P015

Design of a phase shifter in InP Membranes On Silicon based on a slot-waveguide with liquid-crystal

A.J. Millán-Mejía , J.J.G.M. van der Tol, and M.K. Smit

Photonic Integration Group (PhI), Dept. of Electrical Engineering, Technische Universiteit, Eindhoven, Den Dolech 2, 5612 AZ Eindhoven, The Netherlands
A.Millan.Mejia@tue.nl, J.J.G.M.v.d.Tol@tue.nl, M.K.Smit@tue.nl

Abstract: In the development of the InP Membranes On Silicon (IMOS) platform, phase shifters are essential elements for switches or tunable filters. The simulation of slot-waveguides with an organic liquid crystal (5CB) shows that high performance devices with a theoretical predicted optical voltage-length product of $U_{\pi}L = 0.0607\ Vmm$ are possible. These devices present sub millisecond response (~300 μs) and low energy consumption ($\sim 10\ pJ\ per\ transition$).

Introduction

Fig. 1: Schematic of the phase shifter

In the last years, optical interconnects are becoming an essential technology for short distance links. A need for higher speed communication and lower energy consumption devices inside computer chips are the two key factors for this change. The use of a thin optical layer of InP material bonded with BCB on top of silicon wafers is an attractive solution (InP membranes On Silicon (IMOS))[1]. One important element for this platform is a phase shifter. This component allows constructing complex devices such as switches and tunable filters.

Important results in modulators using slot waveguides with electro optical polymer have been demonstrated in Silicon On Insulator (SOI) platform. Low voltage devices ($V_{\pi} = 0.25\ V$)[2] and high speed modulators ($40\ Gbit/s$) with only $250\ \mu m$ length[3] are relevant examples. These results make this structure appealing to be implemented in IMOS platform.

The slot-waveguide is a configuration where the TE optical mode is mostly confined in the low refractive material due to boundary conditions, creating large discontinuities in the electric field at the high index contrast interfaces. Contrary to previous slot waveguide devices, this structure is covered with a SiO_2 layer, and due to the small dimension of the slot; a gap of almost the same dimension of the slot is created. By making openings at the extremes of the slot waveguides and deposit a drop of LC in one side, the capillary forces will fill the created gap with LC. This configuration will provide a protection of the LC, making a most durable device than solutions presented previously in literature[4]. Because a huge part of the optical mode overlaps with the LC, when an electric field is applied, E_0 control the orientation of the LC molecules and a large variation of the refractive index is obtained. Figure 1 show a schematic representation of the slot waveguide phase shifter.

In terms of the electrical part, an n-doped layer of InP next to the slot waveguide will provide the connection with the contacts allowing a high electric field present inside the slot due to the small slot dimension. The integration of the phase shifter with strip waveguides developed in the IMOS platform is obtained by using logarithmic tapered converters[5]. This geometry allows adiabatic transition in a reduced length (~10 μm) and provides electrical isolation, requirements needed for this device.

Geometry optimization

In order to make an optimization of the structure, we assume that the LC molecules inside the slot are aligned parallel to the sidewall of the InP waveguides. In the absence of an electric field ($V = 0$) the electric component of the optical mode is then perpendicular to the LC molecules, obtaining a refractive index inside the slot $n_{\perp} = 1.51$. When a high voltage is applied, (V>>0) the LC molecules orientate in the direction of the electric field applied, which is parallel to the electric component of the optical mode. In this condition, the refractive index in the slot is $n_{\parallel} = 1.68$. We define these as the two states of the phase shifter. The phase difference obtained between these two states is related with the effective refractive index difference (Δn_{eff}). We plot this parameter versus the geometry parameters which are the width of the slot and the sidewall angle. The height of the waveguides was defined to be 300 nm and the connection n-doped InP layer is 50 nm thick. This is compatible with the passive elements already developed for this platform[6]. The width of the strip waveguides was selected to be 240 nm, this was optimized in our previous study of a slot modulator with electro optical polymer[7]. The optimization study was carried out with an eigen mode solver (Lumerical TM MODE solver).

(a)

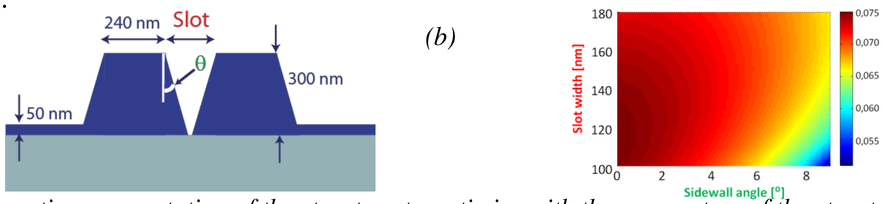

Fig. 2: (a) Schematic representation of the structure to optimize with the parameters of the structure indicated. (b) Effective refractive index difference (Δn_{eff}) between the two liquid crystals states.

In the fabrication of passive elements in IMOS, a sidewall angle between 2° and 5° is obtained depending on the etching process used. As can be seen from figure 2 (b), the maximum of the Δn_{eff} with a sidewall angle of 5° is found with a slot of $140\ nm$ with $\Delta n_{eff} = 0.0715$.

Performance

To analyze the performance of this device, calculation in the phase change versus the length of the device is needed. We consider a complex propagator $\exp(-\beta z)$, the difference in phase is defines as $\Delta\phi/L = \beta(V=0) - \beta(V >> 0) = 2\pi\Delta n_{eff}/\lambda$, if we consider a wavelength of $\lambda = 1.55\ \mu m$, we obtain $\Delta\phi/L = 92\,\pi/mm$. Taking into account the saturation on the orientation of the LC molecules is around $\sim 40V/\mu m$ [5], which correspond to $5.6\,V$ applied between the electrodes, we obtain an voltage-length product of $U_\pi L = 0.0607\ Vmm$. Another important parameter is the time response of the device. It is well known that for planar aligned LC cells the time response is defined by the relaxation time, $\tau_{fall} = \gamma_1 d^2/\pi^2 K_{11}$ [8]. In the case of 5CB LC, and considering a slot of $140\ nm$, $\tau_{fall} = 303.44\ \mu s$. This time can be reduced using different techniques such as bias voltage effect or transient nematic effect. The RC time constant for $1mm$ length device is around $\tau_{RC} = 2\ ps$, leaving room of improvement if different LC with better performance is used. To calculate the energy consumption, we consider the LC works as insulator material without current flowing through this material, so our device works as a capacitor. Miller [9] establishes for devices as the one presented here, the energy consumption is the one needed to charge and discharge the electrodes, which can be calculated as $\Delta E = CV^2$ per cycle. In case we consider a switching of a device of $1\ mm$ length, and the dielectric permittivity $\epsilon_{\parallel} = 18$, the capacitance of the device is $C = 341.52\ fF$. With an operational voltage V=5.6V, the energy consumption per cycle is $E = 10.71\ pJ$. If we switch at $500\ kHz$, which is close to its speed limit. The power needed will be $17\ \mu W$. This is around 2 orders of magnitude lower than high performance thermo optical devices[10].

Conclusions

The use of a slot waveguide connected with n-doped InP layers to the contacts allows for high overlap of the electrical and optical mode with the liquid crystal. These characteristics allow a low energy consumption ($\sim 17\ \mu W$) and high efficiency phase shifter ($U_\pi L$ = 0.0607 Vmm). The time response is in microsecond ($\sim 300\ \mu s$). We consider this device can provide a high performance phase shifter for the IMOS platform and the protection layer of SiO_2 will make it durable. The fabrication of this device is underway.

References

1. J. van der Tol *et al.*, *IET Optoelectronics*, **5**, pp 218-225 (2011)
2. T. Baehr-Jones *et al*. *Applied physics letters*, 92, pp 163303-1- 163303-3 (2008)
3. R. Palmer *et al.*, *OFC conference*, (2014)
4. J. Pfeifle *et al.*, *Optics express*, **20**, pp. 15359-15376 (2012)
5. R. Palmer *et al.*, *IEEE Photonics Journal*, **5**, (2013)
6. J Pello *et al.*, *Proceedings Symposium IEEE Photonics Society Benelux*, pp. 213-216 (2011).
7. A.J. Millan Mejia *et al.*, *Proceedings Symposium IEEE Photonics Society Benelux*, pp. 195–198 (2013).
8. Yadav *et al.*, *Acta physyca polonica A*, **119**, pp. 824-828, (2011)
9. David A.B. Miller, *Optics Express*, **20**, pp. A293-A308, (2012)
10. Lian-Wee Luo *et al*. *Optics Express*, **18**, pp 23079-23087, (2010)