of 0.13 dB. However, just as shown in Fig. 6, the PDL is very sensitive to the MRR's perimeter, and the length deviation from the optimal perimeter should be limited to −4～6 nm (the tolerance limit of 10 nm) for the PDL of less than 1 dB.

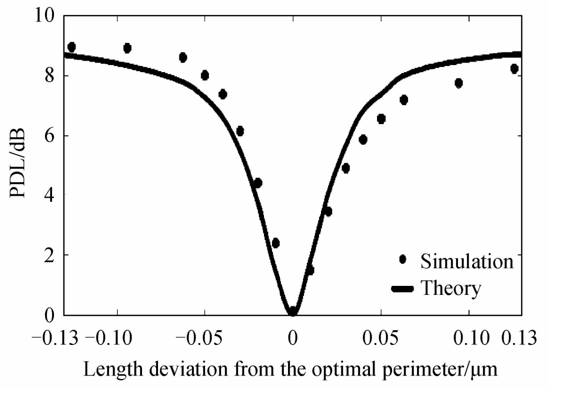

Fig. 6 The sensitivity of the PDL to the MRR's perimeter for simulation and theory

In principle, the tolerance limit may be achieved by means of the thermo-optic effect, the resonant peak drift $\Delta\lambda$ due to the thermo-optic effect should satisfy

$$\Delta\lambda=\frac{\lambda}{n_g}\cdot\Delta n_T \tag{7}$$

where n_g is the group index and Δn_T is the refractive index change quantity of material because of the thermo-optic effect. Assume length deviation of the ring perimeter due to processing technology is ΔL, in order to maintain the design requirement that the resonant peak locate at the desire position, the temperature variation ΔT in the thermo-optic effect should satisfy

$$\Delta L=\frac{L}{n_g}\cdot\frac{\partial n}{\partial T}\cdot\Delta T \tag{8}$$

According to the group index of the predetermined structure and the radius of the micro-ring, a scheme is putting forward that fabrication error of every 2.2 nm can be compensated with the temperature change of 1 K for the thermo-optic coefficient of 1.86×10^{-4}/K[15].

On the other hand, the higher and higher precision of chip fabrication process will also help to develop the polarization-independent MRR switch chips[24].

Finally, it should be pointed out that, the tolerance limit of the MRR's perimeter can be improved by appropriately adjusting the gap between the straight waveguide and the micro ring, at the same time, the MRR's 3 dB bandwidth is increased and the extinction ratio for optical switching is degraded. In this paper, different coupling coefficient is adopted to analyze the relationship between coupling coefficient and PDL. Fig. 7 shows that when the coupling coefficient of TE mode is changing from 0.381 1 to 0.424 7, the PDL is decreasing, but the extinction ratio degrades from 13.5 dB to 11 dB.

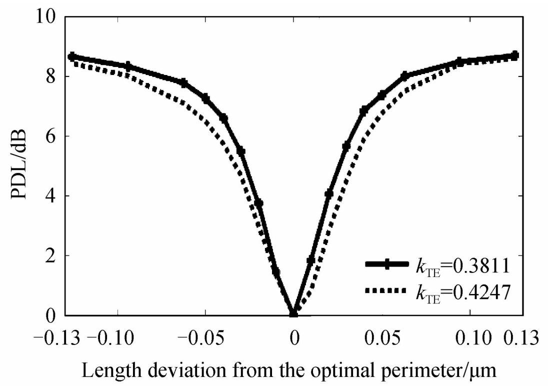

Fig. 7 The influence of the PDL to the MRR's perimeter for the different coupling coefficient

Clearly, we have to compromise by designing the MRR-based optical switch chips for the minimal PDL.

4 Conclusion

A design method of micro-ring resonator (MRR)-based optical switches is described, which are capable of simultaneously providing the transmission of TE and TM modes. The SOI waveguide structure is optimized by considering the parameters such as resonant wavelength, FSR and optical bandwidth. An MRR-based optical switch model is established and the transmission of optical pulses through the optical switch is also simulated by means of MODE Solutions and Interconnect. Calculations show that the PDL of the MRR-based optical switch presented here is very low as 0.13 dB. The deviation from the optimal perimeter should be limited to about 10nm for the PDL of 1 dB. It is feasible to make up the fabrication error through thermo-optic effect, with the perimeter change of 2.2 nm/K for the thermo-optic coefficient of 1.86×10^{-4}/K.

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