Comparison of Integrated Optical Phase Shifters Designed in Different Regime

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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 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 W2.

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
\[ n^2(\lambda) - 1 = \sum_{i=1}^{n} \left[ S_A + X(G_A - S_A) \right] \lambda^2 - \left( S_L + X(G_L - S_L) \right) \lambda^0 \] (3)

where \( n \) is the refractive index of Ge-doped Silica; \( \lambda \) is the wavelength in a vacuum; and \( S_A \), \( S_L \), \( G_A \), and \( G_L \) 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 \( W_i \) varies from 6.6\,\mu m to 7.0\,\mu m at 0.1\,\mu 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°/\,\mu m. Thirdly, slope of phase shifter with respect to wavelength designed in RIDR decreased from –0.021°/\,\mu m at \( W_i = 6.6\,\mu m \) to –0.019°/\,\mu m at \( W_i = 7.0\,\mu m \). 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.](image-url)
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. I 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 $\Delta L$, 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.](image-url)
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.

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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 1x4 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. 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 2x4 MMI coupler serially connected by a 2x2 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.

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              | $2.0 \times 10^{-4}/$ nm | $2.0 \times 10^{-4}/$ nm | $47^\circ/$ RIU                  |
| RIDR             | $2.2 \times 10^{-2}/$ nm | $3.1 \times 10^{-3}/$ nm | $1.0 \times 10^4/$ RIU          |