Piezoelectric characterization of Si-photonic integrated PZT

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Lead Zirconate Titanate (PZT) with its high piezo-electricity and electromechanical coupling coefficient (in bulk) promises to be an efficient transducer for electro-optomechanical applications. Since the development of a deposition method for thin films of PZT on Si-photonic chips using a transparent buffer layer, our focus has been to explore the various properties of this material for integrated photonic applications. In this work, we investigate the piezo-electric response of this PZT film by exciting surface acoustic waves (SAWs) with interdigitated electrodes (IDTs). Furthermore, we demonstrate the optical phase modulation from the SAW on a PZT integrated waveguide circuit.

Introduction

A photonic integrated circuit (PIC) is a fast-growing technology with the applications in several important areas such as telecommunication[1], medicine[2], quantum information processing[3] etc. A PIC consists of several photonic components like source, splitters, filters, modulators, detectors etc. Integration of hybrid materials is essential to realize these components on the photonic chip. In this study, we explore the piezoelectric properties of a Si-photonic integrated thin film of Lead Zirconium Titanate (PZT).

PZT is a ferroelectric material with a very high piezoelectricity and electromechanical coupling coefficient in bulk. This put PZT on the forefront of the integrated photonic material. However, in most cases PZT deposition involves a Pt-buffer layer for preferential crystal orientation and to avoid lead diffusion, which makes it optically lossy. Recently, however, a novel approach for depositing highly textured PZT-films, using a thin transparent lanthanide based buffer layer, was developed by John et.al[4]. The high quality of the resulting film was proven through the demonstration of efficient electro-optic modulators (effective electro-optic coefficient of ±70 pm/V) and low optical loss (1dB/cm)**Error! Reference source not found.**Given the promising electro-optic results, we focused on exploring the piezoelectric response of these thin films here by exciting surface acoustic wave (SAW).

Surface acoustic wave (SAW) excitation with IDTs

A SAW is usually excited by applying RF signal to IDT. An IDT consists of alternate electrodes facilitating alternate electric fields (as shown in fig 1.a) which creates periodic strain in the piezoelectric material beneath IDT. When the RF frequency applied to the IDT matches with its excitation frequency, a SAW is launched in both the directions of IDT. Thus, the wavelength of the primary mode of SAW is equal to the period of IDT.

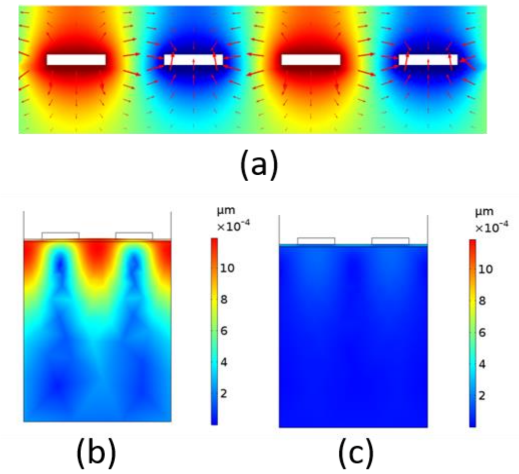


Figure 1: (a) The cross-section view of the electric field distribution of IDT/PZT shows the alternate field polarity. (b) 2D Comsol simulation of the electrically driven total displacement for an in-plane poled PZT (c-orientation). IDT of period 8 µm is excited with 10 V AC signal of frequency equal to the mechanical Eigen-frequency of the structure (SAW frequency). (c) Total displacement for an out-of-plane poled PZT (a-orientation). Thus, the effective actuation of SAW takes place when the PZT dipole domains are oriented in the direction of the applied electric field.

The electro-mechanical simulation results of IDT/PZT/Si structure in fig 1 proves that in order to have an effective excitation of SAW, PZT should be poled in the direction of applied electric field. To achieve that, we first fabricate a parallel electrode bars on PZT/Si sample by direct writing lithography (DWL) and Ti/Au 20nm/350nm deposition. After poling the sample using these electrodes by applying sufficiently high voltage, next we fabricated the stand-alone IDT in the poled region. We characterize the SAW excitation by measuring the electrical reflection parameter S_{11} with vector networking analyzer (VNA).

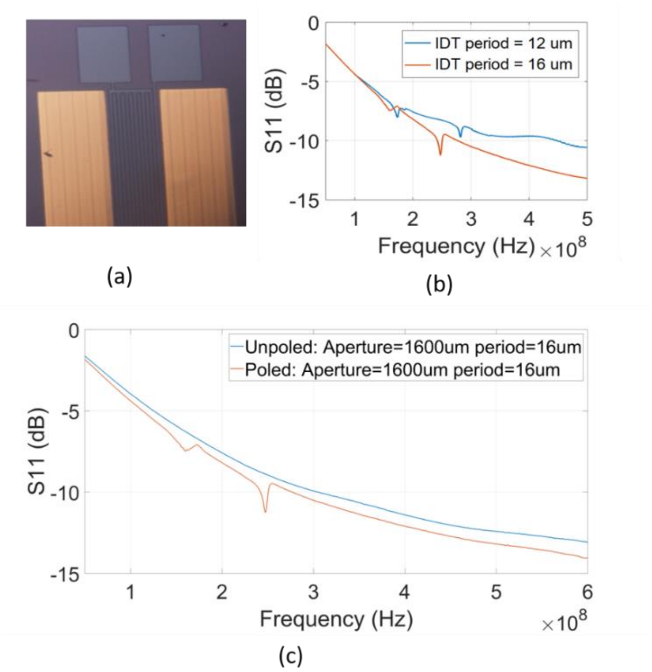
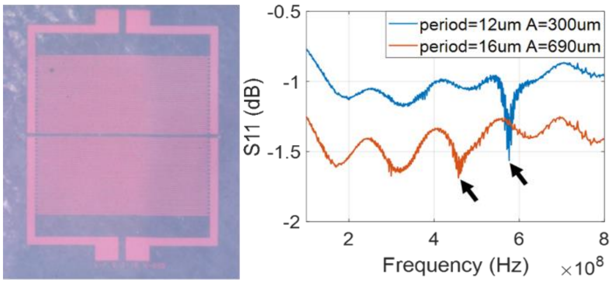


Figure 2: (a) Microscopic image of IDT of period 12 µm (grey color), number of period=6 is fabricated in between the poling electrode bars (yellow color) with spacing of 80 µm. Poling voltage= 820V is applied for ~ 40 minutes **(b)** electrical S_{11} parameter shows the dip (corresponding to SAW excitation frequency) varying consistently with the IDT periods **(c)** electrical S_{11} response shows the SAW excitation for the poled PZT, but unpoled PZT shows no such response, thus corroborating the conclusion from the simulation results.

Although we showed the SAW excitation in an in-plane poled PZT, the biggest drawback of such arrangement is that the IDT structure (e.g. period, number of period etc.) has to be limited in order to fit in a given (limited) poling region. This limit makes this poling method impractical for the integrated devices. Hence, we tested poling the PZT using

IDTs itself. Due to the alternate poling direction in the neighboring electrodes, the excitation frequency of the SAW is supposed to double which we observed in figure 4 (b).

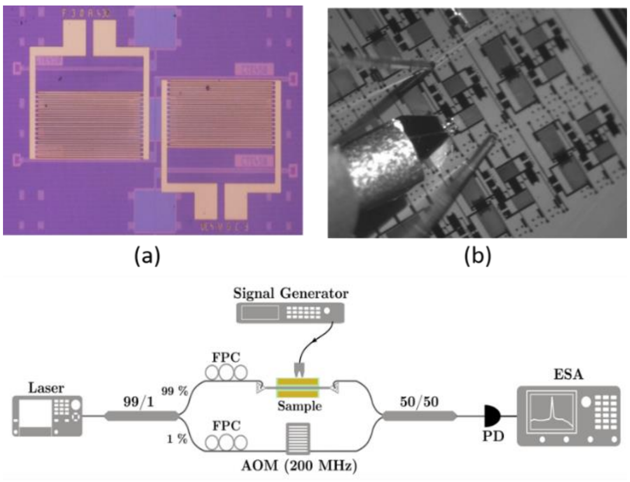


(a) (b)

Figure 3: (a) Microscopic image of an IDT-IDT system. We apply poling voltage on the IDT for 30-40 min and then measure the reflection S_{11} with VNA. (b) S_{11} shows that now for the IDT period 12 µm, the SAW frequency has almost doubled (310MHz to 590 MHz) and it varies consistently with the IDT period change. The ripples in the S_{11} signal is due to the cavity effect from RF cable.

PZT thin-film integration with photonic system

Following the successful demonstration of stand-alone IDTs on a PZT-on-Silicon substrate we integrated similar IDTs with silicon waveguide circuits. The waveguides were defined in a SOI wafer with a 220 nm thick top silicon layer on a 2 µm buried oxide layer. The device included simple straight waveguides but also more complex structures such as Mach-Zehnder Interferometer (MZI). Following waveguide definition, the devices were planarized using oxide deposition and chemical mechanical polishing (CMP). Next, similar as described above we deposited a 20 nm thick Lanthanide buffer layer and a 200 nm thick PZT-layer. We then defined IDTs on top of the PZT layer as shown in fig 4(a).



(C)

Figure 4: (a) A microscopic image of a silicon TE waveguide (width 550nm) integrated with an IDT (period 12 um, 20 periods , aperture size 180um). (b) camera view shows the landing of a GS probe (100µm pitch) on IDT electrode pads. Two optical fibers are aligned with the grating couplers for the optical transmission measurement. (c) A heterodyne-setup is used for the measurement of the phase modulation in a single waveguide.

To characterize the phase modulation in the waveguide from SAW, we built a heterodyne setup (fig 4.c) where we mix the optical signal from DUT with that coming through the acousto-optic modulator (AOM) with a modulated frequency at 200 MHz, in a fast photodetector (PD) and connect them to an electrical spectrum analyzer (ESA). This mixing results into two sidebands at frequencies $\Omega_{SAW} + \omega_{AOM}$ and $|\Omega_{SAW} - \omega_{AOM}|$ which we observe in our preliminary results from the ESA data as shown in figure 5(a).

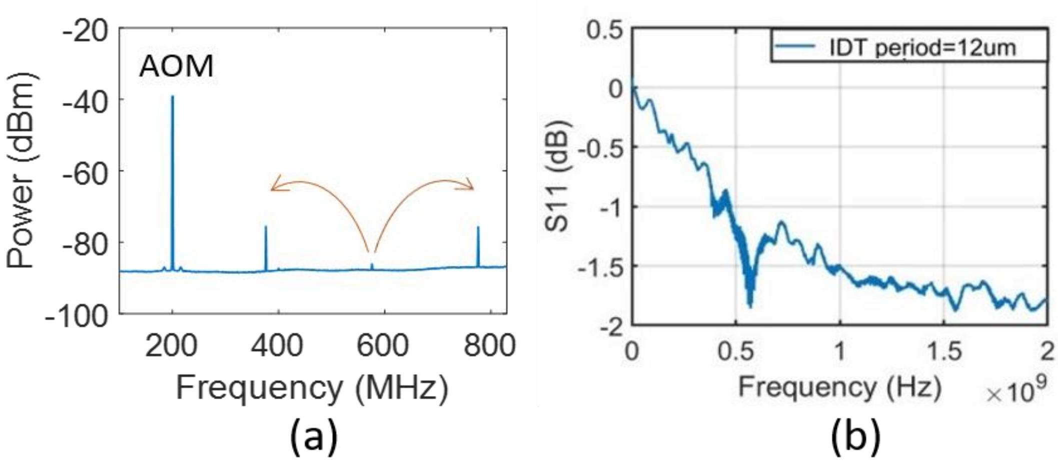


Figure 5: (a) The two sidebands appear from the mixing. The maximum sideband amplitude (phase modulation) occurs at RF frequency of 576 MHz (b) The S_{11} parameter from the same IDT shows dip at 576 MHz. These results prove the excitation of SAW on the PZT and the first order mode frequency of SAW is 576 MHz for the given IDT structure.

The phase modulation from SAW is given by $\phi = \beta * \sin(\Omega_{SAW} * t)$; where β is the maximum phase change and Ω_{SAW} is the SAW excitation frequency. β is calculated from the peak ratio of AOM and sidebands in the ESA spectrum. From the data shown in fig 5.a, β is calculated to be 0.03 radians. This phase change amplitude (β) corresponds to the $V_{\pi}L \approx 3.35$ Vcm. For the similar PZT, earlier an electro-optic modulator has been reported to give $V_{\pi}L \approx 3.2$ Vcm[4]. Hence, we notice that even without any optimization, our very first preliminary result already gives a competitive figure of merit.

Conclusion

We have shown with simulation and experiment that for an efficient SAW transduction, it's essential to have an appropriate poling of the PZT dipole domains. With a suitable poling, we have demonstrated the very first piezoelectric response of our photonic integrated PZT by exciting SAW, which is confirmed with both electrical S_{11} measurement and optical phase modulation in a waveguide. The preliminary phase modulation data, without any device optimization, already shows promising piezo-electro-optomechanical response and thus it opens the possibility for combining piezo-electricity of PZT with photonic components to realize various photonic applications such as filters, on-chip acousto-optic modulations etc.

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