Large bandwidth and low driving voltage generic platform based polarization phase shifter utilizing QCSE

K. Mehrabi[1], W. Yao[1], K. A. Williams[1], and J. J.G.M. Van der Tol[1]

[1] Eindhoven University of Technology, Dept. of Electrical Engineering, 5612 AZ Eindhoven, Netherlands

The control of the phase shift difference between transverse electric (TE) and transverse magnetic (TM) modes is an essential function for the polarization controller of a coherent receiver. This paper presents a small, low driving voltage, and wideband differential phase shifter based on a generic integration platform. Utilizing the quantum confined stark effect(QCSE) in a strain enhanced birefringence-based InGaAsP multi quantum well structure the phase shift difference between TE and TM modes is enlarged. The simulation results indicate that with the voltages of 1.5 V and a length of 1.5 mm more than 2π phase shift difference over a wavelength range of 100 nm can be achieved between TE and TM modes.

Introduction

A coherent receiver become widely adopted in high performance optical telecommunication systems, since it increases receiver sensitivity and thereby improves the system performance [1]. In such receivers, an integrated polarization controller (PC) is a very desirable element to adjust the polarization state of the input signal with the signal of the local oscillator [2]. Among many technological circuits which can be used to realize a polarization controller, the straight-line waveguide based configuration [3] is attractive due to the ease of fabrication and compactness. The basic elements in this kind of polarization controller are a polarization rotator and a phase shifter. A large number of researches focused on polarization rotators [4-6]. Between them, the single section waveguide with one vertical wall and one slanted wall is the most compact and results in a high conversion efficiency [5, 6]. However, one of the operations in a polarization controller is setting the high phase difference between TE and TM, which can be done with a differential phase shifter. But, the previous designs for phase shifters focused only on TE polarization [7, 8]. In order to realize a simplified polarization controller, this paper focused on designing a differential phase shifter that induces a high phase shift difference between TE and TM modes.

The electro absorption effect in multiple quantum wells (MQWs) affects TE and TM modes differently and provides a very promising approach towards increasing the birefringence and realizing a compact and low power optical polarization phase shifter. In the following, we propose and demonstrate a differential phase shifter using quantum confined stark effect (QCSE) based on a generic InP platform.

Design procedure

The p-i-n diode structure is utilized for designing of the waveguide based phase shifter. As is shown in Fig. 1. a multiquantum waveguide based core is designed. When an electric field is applied, the absorption near the band edge changes significantly. In fact, the bands tilt. The confinement of the electrons and holes decreases and a reduction of the overlap of electron and hole wavefunctions results in a decrease in the absorption near the band edge.

To estimate the device performance the absorption change due to an applied electric field is simulated. Afterwards, the effective index change as a function of wavelength and applied reverse bias voltage is calculated, utilizing the Kramers-Kroning relation [9],

$$\Delta n(\lambda_0, \Delta V) = \frac{{\lambda_0}^2}{2\pi^2} P \int_0^{+\infty} \frac{\Delta\alpha_{abs}(\lambda, \Delta V)}{{\lambda_0}^2 - \lambda^2} d\lambda \qquad (1)$$

in which Δn indicates the effective index change at the wavelength λ_0 with the reverse bias voltage changes of ΔV.

Our aim is to maximize the phase shift difference between TE and TM modes. To realize this goal and simultaneously align the absorption edge to get low loss transmission at the communication wavelength of 1.55 µm, a compressive strain of 0.73% is applied to the wells. Moreover, to compensate this negative strain a tensile strain of 1.06% is exerted on the barriers. The widths of the QWs and also barrier are designed for zero net strain while maintaining nearly zero absorption at 1.55 µm wavelength. Fig. 2. indicates the strain of different layers inside the core of the presented phase shifter.

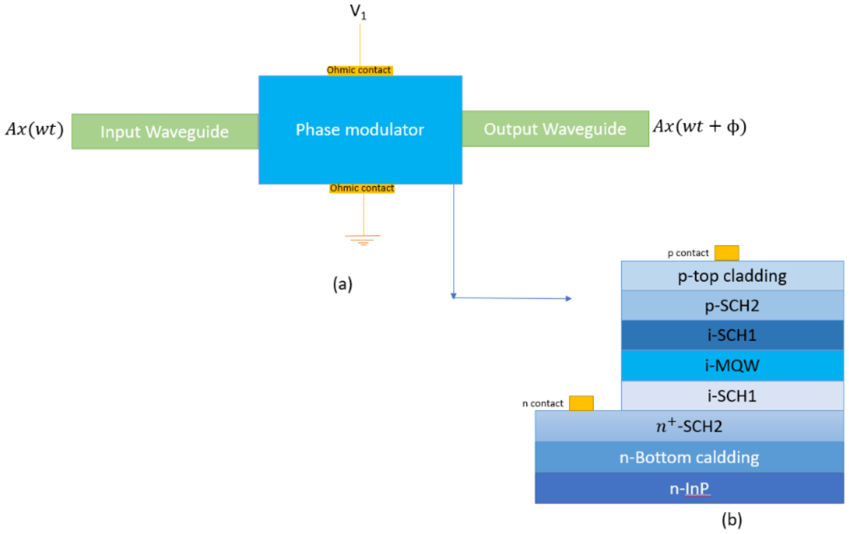

Fig. 1. The phase shifter structure (a) building block and electronic and optical interfaces (b) layer stack.

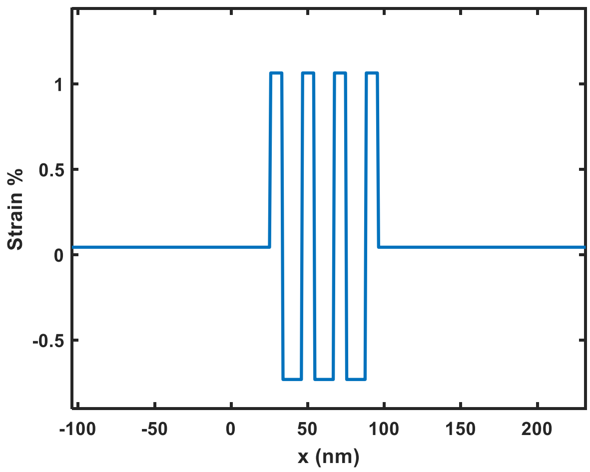

Fig. 2. Strain compensation in the structure

Simulation results

The 1D simulations are performed to obtain the absorption and characterize the device performance. During the absorption process inside the InGaAsP/InP waveguides, the TE modes mainly generate heavy holes while TM light mainly generates light holes [10]. Applying tensile strain to the wells results in a shift of the light holes' energy gap to lower energies. Therefore, the absorption will be controlled by light holes for both TE and TM modes. So, to get a higher absorption change for TE mode, we applied the compressive strain to the well. At the same time by controlling of well widths both the absorption of TE and TM is zero for wavelength larger than 1.413 µm. Applying a voltage moves the bandgap to lower energies. However, as is shown in Fig. 3, it still remains zero at the wavelength of 1.55 µm.

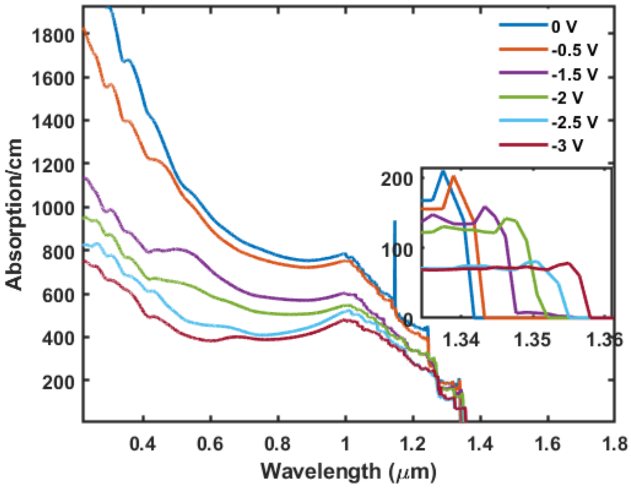

Fig. 3. The absorption curve of the TE mode as a function of wavelength.

The phase shift of the structure is calculated as follows:

$$\Delta\varphi = \frac{2\pi}{\lambda_0}\Delta n(\lambda_0)l \qquad (2)$$

where, λ_0 is the wavelength at which an effective index change of Δn is achieved, based on Kramers-Kronig relation. l represents the device length which is set to 1.5 mm. Fig. 4 shows the calculation results of the phase shift versus wavelength. As is indicated, the presented phase shifter applies high phase shift difference between TE and TM modes over the wide bandwidth of 100 nm around the central wavelength of 1.55 µm. It should be mentioned that based on the equation (2) the device shows linear phase response with length variation. Fig. 5 indicated the phase shift of the TE and TM modes as a function of phase shifter length at the wavelength of 1.55 µm.

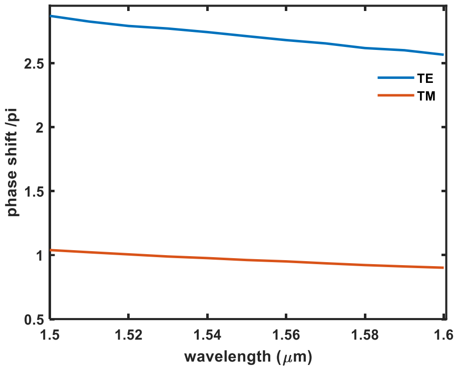

Fig. 4. Phase shift of the TE and TM modes versus wavelength.

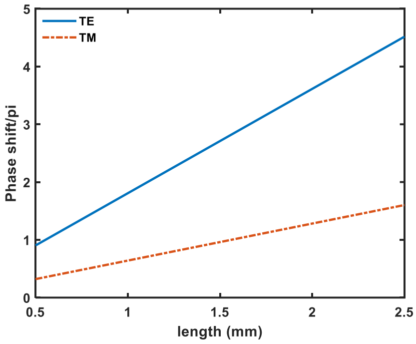

Fig. 5. Phase shift of the TE and TM modes versus the phase shifter length.

Conclusion

This paper presented a waveguide polarization phase shifter on InGaAsP/InP generic platform. By optimizing the strain in the multi quantum well p-i-n structure 2π phase shift difference between TE and TM modes is achieved over 100 nm bandwidths with a bias voltage of 1.5 V. The structure length is achieved as 1.5 mm.

Acknowledgments

This work is part of the PICaboo project supported by EU.

References

[1] L. Tie and K. Xi-Zhen, “Polarization control in the coherent optical detection system,” Infrared Laser Eng. Vol. 41, 3069–3074, 2012.

[2] J. Prat, J. Comellas, and G. Junyent, “Experimental demonstration of an all-fiber endless polarization controller based on Faraday rotation,” IEEE Photon. Technol. Lett., vol. 7, 1430–1432, 1995.

[3] M. Ito, K. Okawa, T. Suganuma, T. Fukui, E. Kato, T. Tanemura, Y. Nakano, “Efficient InGaAsP MQW-based polarization controller without active-passive integration”. Opt. Express, vol. 29, 10538–10545, 2021.

[4] A. E. Elfiqi, R. Kobayashi, R. Tanomura, T. Tanemura, and Y. Nakano, “Fabrication-tolerant half-ridge InP/InGaAsP polarization rotator with etching-stop layer,” IEEE Photon. Technol. Lett. Vol. 32, 663–666, 2020.

[5] J. J.G.M. van der Tol, M. Felicetti, M., and M. K. Smit, “Increasing tolerance in passive integrated optical polarization converters”, *Journal of lightwave technology*, vol. *30*, 2884-2889, 2012.

[6] Y. Zhao, W. Yu, S. Dai, J. Li, T. Lin, M. Li, and J. Liu, “Compact lithium niobate-on-insulator polarization rotator based on asymmetric hybrid plasmonics waveguide,” IEEE Photon. J., vol.13, 4800105, 2021.

[7] N. Dhingra, J. Song, G. J. Saxena, E. K. Sharma, and B. M. A. Rahman, "Design of a compact two-mode multi/demultiplexer consisting of multimode interference waveguides and a wavelength-insensitive phase shifter for mode-division multiplexing transmission." Journal of Lightwave Technology, vol. 30, 2421-2426, 2012.

[8] N. C. Harris, Y. Ma, J. Mower, T. B.-Jones, D. Englund, M. Hochberg, and C. Galland, "Efficient, compact and low loss thermo-optic phase shifter in silicon," Opt. Express, vol. 22, 10487-10493, 2014

[9] G. B. Morriso et al. “Electroabsorption modulator performance predicted from band-edge absorption spectra of bulk, quantum-well, and quantum-well-intermixed InGaAsP structures”. *Solid-state electronics*, vol. *51*, 38-47, 2007.

[10] J. Piprek, Yi-Jen Chiu, and J. E. Bowers, “Analysis of Multi Quantum Well Electroabsorption Modulators”, SPIE Proc. 4646-77, Physics and Simulation of Optoelectronic Devices X, Photonics West, San Jose, CA, 2002.