PZT based acoustic resonator for the refractive index modulation

Irfan Ansari
Photonics Research Group
INTEC dept
Ghent University-IMEC
Email: irfan.ansari@ugent.be

Jeroen Beeckman
Liquid Crystal & Photonics Group
ELIS dept
Ghent University

Dries Van Thourhout
Photonics Research Group
INTEC dept
Ghent University-IMEC

***Abstract*—We propose a PZT based acoustic resonator to modulate the refractive index of a Silicon waveguide. We use an inter-digital transducer (IDT) defined on the PZT film to create a standing acoustic wave resonance in the suspended device. We calculate the effective index change from the acousto-optic overlap integral and illustrate its dependency on the IDT pitch.**

***Index Terms*—Acousto-optic, PZT, Silicon photonics, Ferroelectric thin film, Microwave photonics.**

I. Introduction

Integrated acousto-optic devices are emerging as a potential candidate to achieve efficient microwave to optical conversion [1]. In such devices, the actuated acoustic waves dynamically perturb the refractive index of the material through the photoelastic effect. This perturbation has been achieved with both travelling waves and standing waves. However in case of travelling waves, only partial acoustic energy is utilised for the index modulation, and most of the energy propagates away. On other hand, standing waves in a resonance based device have been demonstrated to achieve higher modulation efficiency [1].

Realization of such acousto-optic devices has been demonstrated mostly on piezoelectric active photonic platforms such as $LiNbO_3$ and GaAs. In case of the silicon photonics platform, integration of a piezoeletric thin film is needed, for example AlN [2]. Recently, a sol-gel process using an optically transparent buffer layer (LaO_2CO_3) to grow a PZT thin film was reported [3]. This opens the possibility to directly integrate a PZT thin film on Si PICs.

In this work, we analyse a PZT based acoustic resonator directly integrated on a Si waveguide, as shown in figure 1. We numerically investigate the interaction between the IDT actuated acoustic field and the optical field in the waveguide and calculate the strain induced index change through the acousto-optic overlap integral.

II. Photoelastic effect

The strain field associated with the acoustic waves perturbs the effective refractive index (n_{eff}) in the Si waveguide through the photoelastic effect. This index change can be described as follows [1]:

$$\Delta n_{eff} = \frac{n_{eff}^3}{2} \frac{\int_D E^* \boldsymbol{pS}\, E\, dr}{\int_D E^* E\, dr} \quad (1)$$

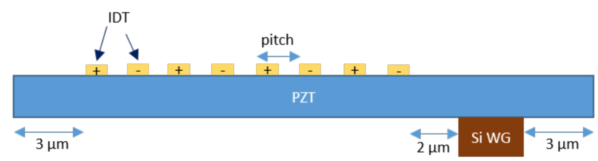

Fig. 1. a 2D schematic of the suspended IDT/PZT/Si waveguide stack. The thickness of the IDT, PZT-layer and Si waveguide is 70 nm, 200 nm and 220 nm respectively. The width of the Si waveguide is 450 nm. The number of finger-pairs in the IDT is 4.

Here D is the 2D cross-section of the waveguide, E is the electric field of the waveguide mode, $\boldsymbol{p}$ is the photoelastic tensor of the waveguide medium and $\boldsymbol{S}$ is the strain field induced by the acoustic wave. Equation 1 can be approximated as:

$$\Delta n_{eff} = \frac{n_{eff}^3}{2} \frac{\int_D \left[(p_{11}s_{xx} + p_{12}s_{yy})E_x^2 + (p_{21}s_{xx} + p_{22}s_{yy})E_y^2\right] dr}{\int_D E^* E\, dr} \quad (2)$$

In our case, since the light propagates along the Si [110] direction, we apply a rotational transformation on the photoelastic tensor of Si taken from [4]. Thus we obtain the following coefficients that we used for calculating the overlap integral: p_{11}= -0.090, p_{12} = 0.013, p_{21} = p_{12} and p_{22} = p_{11}.

III. Acousto-optic simulation

The schematic of the proposed device is shown in figure 1. We define an IDT with 4 finger-pairs on the PZT film to actuate acoustic waves. We set the lateral distance between edge-IDT, IDT-waveguide, and waveguide-edge as 3 μm, 2 μm and 3 μm respectively. We set the PZT thickness as 200 nm, and the waveguide width and thickness as 450 nm and 220 nm respectively.

In the first step of the simulation, we calculate the electric field from the IDT through an electrostatic simulation. Then, we align the PZT domain polarization along these electric field lines. This is done to account for the process whereby the PZT is poled with the IDT itself as discussed in [5]. In the second step, we apply an RF input signal (amplitude 1V) to the

IDT and simulate the piezoelectric actuation in the frequency domain. Thereafter, we calculate the index change due to the photoelastic effect with the overlap integral of equation 2.

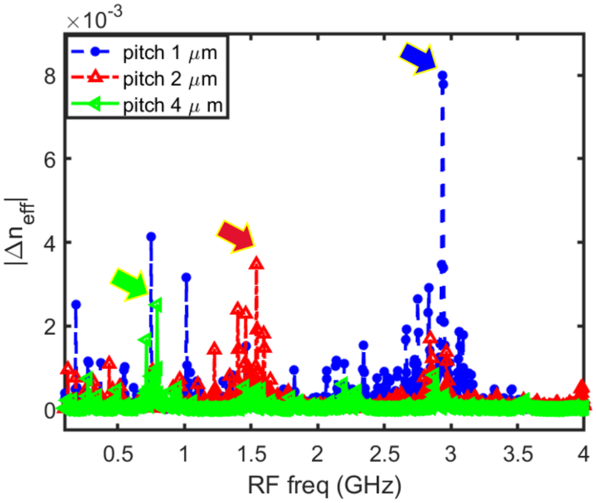

Fig. 2. The calculated refractive index change with respect to the RF frequency applied to IDTs with three different pitches. The arrows indicate the strongest index change for each IDT pitch.

Figure 2 shows $|\Delta n_{eff}|$ calculated for 3 IDTs with different pitch. The arrows indicate the actuation of the primary acoustic mode for the corresponding IDT pitch. As expected, we see that the primary acoustic mode frequency decreases proportionally when the IDT pitch is increased. We also observe that the index modulation is maximum for 1 μm pitch and decreases for larger pitch. This can be understood by looking at the overlap of the optical field and the strain field from the acoustic mode.

In figure 3(a), we show the strain profile (s_{xx}) of the primary acoustic mode (frequency 2.94 GHz) from the IDT with pitch $1\mu m$. We illustrate s_{xx} because this is the dominant component ($p_{11} > p_{12}$) influencing the refractive index in a TE mode as can be seen from equation 2. In the inset, we show the mechanical Eigenmode simulated with the continuous periodic boundary on the left and right boundary of one IDT period. We notice that the Eigenmode frequency (2.94 GHz) and the field profile match well with the piezoelectrically actuated acoustic mode (at RF frequency of 2.94 GHz). This further indicates the primary acoustic mode excitation at 2.94 GHz for the IDT with pitch 1 μm. Figure 3(b) shows the optical mode profile for a TE mode (n_{eff} = 2.4012) confined in the Si waveguide (width 450 nm). Also for the IDT with pitch 1 μm ($\sim$ 2×waveguide width), we notice that the actuated strain profile is mostly confined inside the waveguide region. This results in a strong acousto-optic overlap as the two fields add up constructively, resulting in a high index modulation.

IV. Conclusion

We numerically demonstrated a PZT based acoustic resonator to module the refractive index of an integrated Si

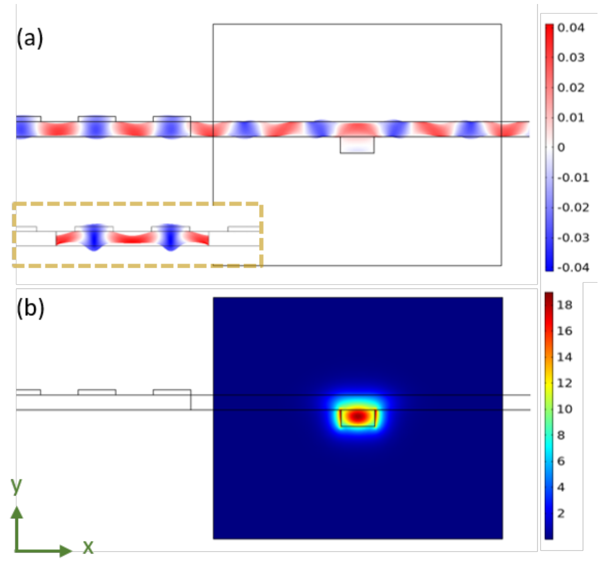

Fig. 3. (a) Simulated strain field (s_{xx}) when the IDT with pitch 1 μm is actuated with 1V RF signal at 2.94 GHz. The inset shows the mechanical Eigenmode of the IDT at 2.94 GHz. (b) TE mode profile in the Si waveguide

waveguide. Our simulation shows that for a strong acousto-optic interaction, the acoustic wavelength (IDT pitch) should be $\sim$ twice the waveguide width. Therefore, given the tight confinement of the optical mode in Si PICs, this scheme can be exploited to fabricate high frequency (GHz) acousto-optic devices that can be used for microwave to optical conversion.

Acknowledgment

This work was supported by the EU commission through Grant agreement No. 732894 (FET proactive HOT) and through the UGent grant BOFGOA2020000103.

References

[1] L. Shao, M. Yu, S. Maity, N. Sinclair, L. Zheng, C. Chia, A. Shams-Ansari, C. Wang, M. Zhang, K. Lai, and M. Lončar, "Microwave-to-optical conversion using lithium niobate thin-film acoustic resonators," *Optica*, vol. 6, no. 12, pp. 1498–1505, Dec 2019.

[2] C. Xiong, W. H. P. Pernice, X. Sun, C. Schuck, K. Y. Fong, and H. X. Tang, "Aluminum nitride as a new material for chip-scale optomechanics and nonlinear optics," *New Journal of Physics*, vol. 14, no. 9, p. 095014, sep 2012. [Online]. Available: https://doi.org/10.1088/1367-2630/14/9/095014

[3] J. P. George, P. F. Smet, J. Botterman, V. Bliznuk, W. Woestenborghs, D. Van Thourhout, K. Neyts, and J. Beeckman, "Lanthanide-assisted deposition of strongly electro-optic pzt thin films on silicon: Toward integrated active nanophotonic devices," *ACS Applied Materials & Interfaces*, vol. 7, no. 24, pp. 13 350–13 359, 2015.

[4] D. Biegelsen, "Frequency dependence of the photoelastic coefficients of silicon," *Physical Review B*, vol. 12, no. 6, p. 2427, 1975.

[5] I. Ansari, T. V. de Veire, J. P. George, G. Feutmba, J. Beeckman, and D. V. Thourhout, "Si-photonic integrated pzt thin film for acousto-optic modulation," in *Conference on Lasers and Electro-Optics*. Optical Society of America, 2020, p. JTh2B.24.