Comparison of Integrated Optical Phase Shifters Designed in Different Regime

Hao Chen^{1,3}, Haoran Meng², Xinyue Liu², Junke Ding^{1,3}, Jianguang Jiang^{1,3}, Gang Chen³ and Yinlei Hao^{1,3*}

¹College of Information Science & Electronic Engineering, Zhejiang University, Hangzhou, China
²Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, China
³Institute of Zhejiang University, Shenzhen, China

Abstract. A comparative study, in aspects of both wavelength dependence and fabrication tolerance, is carried out between silica-based phase shifters designed in two different regime, namely length difference regime and refractive index difference regime. Results show that in the wavelength range of 1500-1600 nm, phase shifter designed in refractive index difference regime has a working wavelength range 2.8~3.1 times wide as that designed in length difference regime; while in the aspect of fabrication tolerance, phase shifter designed in length difference regime is advantageous, with respect to waveguide core dimension error, and waveguide core refractive index error as well.

1 INTRODUCTION

Since the concept of integrated optics was proposed at the end of 1960s, integrated optics theory and technology have been developing rapidly. Up to recent years, integrated optical technologies have been brought out from laboratory and into the realm of practical application. A variety of integrated optical elements, couplers, modulators and wavelength division multiplexers for instance, are widely applied in the fields of optical communication, optical interconnects, and optical sensing as well.

Phase shifter, which is applied to introduce phase difference between optical waveguide branches, has been widely used in the integrated optical devices based on interference principle, e.g. Mach-Zehnder interferometer[1,2], optical isolator[3,4], arrayed waveguide grating(AWG) [5,6], and optical mixer [7,8]. The structure selection of phase shifter plays a key role in optimizing the performance of integrated optical devices. There exists two common regimes for generating phase shifts between different optical waveguide branches: one regime is to generate phase difference by introducing waveguide length difference between waveguides (named length difference regime, or LDR, in this paper), as widely applied in design of arrayed waveguides in AWG; the other regime is to generate phase difference by introducing the effective refractive index difference between different waveguides (named refractive index difference regime, or RIDR in this paper), which can be implemented by changing the geometric dimension of the waveguide cross section. These two phase shift design regimes will produce

integrated optical devices of different performance. For example, Pierre Labeye and his team show that the phase shifter based on refractive index difference regime has better performance in terms of the range of working wavelength [9]. But up to now, there is few reports on the comprehensive performance of the two phase shifters, for example, there is a lack of comparison fabrication tolerance between the two phase shifting regimes.

In the current article, a comprehensive comparison of SiO₂ based waveguide have been presented between phase shifters designed by the two phase shifting regimes, LDR and RIDR, based on calculation of the wavelength dependence and fabrication tolerance behavior.

2 THEORY AND METHOD

The two phase shifting regimes are shown in Fig.1. Fig.1 (A) represents LDR, in which phase difference is generated by increasing length of the waveguide 2 (WG2) with respect to waveguide 1 (WG1) by ΔL ; Fig. 1 (B) represents the RIDR, in which phase difference is generated by locally increasing WG2 width to W_1 .

For phase shifter designed in LDR, considering wavelength dependence of waveguide effective refractive index, phase difference generated between the two waveguides, WG1 and WG2 shown in Fig.1 (A), is expressed as

*Corresponding Author: haoyinlei@zju.edu.cn

Fig 1. Schematic diagram of the two phase shifting regimes, where (A) represents LDR and (B) represents RIDR.

$$\Delta\Phi_1(\lambda) = \frac{2\pi}{\lambda} \cdot N_{eff}(W_0, \lambda) \cdot \Delta L \quad (1)$$

where λ is wavelength; W_0 is waveguide core width; N_{eff} is waveguide effective refractive index; ΔL is length difference between the two waveguides. Correspondingly, for phase shifter designed in RIDR, phase difference between WG1 and WG2 can be expressed as

$$\Delta\Phi_2(\lambda) = \frac{2\pi}{\lambda} \cdot [N_{eff}(W_1, \lambda) - N_{eff}(W_0, \lambda)] \cdot L \quad (2)$$

where W_1 is width of the waveguide in the phase shift section; L is length of phase shifter, as shown in Fig.1 (B).

Silica-based optical waveguides with refractive index contrast of 0.45% are adopted, height of waveguide core is assumed to be $6.5\mu\text{m}$, and the width of the waveguide varies between $6.6\mu\text{m}$ and $7.0\mu\text{m}$. These waveguide parameters ensure waveguide working in single-mode regime. Effective refractive index of the optical waveguide is obtained by solving the Maxwell equations using the half-vector method.

Refractive index for the Ge-doped silica is calculated using the well-proved Sellmeier dispersion equation [10]

$$n^2(\lambda) - 1 = \sum_{i=1}^3 \frac{[SA_i + X(GA_i - SA_i)]\lambda^2}{\lambda^2 - [SL_i + X(GL_i - SL_i)]} \quad (3)$$

where n is the refractive index of Ge-doped Silica; λ is the wavelength in a vacuum; and SA_i , SL_i , GA_i , and GL_i are the Sellmeier coefficients for the SiO_2 and GeO_2 , respectively. X is the GeO_2 concentration in mol%.

3 RESULTS AND DISCUSSION

3.1 Wavelength Dependence

Two kinds of 90 degree phase shifters are designed at central wavelength of 1550 nm, in LDR and RIDR, respectively. Wavelength dependence of these phase shifters is shown in Fig. 2. For RIDR, the wavelength dependence of the phase shifter for W_1 varies from $6.6\mu\text{m}$ to $7.0\mu\text{m}$ at $0.1\mu\text{m}$ interval. Several phenomenon can be observed from Fig.2 as follow: Firstly, phase shift of phase shifters designed in both regime are linearly dependent on wavelength in the wavelength range of 1500-1600 nm; Secondly, for the phase shifter designed in LDR, slope of phase shift of with respect to wavelength is approximately $0.059^\circ/\text{nm}$. Thirdly, slope of phase shifter with respect to wavelength designed in RIDR decreased from $-0.021^\circ/\text{nm}$ at $W_1 = 6.6\mu\text{m}$ to $-0.019^\circ/\text{nm}$ at $W_1 = 7.0\mu\text{m}$. On the basis of these phenomenon it can be concluded that phase shifter in RIDR have a working bandwidth approximately 2.8~3.1 times as that of phase shifter in LDR.

3.2 Fabrication Tolerance

Fig 2. Wavelength dependence of 90 degree phase shifter designed in LDR and RIDR, respectively.

Due to inevitability of waveguide core dimension error, as well as refractive index error, induced in the process of waveguide fabrication, it is of importance to take these errors into consideration while designing a phase shifter.

Phase shift of the two 90 degree phase shifter designed at the wavelength of 1550 nm in different regimes and presented in Fig.3, with width, height, waveguide core refractive index taken into consideration. Tab. 1 gives phase shift change slope with respect error of waveguide width, waveguide height, and waveguide core refractive index as well. It can be seen clearly that phase shifter designed in RIDR is more sensitive to

fabrication errors, compared with that designed in LDR. Difference between is ascribed to the length of phase shifter. For a 90 degree phase shifter in LDR, the length difference, as denoted above as ΔL , is only 268nm; while for the phase shifter designed in RIDR, the shifter length is several mm, a much larger value than that in LDR. Since waveguide fabrication error exist over the waveguide part that are different between WG1 and WG2, device of large length suffer much seriously from fabrication error.

Fig 3. Fabrication tolerance of 90 degree phase shifter designed in LDR and RIDR, respectively.

Table 1. Phase shift change rate with respect to waveguide width, waveguide height, and waveguide core refractive index as well.

	Width dependence	Height dependence	Refractive index dependence
LDR	$2.0 \times 10^{-5} \text{ }^\circ / \text{nm}$	$2 \times 10^{-5} \text{ }^\circ / \text{nm}$	$47 \text{ }^\circ / \text{RIU}$
RIDR	$2.2 \times 10^{-2} \text{ }^\circ / \text{nm}$	$3.1 \times 10^{-3} \text{ }^\circ / \text{nm}$	$1.0 \times 10^4 \text{ }^\circ / \text{RIU}$

4 CONCLUSIONS

In this paper, a comparative study, in aspects of wavelength dependence and fabrication tolerance, is carried out between integrated optical phase shifters designed in two different regimes, namely LDR and RIDR. The results show that in the wavelength range of 1500-1600 nm, the phase shifter designed in LDR are more sensitive to wavelength, but possesses much higher fabrication tolerance; while the phase shifter designed in RIDR have an operating wavelength range 2.8~3.1 times wide as that in LDR, but it suffers much seriously from waveguide fabrication error.

ACKNOWLEDGEMENT

The Project is supported by Zhejiang Provincial Natural Science Foundation under Grant LY17F050007, in part by Shenzhen science and technology project under Grant JCYJ201708161724 09618; in part by National Natural Science Foundation of China under Grant 61428502, in part by Shenzhen Medical High-energy Focused Non-invasive Therapy Engineering Laboratory.

REFERENCES

1. N. Takato, T. Kominato, A. Sugita, K. Jinguji, H. Toba and M. Kawachi, 1990. Silica-based integrated optic Mach-Zehnder multi/demultiplexer family with channel spacing of 0.01-250 nm. *IEEE Journal on Selected Areas in Communications*. 8(6), 1120-1127.
2. K. Suzuki, T. Yamada, M. Ishii, T. Shibata and S. Mino, 2007. High-Speed Optical 1×4 Switch Based on Generalized Mach-Zehnder Interferometer With Hybrid Configuration of Silica-Based PLC and Lithium Niobate Phase-Shifter Array. *IEEE Photonics Technology Letters*. 19(9), 674-676.
3. F. Auracher, H.H. Witte, 1975. A new design for an integrated optical isolator. *Optics Communications*. 13(4), 435-438.
4. H. Yokoi, T. Mizumoto, N. Shinjo, N. Futakuchi, and Y. Nakano, 2000. Demonstration of an optical isolator with a semiconductor guiding layer that was obtained by use of a nonreciprocal phase shift. *Appl. Opt.* 39(33), 6158-6164.
5. K. A. McGreer, 1998. Arrayed waveguide gratings for wavelength routing. *IEEE Communications Magazine*. 36(12), 62-68.
6. H. Takahashi, S. Suzuki, K. Kato and I. Nishi, 1990.
7. Arrayed-waveguide grating for wavelength division

multi/demultiplexer with nanometer resolution. *Electronics Letters*. 26(2),87-88.

8. S. Jeong and K. Morito, 2010. Compact optical 90° hybrid employing a tapered 2×4 MMI coupler serially connected by a 2×2 MMI coupler. *Opt. Express*. 18(5), 4275-4288.
9. S. Jeong and K. Morito, 2009. Optical 90° hybrid with broad operating bandwidth of 94 nm. *Opt. Lett.* 34(22), 3505-3507.
10. Labeye P, 2008. PhD thesis, Institut National Polytechnique de Grenoble.
11. J. W. Fleming, 1984. Dispersion in GeO₂-SiO₂ glasses. *Appl. Opt.* 23(24), 4486-4493.