# Acousto-optic modulation in a Si-waveguide

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***Abstract*—We demonstrate acousto-optic modulation ($V_\pi L$ ~3.6 Vcm) in a Si waveguide circuit by integrating a photonic compatible PZT film on the SOI chip. We then fabricated a small footprint inter-digital transducer (IDT) on the film to piezoelectrically actuate acoustic waves at GHz frequencies.**

## I. Introduction

Lead Zirconate Titanate (PZT) is one of the most commonly used piezoelectric ceramic materials due to its strong piezo-electricity, high electromechanical coupling coefficient and high temperature compatibility (Curie point ~ 370°C) [1], [2]. Given its centro-symmetric crystal lattice, Si does not exhibit a piezoelectric effect and hence the integration of a textured PZT thin film on the SOI platform could be a promising alternative for enabling electro-optomechanical interactions in Si photonic integrated circuits (PIC).

In this paper, we first give a brief theoretical description of the acousto-optic interaction with a waveguide mode. Then we experimentally show acousto-optic modulation in a Si waveguide circuit with a figure of merit comparable to state-of-the-art modulators based on SOI [3]. The acoustic waves are generated using an inter-digital transducer (IDT) deposited on PZT. This PZT film is directly deposited on an SOI chip using a transparent Lanthanide based seed layer making it photonic compatible [4], unlike the traditional PZT films grown with a Pt buffer layer, which makes them optically lossy [5]. The primary surface acoustic wave (SAW) resonance frequencies measured from the modulation spectra match well with the simulated mechanical eigenmode frequencies of the IDTs deposited on PZT/SOI.

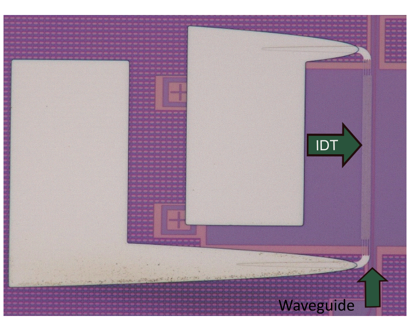


Fig. 1. (a) Microscope image showing an ebeam lithography patterned IDT (100 nm thick Al) with finger-width and finger-finger spacing of 0.5 $\mu$m, aperture 70 $\mu$m and 4 finger-pairs fabricated on 200 nm PZT/SOI

## II. Acousto-optic interaction in a waveguide

The electric field of a waveguide mode travelling (along $x$) with effective index $n_{eff}$ can be written as,

$$\psi(x,t) = A\Re e^{i(\omega_0 t - k_0 n_{eff} x)} \tag{1}$$

Where A is the electric field amplitude, $\omega_0$ is the angular frequency, $k_0 = 2\pi/\lambda_0$ with $\lambda_0$ the wavelength in free space.

When an acoustic wave is actuated perpendicular to the waveguide, the strain profile travelling through the waveguide perturbs its refractive index through the photoelastic effect. The modulated effective index of the waveguide mode can be approximated as,

$$n_{eff}(t) = n^0_{eff} + \Delta n_{eff}\sin(\Omega\, t) \tag{2}$$

Where $n^0_{eff}$ is the effective mode index without any index perturbation and $\Delta n_{eff}$ is the effective index change from the modulation. $\Delta n_{eff}$ depends on the coupling between the actuated strain field and the optical field [3].

We assume the modulator length is very small, so that the change in $n_{eff}$ along the modulator can be ignored as $\Omega\,\Delta t = \Omega\, L/v_p << 1$, where $v_p$ is the light phase velocity. Therefore, the waveguide mode in the modulation region can be written as:

$$\psi(x,t) = A\Re e^{i(\omega_0 t - k_0 n^0_{eff}\, x)} e^{i\alpha(x)\sin(\Omega\, t)} \tag{3}$$

Where $\alpha(x) = -k_0 \Delta n_{eff}\, x$ is the amplitude of the phase modulation. The sinusoidal term in equation (3) can be expanded in terms of Bessel function ($J_N$) $\implies e^{i\alpha\sin(\Omega\, t)} = \sum_{-\infty}^{\infty} J_N(\alpha) e^{iN\Omega t}$, where $N$ is an integer. So equation (3) gives,

$$\psi(x,t) = A\Re\, e^{i(\omega_0 t - k_0 n^0_{eff}\, x)} \Big[J_0(\alpha(x)) + \sum_{N=1}^{\infty} J_N(\alpha(x)) \left[e^{iN\Omega t} + (-1)^N e^{-iN\Omega t}\right]\Big] \tag{4}$$

Here $\alpha(x) << 1$ as the modulator length is assumed very small. Hence, the Bessel function can be simplified as $J_N(\alpha(x)) \approx \alpha(x)^N/(2^N N!)$, and the higher order terms in equation (4) can be neglected,

$$\psi(x,t) = A\Re\, e^{-ik_0 n^0_{eff}\, x} \Big[e^{i\omega_0 t} + \frac{\alpha(x)}{2}\left[ e^{i((\omega_0+\Omega)t} - e^{i((\omega_0-\Omega)t}\right]\Big] \tag{5}$$

Thus, we notice that as the carrier mode propagates along the elastic wave (modulator) region, it is diffracted into two sideband signals, Stokes and Antistokes with frequencies $\omega_0 \pm \Omega$.

Considering the acoustic frequency to be small i.e. $\Omega << \omega_0$, the phase difference between the modulated signals at the beginning and end of the modulator can be approximated as,

$$\Delta\phi_L = L\Omega/v_g$$

Where $v_g$ is the group velocity of the waveguide mode at $\omega_0$. For a short modulator, this phase difference will be negligible and the modulated signals will add up constructively. For our modulators, this phase difference was indeed negligible, e.g. $\Delta\phi_L$ was estimated to be $\approx 0.011 << \pi$ for IDT3 with the aperture length 70 $\mu$m and SAW frequency 2 GHz.

## III. Phase Modulation Measurement

We use a heterodyne setup to measure the acousto-optic phase modulation in the waveguides [6]. The output spectrum measured by the electrical spectrum analyzer (ESA) contains a carrier peak at the reference oscillator frequency (AOM driving frequency) and two sideband peaks due to the modulation as described in equation (5).

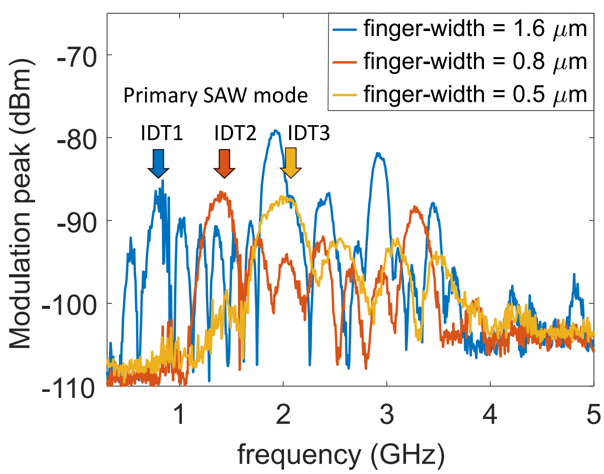


Fig. 2. The measured modulation (Antistokes) peak power with respect to the driving RF frequencies (driving RF power 12 dBm) applied to the IDT.

In figure 2, we show the modulated peak power with respect to the driving RF frequency for 3 IDTs. The peaks indicate the resonance behavior of the actuated acoustic waves. The first peak is typically obtained at the resonance frequency of the primary surface acoustic wave (SAW) mode. A brief summary of the results from the three IDTs is tabulated below.

| | IDT1 | IDT2 | IDT3 |
|---|---|---|---|
| Finger-width ($\mu m$) | 1.6 | 0.8 | 0.5 |
| Aperture length ($\mu m$) | 100 | 100 | 70 |
| No. of finger-pairs | 4 | 4 | 4 |
| Measured SAW mode $f_0$ (GHz) | 0.84 | 1.4 | 2 |
| Simulated Eigen-mode $f_0$ (GHz) | 0.85 | 1.5 | 2.2 |

Prior to the measurement, the PZT film under the IDT is poled to align its domains along the applied electric field (for an efficient longitudinal actuation). A sufficiently high electric field is applied using the IDT itself, thus the PZT under the IDT finger-pairs gets poled in alternate orientations. By taking this alternate poling into account, a COMSOL simulation is done for one IDT period to calculate the mechanical eigenmodes of the IDT/PZT/SOI stack. As we can see from the above table, the simulated mechanical mode frequencies match well with the measured SAW resonance frequencies. This confirms the acousto-optic interaction via excitation of a SAW. Other higher order modulation peaks in figure 2 indicate the excitation of higher order acoustic modes. From the modulation spectrum for IDT3 (aperture length 70 $\mu$m), we calculate the SAW phase modulation amplitude $\alpha(L)$ to be 0.0077 radians with 12 dBm driving RF power, equivalent to $V_\pi L \sim 3.6$ Vcm. Thus we obtain a promising figure of merit without patterning the PZT film nor suspending the device.

## IV. Conclusion

We gave a brief theoretical description of the acousto-optic interaction in a waveguide. Then we integrated a PZT film on SOI photonic chip and fabricated IDTs on top of it to excite acoustic waves. We experimentally showed the acousto-optic modulation in the waveguide from actuated acoustic waves. We obtained a promising figure of merit $V_\pi L \sim 3.6$ Vcm from the SAW. This work illustrates the potential for efficient light-sound interactions in Si photonic integrated circuits.

## Acknowledgment


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