Thin-film Lithium Niobate Photonics for Electro-optics, Nonlinear Optics, and Quantum Optics on Silicon

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THIN-FILM LITHIUM NIOBATE PHOTONICS FOR ELECTRO-OPTICS, NONLINEAR OPTICS, AND QUANTUM OPTICS ON SILICON

by

ASHUTOSH RAO
B.Tech., Indian Institute of Technology Bombay 2013
M.Tech., Indian Institute of Technology Bombay 2013

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the College of Optics and Photonics at the University of Central Florida Orlando, Florida

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Major Professor: Sasan Fathpour
ABSTRACT

Ion-sliced thin-film lithium niobate (LN) compact waveguide technology has facilitated the resurgence of integrated photonics based on lithium niobate. These thin-film LN waveguides offer over an order of magnitude improvement in optical confinement, and about two orders of magnitude reduction in waveguide bending radius, compared to conventional LN waveguides. Harnessing the improved confinement, a variety of miniaturized and efficient photonic devices are demonstrated in this work. First, two types of compact electrooptic modulators are presented – microring modulators, and Mach-Zehnder modulators. Next, two distinct approaches to nonlinear optical frequency converters are implemented – periodically poled lithium niobate, and mode shape modulation (grating assisted quasi-phase matching). Following this, stochastic variations are added to the mode shape modulation approach to demonstrate random quasi-phase matching. Afterward, broadband photon-pair generation is demonstrated in the miniaturized periodically poled lithium niobate, and spectral correlations of the biphoton spectrum are reported. Finally, extensions of the aforementioned results suitable for future work, are discussed.
To my family
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<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AlGaAs</td>
<td>Aluminum gallium arsenide</td>
</tr>
<tr>
<td>AlN</td>
<td>Aluminum nitride</td>
</tr>
<tr>
<td>APE</td>
<td>Annealed proton exchange</td>
</tr>
<tr>
<td>a-Si</td>
<td>Amorphous silicon</td>
</tr>
<tr>
<td>BCB</td>
<td>Benzocyclobutene</td>
</tr>
<tr>
<td>BEOL</td>
<td>Back-end-of-lineTwo-photon absorption</td>
</tr>
<tr>
<td>ChG</td>
<td>Chalcogenide glass (Ge$_{23}$Sb$<em>7$S$</em>{70}$)</td>
</tr>
<tr>
<td>COTS</td>
<td>Commercial-off-the-shelf</td>
</tr>
<tr>
<td>CIS</td>
<td>Crystal ion slicing</td>
</tr>
<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>DFG</td>
<td>Difference frequency generation</td>
</tr>
<tr>
<td>EA</td>
<td>Electroabsorption</td>
</tr>
<tr>
<td>EBL</td>
<td>Electron beam lithography</td>
</tr>
<tr>
<td>EFISHG</td>
<td>Electric field induced SHG</td>
</tr>
<tr>
<td>EO</td>
<td>Electrooptic</td>
</tr>
<tr>
<td>$EO S_{21}$</td>
<td>Electro-optic $S$ parameter</td>
</tr>
<tr>
<td>ER</td>
<td>Extinction ratio</td>
</tr>
<tr>
<td>GaAs</td>
<td>Gallium arsenide</td>
</tr>
<tr>
<td>GaN</td>
<td>Gallium nitride</td>
</tr>
<tr>
<td>GA-QPM</td>
<td>Grating-assisted QPM</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------------------</td>
</tr>
<tr>
<td>GHZ</td>
<td>Grating-assisted QPM</td>
</tr>
<tr>
<td>GSG</td>
<td>Ground signal ground</td>
</tr>
<tr>
<td>IMD</td>
<td>Intermodulation distortion</td>
</tr>
<tr>
<td>InP</td>
<td>Indium phosphide</td>
</tr>
<tr>
<td>JSI</td>
<td>Joint spectral intensity</td>
</tr>
<tr>
<td>L</td>
<td>Device length</td>
</tr>
<tr>
<td>LN</td>
<td>Lithium Niobate</td>
</tr>
<tr>
<td>LNME</td>
<td>Local normal mode expansion</td>
</tr>
<tr>
<td>LNOI</td>
<td>Lithium niobate on insulator</td>
</tr>
<tr>
<td>LPCVD</td>
<td>Low pressure chemical vapor deposition</td>
</tr>
<tr>
<td>m(f)</td>
<td>Optical response of a modulator</td>
</tr>
<tr>
<td>MRM</td>
<td>Microring modulator</td>
</tr>
<tr>
<td>MZ</td>
<td>Mach-Zehnder</td>
</tr>
<tr>
<td>MZM</td>
<td>Mach-Zehnder modulator</td>
</tr>
<tr>
<td>n</td>
<td>Optical or RF mode index</td>
</tr>
<tr>
<td>NRZ</td>
<td>Non-return to zero</td>
</tr>
<tr>
<td>OER</td>
<td>Optical extinction ratio</td>
</tr>
<tr>
<td>OOK</td>
<td>On-off keying</td>
</tr>
<tr>
<td>OPA</td>
<td>Optical parametric amplification</td>
</tr>
<tr>
<td>OPGaAs</td>
<td>Orientation patterned GaAs</td>
</tr>
<tr>
<td>OPO</td>
<td>Optical parametric oscillation</td>
</tr>
<tr>
<td>PE</td>
<td>Proton exchange</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>PECVD</td>
<td>Plasma-enhanced chemical vapor deposition</td>
</tr>
<tr>
<td>PIC</td>
<td>Photonic integrated circuit</td>
</tr>
<tr>
<td>PM</td>
<td>Phase-matching</td>
</tr>
<tr>
<td>PPLN</td>
<td>Periodically poled lithium niobate</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadrature amplitude modulation</td>
</tr>
<tr>
<td>QPM</td>
<td>Quasi phase matching</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature phase shift keying</td>
</tr>
<tr>
<td>RF</td>
<td>Radio-frequency</td>
</tr>
<tr>
<td>RPE</td>
<td>Reverse proton exchange</td>
</tr>
<tr>
<td>rQPM</td>
<td>Random QPM</td>
</tr>
<tr>
<td>$S_{11}$</td>
<td>Return loss $S$ parameter</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscope</td>
</tr>
<tr>
<td>SFDR</td>
<td>Spurious free dynamic range</td>
</tr>
<tr>
<td>SFG</td>
<td>Sum frequency generation</td>
</tr>
<tr>
<td>SFWM</td>
<td>Spontaneous four-wave mixing</td>
</tr>
<tr>
<td>SHG</td>
<td>Second harmonic generation</td>
</tr>
<tr>
<td>Si</td>
<td>Silicon</td>
</tr>
<tr>
<td>SiGe</td>
<td>Silicon germanium</td>
</tr>
<tr>
<td>SiN</td>
<td>Silicon nitride</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>Silicon dioxide</td>
</tr>
<tr>
<td>SNSPD</td>
<td>Superconducting nanowire single-photon detector</td>
</tr>
<tr>
<td>SOI</td>
<td>Silicon on insulator</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>SOLT</td>
<td>Short-open-load-through</td>
</tr>
<tr>
<td>SPDC</td>
<td>Spontaneous parametric down conversion</td>
</tr>
<tr>
<td>Ta₂O₅</td>
<td>Tantalum pentoxide</td>
</tr>
<tr>
<td>TE</td>
<td>Transverse electric</td>
</tr>
<tr>
<td>Ti:LN</td>
<td>Titanium-lithium niobate</td>
</tr>
<tr>
<td>TiO₂</td>
<td>Titanium dioxide</td>
</tr>
<tr>
<td>TM</td>
<td>Transverse magnetic</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>$V_{\pi}$</td>
<td>Half-wave voltage</td>
</tr>
<tr>
<td>$V_{\pi}L$</td>
<td>Half-wave voltage-length product</td>
</tr>
<tr>
<td>VNA</td>
<td>Vector network analyzer</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength division multiplexing</td>
</tr>
<tr>
<td>Z</td>
<td>Impedance</td>
</tr>
<tr>
<td>$Z_0$</td>
<td>Characteristic impedance</td>
</tr>
<tr>
<td>ZnSe</td>
<td>Zinc selenide</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>Reflection coefficient</td>
</tr>
<tr>
<td>$\chi^{(2)}$</td>
<td>Second-order nonlinear susceptibility</td>
</tr>
</tbody>
</table>
CHAPTER 1: INTRODUCTION: THIN-FILM LITHIUM NIOBATE PHOTONICS

The contents of this chapter have been submitted to IEEE J. Select. Topics Quantum Electron. 2018 as: A. Rao, and S. Fathpour, “Heterogeneous Thin-film Lithium Niobate Integrated Photonics for Electrooptics and Nonlinear Optics.”

Abstract— Ion-sliced thin-film lithium niobate (LN) compact waveguide technology has facilitated the resurgence of integrated photonics based on the material. The thin-film waveguides offer over an order of magnitude improvement in optical confinement and bending radius compared to conventional LN waveguides. The thin-film technology can also be implemented on versatile silicon substrates. Harnessing the improved confinement, a variety of miniaturized and efficient photonic devices have been realized. The state of the art of thin-film LN integrated photonics is reviewed, focusing on heterogeneous integration, electrooptic modulation, and nonlinear frequency conversion. The potential applications and associated challenges of next-generation LN-based integrated photonics are discussed.

1.1 Introduction

has enjoyed widespread commercial success through its applications in telecommunications [1] and nonlinear optics [2,3]. Modulators and switches, which benefit from the strong electrooptic (EO) effect in LN, have been vital to the development of optical telecommunications [4-9]. In addition, periodically-poled LN (PPLN), which relies on ferroelectric domain reversal and the material’s strong second-order nonlinear effect, has been
central to the development of numerous nonlinear devices, such as optical frequency converters and parametric oscillators [10-15]. LN has been used in many other applications as well, for example, as $Q$-switches for lasers [16-18], and as entangled photon-pair sources for quantum optics applications [19,20].

However, conventional LN devices usually have large on-chip footprints. For example, a typical commercial-off-the-shelf (COTS) LN EO modulator is 5 to 10 cm long (Fig. 1-1). Recently, there has been a push towards miniaturizing LN-based photonic devices, with the goal of forming complex and compact integrated circuits. The desired reduction in size is usually accompanied by an increase in efficiency (specific to each device), as discussed later. Furthermore, monolithic integration of these compact LN devices on silicon substrates enables potential compatibility with silicon photonics and back-end-of-line (BEOL) foundry fabrication.

These objectives have been pursued using thin-film LN integrated photonics, the focus of this chapter. Section 1.2 briefly introduces the relevant material properties of LN. Section 1.3 describes the modernization of LN photonics from large diffused waveguides to submicron thin-films that are compatible with current trends in integrated photonics, particularly on silicon substrates. The heterogeneous integration of thin-film LN with a variety of other optical materials is reviewed in Section 1.4. Section 1.5 discusses thin-film LN electrooptic and nonlinear optical devices. Finally, we conclude with an outlook on the potential future uses of thin-film LN and a summary on the state of the art.
Figure 1-1: A fully-packaged commercial LN EO Mach-Zehnder modulator. The total packaged length is ~ 13 cm, and the internal LN chip is ~ 9 cm long. The long length is a consequence of high voltage-length product, and high bending radius; both of these shortcomings of conventional LN waveguides are addressed through the presented thin-film platform.

1.2 Lithium Niobate

1.2.1 Physical properties of lithium niobate

Lithium niobate is a synthetic dielectric that exhibits ferroelectricity (spontaneous electric polarization) below its Curie temperature. The use of the Czochralski technique [21] for the growth of ferroelectrics [22], and the synthesis of single crystals of LN and their associated material properties, were studied in detail in the 1960s, particularly in Bell Laboratories [23-29]. By the late 1970s, research on LN had caught up with barium titanate, a longstanding popular choice for the study of fundamental science and applications in ABO$_3$-type ferroelectrics. LN is primarily grown in two variants – congruent (lithium deficient), and stoichiometric [30]. Congruent LN has been widely used in optical applications due to its low absorption and high
homogeneity. Nonetheless, stoichiometric LN has been pursued more recently due to its reduced lattice defects and lower localized field distortions. A notable consequence of the improved stoichiometry is a strong reduction in the internal coercive field.

Figure 1-2: (a) Crystal structure of ferroelectric lithium niobate. The blue spheres represent oxygen atoms, which form planes normal to the crystal $c$-axis. The positions of the niobium (gold colored spheres) and lithium (black colored spheres) ions dictate the ferroelectric domain orientation (upwards here). The periodic vacancy is visible between the upper lithium and niobium atoms. After [31]. (b) X, Y and Z-cuts of LN wafers are important for optical applications.
<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal structure</td>
<td>Trigonal</td>
</tr>
<tr>
<td>Point group</td>
<td>3m</td>
</tr>
<tr>
<td>Space group</td>
<td>R3c</td>
</tr>
<tr>
<td>Coefficient of thermal expansion (300 K)</td>
<td></td>
</tr>
<tr>
<td>$\alpha_a$ (K$^{-1}$)</td>
<td>14.1</td>
</tr>
<tr>
<td>$\alpha_c$ (K$^{-1}$)</td>
<td>4.1</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>1240</td>
</tr>
<tr>
<td>Curie Temperature (°C)</td>
<td>1140</td>
</tr>
<tr>
<td>Spontaneous polarization (μC/cm$^2$)</td>
<td>71</td>
</tr>
<tr>
<td>Hardness (mohs)</td>
<td>5</td>
</tr>
<tr>
<td>Low-frequency relative permittivity (unclamped)</td>
<td>$\varepsilon_{xx} = \varepsilon_{yy} = 84.1, \varepsilon_{zz} = 84.1$</td>
</tr>
<tr>
<td>Low-frequency relative permittivity (clamped)</td>
<td></td>
</tr>
<tr>
<td>Electrooptic tensor $r$ (pm/V)</td>
<td>$r_{33} = 30.8, r_{13} = r_{23} = 8.6,$</td>
</tr>
<tr>
<td></td>
<td>$r_{22} = -r_{12} = -r_{61} = 3.4,$</td>
</tr>
<tr>
<td></td>
<td>$r_{31} = r_{42} = 28$</td>
</tr>
<tr>
<td>Nonlinear tensor $d$ (pm/V)</td>
<td>$d_{33} = 30,$</td>
</tr>
<tr>
<td></td>
<td>$d_{31} = d_{32} = d_{24} = d_{15} = 5.9, d_{22} = -d_{21}$</td>
</tr>
<tr>
<td></td>
<td>$= -d_{16} = 3.0$</td>
</tr>
</tbody>
</table>

The ferroelectric phase of LN is a trigonal crystal (Fig. 1-2(a)) belonging to the 3m point group and the $R3c$ space group [25,31]. LN has been doped with many different materials (e.g.,
magnesium, zinc, indium, zirconium, hafnium, and tin) to ameliorate its susceptibility to optical damage [32-38].

LN has been widely studied for its pronounced piezoelectric, pyroelectric, photoelastic, nonlinear optical, and electrooptical properties. The tensors describing these properties are commonly given with respect to the orthohexagonal axes of LN. The material is anisotropic, and its low-frequency relative permittivity is given in Table 1-1 for both unclamped (zero mechanical stress) and clamped (zero mechanical strain) crystals. Other material properties are also summarized in Table 1-1. In addition, the coefficients to a three-oscillator Sellmeier equation [39],

\[
\begin{bmatrix}
  n_o & 0 & 0 \\
  0 & n_o & 0 \\
  0 & 0 & n_e
\end{bmatrix},
\]

\[
n_{e/o}^2 = 1 + \frac{A\lambda^2}{\lambda^2-B} + \frac{C\lambda^2}{\lambda^2-D} + \frac{E\lambda^2}{\lambda^2-F},
\]

for the ordinary and extraordinary refractive indices of congruently grown LN at optical frequencies are listed in Table 1-2 [40].
Table 1-2 Three-oscillator Sellmeier coefficients for congruently grown LN [40]

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>n_c</th>
<th>n_o</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.9804</td>
<td>2.6734</td>
</tr>
<tr>
<td>B</td>
<td>0.02047</td>
<td>0.1764</td>
</tr>
<tr>
<td>C</td>
<td>0.5981</td>
<td>1.2290</td>
</tr>
<tr>
<td>D</td>
<td>0.0666</td>
<td>0.05914</td>
</tr>
<tr>
<td>E</td>
<td>8.9543</td>
<td>12.614</td>
</tr>
<tr>
<td>F</td>
<td>416.08</td>
<td>474.6</td>
</tr>
</tbody>
</table>

1.2.2 Pockel’s effect

The EO coefficients of LN are large, and have therefore been used to form optical modulators in both bulk crystals and integrated waveguides. The linear EO effect, also called the Pockel’s effect [41], describes the change in the refractive index of a material upon the application of a direct-current (DC) or radio-frequency (RF) electric field. The refractive index change is proportional to the applied electric field. The EO effect is quantified as

$$\Delta \left( \frac{1}{n_{ij}^2} \right) = \sum_k z_{ijk} E_k ; i, j, k = x, y, z,$$  \hspace{1cm} (1-2)
where the coefficients \( z_{ijk} \) form the third-rank Pockel’s tensor, \( n_{ij} \) is the \((i, j)\) element of the second-order refractive index tensor, and \( E_k \) is the \(k\)th Cartesian component of the external electric field. Using symmetry arguments, the third-rank Pockel’s tensor is commonly contracted to a \(6 \times 3\) matrix, \( r \), called the EO matrix [3]. The \( r \) matrix coefficients for LN are listed in Table 1-1.

When an external electric field, \( E \), is applied along the crystalline \( c \)-axis (or the \( z \) axis) of LN, the material refractive index is perturbed as \( \Delta n = -n_e^2 r_{33} E/2 \) [42]. Then, the effective refractive index, \( n_{\text{eff}} \), of a guided mode propagating perpendicular to and polarized along the \( c \)-axis is accordingly modulated, within a first-order Taylor approximation, as

\[
n_{\text{eff}}(E) \approx n_{\text{eff}} - n_e^4 r_{33} E/(2 n_{\text{eff}}).
\]  

(1-3)

This refractive index modification is at the core of LN EO modulators. It is noted that in conventional EO modulator models, it is common and fair to assume \( n_{\text{eff}} \approx n_e \) in Eqn. 1-3 [42]. However, in modern compact devices with much higher core-clad index contrast (e.g., LN of \( \sim 2.1 \) vs. SiO\(_2\) of \( \sim 1.5 \)), it is important to differentiate between the two indices. An electromagnetic wave of wavelength \( \lambda \), traveling perpendicular to and polarized along the \( z \)-axis, accumulates a change in optical phase due to the electric field along the \( z \)-axis,
\[ \Delta \Phi(E) = \frac{2\pi L(n_{eff}(E(t)) - n_{eff})}{\lambda} = \frac{\pi L n_{e4r33}^* E(t)}{\lambda n_{eff}}, \]  

(1-4)

where \( L \) is the length traversed, and the variation of \( E \) with time leads to phase modulation. The interference of two such phase-modulated waves leads to intensity modulation. The state of the art of thin-film LN EO modulators is reviewed in Section 1.4.

1.2.3 Second-order optical nonlinearity

LN has been widely used for second-order nonlinear optics because of its high nonlinear coefficients, low optical absorption, wide optical transmission window, and ferroelectric nature, which permits the engineering of efficient nonlinear interactions via ferroelectric domain reversal (often called periodic poling). Second-order nonlinear optics, or three-wave mixing, addresses nonlinear interactions between three photons that are mediated by the second-order nonlinear susceptibility, \( \chi^{(2)} \), a third-rank tensor. Three-wave mixing processes include sum, difference, and second harmonic generation (SFG, DFG, and SHG), optical parametric amplification and oscillation (OPA and OPO), and spontaneous parametric down-conversion (SPDC).

The second-order nonlinear polarization, \( P^{(2)} \), is the driving force for \( \chi^{(2)} \) interactions. \( P^{(2)} \) for SFG is given by [3]

\[ P^{(2)}_i(\omega_3) = e_0 \sum_j \sum_k \chi^{(2)}_{ijk}(\omega_3; \omega_1, \omega_2) E_j(\omega_1) E_k(\omega_2) e^{i\Delta \beta_{ijk}}, \]  

(1-5)
where $i, j, k$ refer to the Cartesian axes, $\omega_3 = \omega_1 + \omega_2$ is the sum of the two incident angular frequencies $\omega_1$ and $\omega_2$, $E_j(\omega_m)$ is the $j^{th}$ component of the interacting electric fields at frequency $\omega_m$, $\Delta \beta_{ijk}$ is the phase difference between the interacting waves, and $\chi^{(2)}_{ijk}$ is the $(i,j,k)^{th}$ element of the $\chi^{(2)}$ tensor. Depending on the incident polarizations, only certain elements of $\chi^{(2)}$ contribute to the interaction. Following symmetry arguments, $\chi^{(2)}$ is often contracted to the nonlinear tensor $d$, expressed by a $3 \times 6$ matrix. The $d$ tensor for LN is listed in Table 1-1. The null elements are determined by the crystal symmetries of LN. Efficient three-wave interactions require phase-matching (PM), a compensation of momentum mismatch between the interacting waves. This implies that $\Delta \beta_{ijk}$ is required to be either zero, or compensated for by a spatial modulation in the product of the nonlinear susceptibility and the electric field modes. A few significant approaches for nonlinear frequency conversion in thin-film LN are reviewed in Section 1.4.
Figure 1-3: (a) Optical mode of a typical titanium-diffused LN waveguide at 1550 nm. The low index contrast offered by the diffusion limits the minimum size of the waveguide mode, and the gap between the two gold electrodes. A smaller gap results in significant electrode metal-induced optical loss; (b) In contrast, thin-film LN waveguides offer submicrometer optical confinement, enabling electrode gap reduction by over a factor of 3 compared to (a). (a) and (b) are drawn to scale to emphasize the increase in optical confinement; (c) Magnified image of the optical mode in (b). The LN thin-film is 300 nm thick, and the 400-nm-tall rib, which can be a heterogeneously integrated material, or etched LN itself, has an index of 2.2; (d) – (g) Effect of increased optical confinement (shown in the legends), on second-harmonic generation efficiency with different pump powers and propagation losses, plotted vs. propagation length. The smaller waveguides offer higher nonlinear frequency conversion, even at losses of 1 dB/cm.
1.3 Modernization of Lithium Niobate Photonics

The success of LN for photonics applications was driven, in part, by stripe waveguide optimization which led to salutary low propagation and coupling loss, along with other application-specific improvements [43-47]. Traditionally, the in-diffusion of titanium around 1000°C has been used to form stripe waveguides (Ti:LN) in bulk LN wafers [43-45]. Ti:LN waveguides were widely studied and improved for commercial applications such as EO modulators. Titanium diffusion increases both the ordinary and the extraordinary indices of refraction. Therefore, both transverse-electric (TE) and transverse-magnetic (TM) modes can be guided, depending on the characteristics of the Ti diffusion. A different diffused waveguiding approach uses proton exchange (PE) [48,49], where the LN is locally exposed to a proton-rich acid bath, typically at low temperatures (up to 300°C). Protons replace Li ions through diffusion to form a series of distinct graded phases with varying ratios of protons to Li ions. The extraordinary index increases in the PE layers, usually accompanied by local refractive index instability, increased optical scattering, and degraded EO and nonlinear coefficients, while the ordinary index remains unaffected. PE is followed by a controlled high-temperature processing step, forming annealed proton exchanged (APE) waveguides [50], to diminish some of the aforementioned undesired effects of PE. Finally, the APE process can be followed by a reverse proton exchange (RPE) step [51]. RPE uses a controlled and limited local reversal of the first PE step by immersion in a lithium-rich melt, leading to an enhanced nonlinear mode overlap for nonlinear applications.
Figure 1-4: Fabrication of thin-film LN on Si wafers, beginning with (a) helium ion implantation on a single crystal LN wafer; (b) The implanted LN wafer is bonded to an oxidized Si wafer, and (c) heated to thermally exfoliate a thin-film of LN around the implantation peak; (d) A fully-processed 3-inch X-cut LN thin-film bonded to an oxidized 4-inch Si wafer [54].

While APE waveguides offer sufficient EO coefficient recovery for EO applications, and RPE waveguides resolve the insufficient nonlinear mode overlap of APE waveguides for nonlinear optical applications, alternative solutions have been explored for further improvement in the performance of devices through waveguide optimization. For example, a combination of dry etching and Ti diffusion can be used to form wide etched ridge Ti:LN waveguides in single crystal bulk LN substrates for EO modulators. Ridge Ti:LN waveguides have been important in
advancing EO modulator technology by enabling drive voltage reduction, to a certain extent, and increased RF modulation bandwidths [52]. Nonetheless, the optical confinement offered by such schemes remains insufficient to meet the demands of modern integrated photonics – small device footprints, tight bending radii, low power consumption, etc.

Improved optical confinement would offer ample improvements from a single-device perspective as well. Electrodes could be brought closer to increase the electric field per volt applied to the electrodes, thereby enhancing EO modulation efficiency (Fig. 1-3(a)-(c)). Nonlinear optical interaction efficiencies would drastically increase because of the stronger nonlinear interaction and overlap (Fig. 1-3(d)-(g)). The increase in efficiencies would be accompanied by a reduction in device size and both electrical and optical power consumption. Also, the success of silicon photonics has led to integrability on silicon substrates being an important concern as well.

All of these considerations can be met in photonic platforms that are based on thin films of LN in order to fabricate tightly-confined waveguides [53-57]. The first demonstration of monolithic integration of LN thin films on silicon substrates, as well as waveguides and EO modulators on the new platform, was reported by researchers at CREOL in 2013 [54]. As summarized in Fig. 1-4, helium ions are implanted into a donor LN wafer, which is bonded to a layer of SiO₂ on a Si handle wafer. The donor-handle wafer combination is then annealed to slice the donor wafer close to the implanted region, in order to form a thin-film of LN bonded to SiO₂ on a Si substrate.
Alternatively, micro-platelets may be exfoliated in the absence of a handle wafer. The micro-platelets can then be transferred in a pick-and-place scheme to specific locations on pre-patterned dies [58,59]. Naturally, the former wafer-bonding approach is more scalable than the latter technique. Wafers of thin-film LN on Si substrates [54] are of more technological interest than thin-film LN on LN substrates [55]. The latter technology on LN substrates is sometimes called LN on insulator (LNOI). Nowadays, 75-mm diameter thin-film LN wafers are commercially available on both LN and Si substrates. 150-mm diameter thin-film LN wafers may be available soon – the bonding process is repeatable and reliable, and 150-mm single crystalline LN wafers are already available.

1.4 Heterogeneous Integration of Thin-film Lithium niobate

Heterogeneous integration has enabled significant advances in integrated photonics [60-63]. In the context of thin-film LN, heterogeneous integration has been used to form rib-loaded waveguides for electrooptics [54,63-67], $\chi^{(2)}$-based nonlinear optics [57,68-70], and third-order or $\chi^{(3)}$-based nonlinear optics [71,72]. Rib-loading thin-film LN with an easy-to-process material is one of the most straightforward routes to forming thin-film LN waveguides. It circumvents the need to process the LN directly, and avoids the limited optical confinement of the aforementioned diffused waveguides [73]. While recent efforts have realized low loss thin-film LN waveguides by etching LN [74,75], the rib-loading approach is simpler and is far more commonly used. Results from both rib-loaded and etched-LN are included in Section 1.5 for
Direct thin-film deposition and bonding are the two main methods that are used for heterogeneous LN integration, encompassing a very wide range of materials, as follows:

![Figure 1-5: Scanning-electron micrographs of directly deposited thin-film LN waveguides using (a) silicon nitride [69], and (b) titanium dioxide [88].](image)

**1.4.1 Direct thin-film deposition**

Direct deposition has been used to integrate thin-film LN with a variety of materials, such as plasma-enhanced chemical vapor deposited (PECVD) silicon nitride (SiN), amorphous silicon (a-Si), chalcogenide glass (ChG), tantalum pentoxide (Ta$_2$O$_5$), and titanium dioxide (TiO$_2$), using a range of deposition techniques, as follows.

PECVD is a mature technique that has been used for making integrated photonic devices at a range of temperatures from room temperature to over 300°C, offering a photonic-foundry compatible process. PECVD SiN has been used as a passive rib-loading dielectric for electrooptic modulation [66,67] and nonlinear frequency conversion [57,68-70] in thin-film LN.
Interestingly, PECVD SiN can be used for more than passive rib-loading [76,77]. It is a versatile material whose stoichiometry can be altered through deposition conditions [78,79], thereby tuning the refractive index, dispersion, optical bandgap, and the $\chi^{(3)}$ susceptibility. For example, the nonlinear refractive index, $n_2$, which directly scales with $\chi^{(3)}$, can be up to ~500 times higher in silicon-rich SiN compared to stoichiometric SiN [79]. Amorphous silicon, which can be considered the extreme case of silicon-rich PECVD SiN, has been deposited via PECVD on thin-film LN [80].

Chalcogenide glasses, such as Ge$_{23}$Sb$_7$S$_{70}$, a germanium-antimony-sulfide glass [80-84], have been used for passive rib-loading on thin-film LN to form electrooptic MZ and microring modulators [64,65]. ChG itself has been used for supercontinuum generation [83] and flexible photonics [84]. ChG on thin-film LN is also being explored for demonstrations of $\chi^{(3)}$ nonlinear optics, such as four-wave mixing and supercontinuum generation, which benefit from the high $\chi^{(3)}$ coefficient of ChG [85]. ChG can be reliably deposited by both electron-beam and thermal evaporation at low temperatures (<400°C).

Ta$_2$O$_5$ and TiO$_2$ have been used for rib-loading thin-film LN as well [54,86-88] (Fig. 1-5(b)). Both materials have strong potential for $\chi^{(3)}$ nonlinear optics on thin-film LN, and can be deposited by sputtering or evaporation and post-deposition oxidation of the constituent metals. Alternatively, reactive sputtering may be used.
Figure 1-6: (a) Micrograph of a ~ 1 cm\(^2\) LN thin film bonded onto a LPCVD SiN chip [71]; (b) Scanning electron micrograph of a micron-scale thin-film LN platelet bonded onto a SOI racetrack resonator [91].

1.4.2 Thin-film bonding

The deposition conditions of certain materials are incompatible with thin-film LN. An example is low-pressure chemical vapor deposited (LPCVD) SiN. LPCVD SiN, a popular alternative to PECVD SiN, has been used for numerous demonstrations of ultra-low loss waveguides, and \(\chi^{(3)}\) nonlinear optics such as four-wave mixing, supercontinuum generation, and frequency comb generation, among others [89,90]. The stoichiometry of LPCVD SiN can be varied, similar to PECVD SiN. LPCVD SiN is usually deposited around 800°C, a temperature that, due to differences in thermal expansion, would crack LN thin films on Si.

Chip- and wafer-scale bonding is the most straightforward way to integrate materials with thin-film LN that cannot be directly deposited (Fig. 1-6). For example, thin-film LN on Si chips have been bonded, mediated by SiO\(_2\), to LPCVD SiN chips [71], followed by removal of the Si
substrate and SiO₂ cladding. Similarly, chip and platelet scale bonding is the method of choice for integrating thin-film LN with silicon photonics. Microplatelets of free-standing thin-film LN have been bonded onto silicon microrings to form EO modulators [59,91]. Chips of thin-film LN have been bonded, but without substrate removal, to waveguides on the silicon-on-insulator (SOI) platform [92].

The reduction in bending radius offered by heterogeneous integration of thin-film LN compared to conventional LN waveguides is shown in Fig. 1-7.
Figure 1-7: Bending loss variation with bending radius for different heterogeneously integrated thin-film LN platforms. Based on the high refractive index of silicon, the thin-film LN bonded on to SOI can offer the lowest bending radii by trading off the optical power confined in the LN thin-film with the bending radius (data extracted from [92]). The rib-loaded structures offer bending radii around 20 μm (data extracted from [63]). Proton-exchanged waveguides in both thin-film and bulk LN have bending radii > 2000 μm (data extracted from [73] and [93]). Clearly, thin-film LN offers orders of magnitude improvement in bending losses. Details of the exact structures used can be found in the respective references.
1.5  Thin-film LN Optical Modulators and Nonlinear Optical Frequency Converters

1.5.1  Electrooptic modulators

EO modulators using thin-film LN have been a subject of intense investigation in the past years, and the overall performance of thin-film EO modulators is on par with commercial off-the-shelf (COTS) EO modulators [63]. A number of parameters qualify the performance of EO modulators, shown in Fig. 1-8. These include the drive voltage/power consumption, or half-wave voltage via the half-wave voltage length product, $V_\pi L$, (Fig. 1-8(a) and (c)) tunability for resonant structures, 3-dB modulation bandwidth (Fig. 1-8(b) and (d)), optical insertion loss, optical extinction ratio, optical bandwidth, chirp, and optical bandwidth. Specific applications have additional performance metrics. For example, the electrical extinction ratio (EER) is central to long-reach digital transmission, while link linearity and modulator linearity are key in RF photonic links. Short-reach datacom links have significantly relaxed EER requirements compared to long-reach transmission. The device footprint is important for the integration of multiple modulators to form complex photonic integrated circuits (PIC).
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<tr>
<td>3-dB modulation</td>
<td>33</td>
<td>30</td>
<td>25 – 70</td>
</tr>
<tr>
<td>bandwidth (GHz)</td>
<td></td>
<td></td>
<td>[52,95,96]</td>
</tr>
<tr>
<td>DC half-wave voltage length product (V.cm)</td>
<td>3.1</td>
<td>NA</td>
<td>~10</td>
</tr>
<tr>
<td>RF half-wave voltage length product (V.cm)</td>
<td>&lt; 6.5 (at 50 GHz)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Tunability (pm/V)</td>
<td>NA</td>
<td>7</td>
<td>NA</td>
</tr>
<tr>
<td>Optical extinction ratio (dB)</td>
<td>18</td>
<td>3</td>
<td>&gt;20</td>
</tr>
<tr>
<td>Linearity in 1 to 10 GHz (dB.Hz^{2/3})</td>
<td>~95</td>
<td>NA</td>
<td>90 – 120 [98]</td>
</tr>
<tr>
<td>NRZ transmission (Gbps)</td>
<td>NA</td>
<td>40</td>
<td>40 [52,95]</td>
</tr>
<tr>
<td>(3-dB extinction)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waveguide loss (dB/cm)</td>
<td>1</td>
<td>3</td>
<td>0.2–0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>[44,45]</td>
</tr>
</tbody>
</table>
There are two major types of modulators – travelling wave, for example MZ modulators, and resonant, such as microring modulators. Depending on the application and the desired level
of on-chip integration, either MZ, or microring modulators may be preferable. In some cases, combinations of both may be advantageous. MZ modulators usually have higher extinction ratios and modulation bandwidths relative to microring modulators. However, apart from the reduced device footprint, microring modulators require simple RF electrode design, centered primarily on the resistive-capacitive (RC) time constant. Travelling wave electrode design is more involved, with impedance matching, RF metal loss, and velocity matching between the optical and RF mode being important factors. Fortunately, thin-film LN offers near intrinsic velocity matching, circumventing the need for buffer layers as used in COTS LN MZ modulators. In addition, the refractive index of the rib material can be adjusted as required to fine-tune the velocity matching.

A comprehensive review of thin-film LN EO modulators along with a detailed analysis of performance metrics and guidelines for design can be found in [63]. Here, we briefly summarize the state-of-the-art in Table 1-3, which details the aforementioned performance metrics of two of the best performing thin-film MZ and microring modulators, and of COTS MZ modulators. Evidently, the performance of thin-film LN EO modulators is better than or comparable to the COTS counterparts.

1.5.2 Nonlinear Frequency Converters

Second-order nonlinear optics on silicon is still a nascent field. There have been only a handful of demonstrations of $\chi^{(2)}$ -based frequency conversion on silicon substrates, a few of which have employed thin-film LN. A detailed review of SHG on silicon substrates can be found in [57]. Here, we focus on SHG in thin-film LN on both Si and LN substrates. A variety of
PM techniques have been employed for implementing SHG, including quasi-phase matching (QPM) by periodic poling (Fig. 1-9(a)-(d)), mode-shape modulation (Fig. 1-9(e)-(g)), grating-assisted QPM (Fig. 1-9(h)), modal dispersion engineering (Fig. 1-9(i)-(l)), cyclic PM and modal dispersion in microresonators (Fig. 1-10(a)-(c)), and grating induced mode conversion (Fig. 1-10(d) and (e)). SHG is arguably the easiest of the $\chi^{(2)}$ phenomena to experimentally verify, and is therefore broadly employed for first and proof-of-concept demonstrations.

Of the various methods listed in Table 1-4, periodic poling (in conventional LN crystals) has arguably been used most widely for nonlinear frequency conversion in both research and commercial settings. Periodic poling relies on a regular periodic reversal of the ferroelectric domain, where the sign of the relevant coefficient of the $\chi^{(2)}$ tensor alternates in sign, and has been successfully adapted to thin-film LN [68,69].

However, poling relies on ferroelectricity and not all $\chi^{(2)}$ nonlinear materials are ferroelectric, i.e., there are materials like gallium arsenide that cannot be poled. An alternative method for QPM in such materials is mode-shape modulation [70] and grating-assisted QPM [98]. This approach relies on perturbation of the nonlinear medium, or the interacting waveguide modes, to induce a periodic variation in the nonlinear overlap integral for QPM [57]. Perfect PM can be achieved by engineering the mode dispersion of the nonlinear waveguide to realize zero phase mismatch between the interacting optical modes. However, this comes at the cost of using a higher-order mode at the lower wavelength(s) to compensate for material dispersion, thereby compromising the nonlinear overlap and the nonlinear efficiency [99,100].
Table 1-4 Comparison of nonlinear optical frequency conversion methods in thin-film LN

<table>
<thead>
<tr>
<th>Phase-matching Technique</th>
<th>Substrate</th>
<th>Efficiency</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Periodic poling [68,69]</td>
<td>Si &amp; LN</td>
<td>Up to 160% W^{-1}cm^{-2}</td>
<td>Maximum nonlinear mode overlap can be utilized.</td>
</tr>
<tr>
<td>Mode-shape modulation [70] &amp; Grating-assisted QPM [99]</td>
<td>Si &amp; LN</td>
<td>Up to 12% W^{-1}cm^{-2}</td>
<td>Nonlinear efficiency must be balanced with grating-induced propagation loss.</td>
</tr>
<tr>
<td>Modal dispersion engineering [99,100]</td>
<td>LN</td>
<td>Up to 48% W^{-1}cm^{-2}</td>
<td>Typically uses higher-order modes for PM, which reduces the nonlinear mode overlap.</td>
</tr>
<tr>
<td>Modal and cyclic PM in microresonators [101,102]</td>
<td>LN</td>
<td>Up to 0.36% W^{-1}</td>
<td>Limited to high free-spectral range and high-quality factor resonant cavities, and the conversion bandwidth is limited by the cavity linewidth.</td>
</tr>
<tr>
<td>Phase-matching Technique</td>
<td>Substrate</td>
<td>Efficiency</td>
<td>Comments</td>
</tr>
<tr>
<td>--------------------------</td>
<td>-----------</td>
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</tr>
<tr>
<td>Grating-induced mode conversion</td>
<td>LN</td>
<td>Up to 1600% W⁻²cm⁻²</td>
<td>Limited to ~ 50 μm length, leading to overall low device efficiency. Also limited by high losses of ~ 900 dB/cm at the second harmonic wavelength.</td>
</tr>
</tbody>
</table>

Microresonators have been used in attempts to enhance the nonlinear interaction, where PM has been effected via cyclic PM [100] and modal dispersion [102]. However, the demonstrations reported so far have yet to realize the full efficiency enhancement offered by resonant confinement. Finally, grating-induced mode conversion has been utilized for SHG, but this approach at present is accompanied by prohibitive propagation losses of 10% per 5 μm, corresponding to ~ 900 dB/cm [103].
Figure 1-9: Periodically-poled thin-film LN [68,69]: (a) schematic [68]; (b) Scanning-electron micrograph showing ferroelectric domain reversal [68]; (c) optical spectrum showing SHG [68]; and (d) SHG tuning curve [69]. Mode shape modulation: (e) schematic [70]; (f) micrograph showing grating waveguide [70]; and (g) optical spectrum showing SHG [70]. (h) SHG tuning curve of grating assisted QPM [99]. Modal dispersion engineering: (i) simulation showing point of modal PM of the modes shown in (j), and, (k) [99] and (l) [100] are two modal PM based SHG tuning curves.

Each of the above methods requires precise fabrication to achieve high conversion efficiency at the desired wavelengths, and comes with its own merits and shortcomings. A study
on the effects of fabrication tolerances on the efficiency of QPM, applied to conventional PPLN devices, can be found in [104]. The nonlinear conversion efficiency (see [57] for a formal definition and analysis) is the main metric that is used to compare the performance of nonlinear frequency converters. However, there are other considerations such as the nonlinear conversion bandwidth. It is interesting to note that the conversion bandwidth decreases with increasing pump depletion [105]. Overall, the conversion bandwidth is constrained by PM, pump depletion or conversion efficiency, and the use of resonant configurations.

Figure 1-10: Cyclic PM and modal dispersion in microresonators [101,102]: (a) scanning-electron micrograph [101], and SHG outputs ((b) [101] and (c) [102]); Grating-induced mode conversion: (d) schematic [103], and (e) SHG output [103].
1.6 Outlook

Thin-film LN integrated photonics has enabled several noteworthy advancements in the miniaturization and efficiency enhancement of EO modulators and nonlinear frequency converters. Along with these achievements, heterogeneous thin-film LN integration has also facilitated the incorporation of high $\chi^{(3)}$ materials for advanced nonlinear applications [71,72]. In keeping with the integration schemes discussed in Section 1.4, the integration of quantum dots [106], typical III-V epitaxial structures, and other desirable functional materials with thin-film LN is an attractive proposition.

Small-footprint LN EO modulators now operate with low drive voltages of around 1 V, high extinction ratios of over 20 dB, high modulation bandwidths of up to 33 GHz, and modulation up to 110 GHz. However, optical and electrical packaging, thermal and DC drift [107-109], and overall reliability are some key concerns that need to be studied and potentially addressed for commercial viability. Some of the potential applications are: (a) telecommunications, as optical interconnects in data centers, as low power switches, and terrestrial and sub-marine links [7-9,110]; (b) highly-linear RF-photonic links integrated into vehicles [111,112]; (c) millimeter-wave beam formation and imaging [113]; and (d) high sensitivity electric field sensors [114].

Simultaneously, a variety of efficient nonlinear optical frequency converters have been realized, as discussed in the previous section. The emergent pursuit of second-order nonlinear submicron integrated photonics holds tremendous promise in diverse applications, including: (a)
efficient coherent links between near-infrared and visible frequencies for optical self-referencing frequency metrology [115,116]; (b) mid-infrared light generation for spectroscopy [117]; (c) quantum photonics at telecom wavelengths [118,119]; (d) high-harmonic generation [120], which establishes a link between mid-infrared and ultraviolet frequencies; (e) engineering optical frequency conversion in semiconductor and polycrystalline materials [70,121]; and (f) efficient optical parametric oscillators [122]. Apart from EO and nonlinear optical applications, thin-film LN may lead to further novel investigations of the material properties of LN [123-125] and demonstrations of sensors [126].

In addition to stand-alone applications of LN photonic devices, a wide variety of integrated optical systems may be envisioned, encouraged by the demonstrated potential of silicon photonic integration. Increased data rates can be addressed by higher order modulation formats that require composite modulators comprised of combinations of phase and amplitude modulators. Ultracompact LN modulators are very attractive for such applications because of their small device footprint and low power consumption. Compatibility with silicon photonic foundry processes may require solutions that introduce LN in the BEOL stage of fabrication.

In a similar vein, cascaded nonlinear devices on the same LN chip can generate entangled photon states beyond two-photon states. Moreover, the possibility of realizing EO and nonlinear optical functions in a single LN PIC heralds the realization of sources of complex entangled quantum optic states of light that can be dynamically tuned via the EO effect. EO circuits could be also utilized for further on-chip processing and manipulation.
1.7 Conclusion

Thin film technologies have rejuvenated lithium niobate photonics in the past years and have made the versatile material a competing candidate for modern integrated platforms. Improvements in electrical and optical efficiency have been realized in electrooptics and nonlinear optics, respectively, as a direct consequence of the increased optical confinement. The compact electrooptic modulators perform as well as commercial-off-the-shelf counterparts, with smaller footprints, lower switching voltages, and comparable digital and analog operation. Also, efficient nonlinear optical frequency converters have been developed based on the high-contrast thin-film waveguide. These devices can be integrated on silicon, with small bending radii, and are ideal for forming densely heterogeneous photonic integrated circuits.

1.8 References


CHAPTER 2: COMPACT ELECTROOPTIC LITHIUM NIOBATE MODULATORS


Abstract— Lithium niobate (LN), spurred by its success for fiber-optic communications, has remained the material of choice for high-performance electrooptic (EO) modulators. The past decade has seen a surge in efforts aimed at miniaturizing LN EO modulators with higher order modulation formats, data centers, and optical interconnect applications in mind. The state of the art of these compact modulators, with a focus on fabrication, design, and high-speed performance is reviewed. Guidelines for design optimization and key performance metrics of these important integrated photonic devices are presented. Furthermore, an outlook on the road towards commercial viability, along with potential novel applications is provided.

2.1 Introduction

Lithium niobate (LN) electrooptic (EO) modulators are widely available as packaged commercial off-the-shelf (COTS) components from several suppliers (e.g., [1-6]). Numerous technological advances followed the development of LN EO modulators for high-speed communications [7-9] and optical switches [10-12]. Waveguide propagation loss [13,14], coupling loss [15-17] and thermal and direct current (DC) drift effects [18-20] have been suppressed along with advances in packaging. Modulation bandwidths are increased thanks to
improved radio-frequency (RF) design considerations [21-25]. Finally, the development of erbium-doped fiber amplifiers was instrumental in the deployment of long-haul optical transmission systems, in which LN EO modulators play a central role and have enjoyed tremendous success [26-28].

Meanwhile, coherent optical transmission has been advanced by wavelength division multiplexing (WDM) [29-31] and higher order modulation formats [32,33]. More recently, short reach optical interconnects have become important for data centers [34-36], and for potential integration with electronics [37,38]. The ability to form compact optical modulators, and integrate many of them on a chip is vital to the continued development of these domains.

The low-loss stripe waveguides of COTS LN EO modulators are usually formed by proton exchange (PE) [39-41] or in-diffusion of titanium [13-15,42]. These low-index-contrast waveguides present poor optical confinement leading to certain diminished performances, particularly high drive voltages, length and bending radii [43]. These factors render them incompatible with the fundamental philosophies of modern integrated photonics – compact devices, low drive voltages and power consumption, small bending radii, and dense on-chip integration. Nonetheless, they present remarkable modulation bandwidths, in excess of 100 GHz, and excellent performance, e.g., high extinction ratio for digital and high linearity for analog applications [42,44]. These positive attributes have motivated the pursuit of solutions for the aforementioned shortcomings, towards the realization of miniaturized LN EO modulators – the focus of this review paper.
For completeness, we mention that LN is not the only material pursued for compact modulator applications. The free-carrier plasma-dispersion effect (sometimes wrongly confused with the true EO or Pockel’s effect) has been used in silicon-on-insulator (SOI) waveguides to form modulators [45-47]. Electroabsorption (EA) modulators on III-V compound semiconductors, e.g., indium phosphide (InP) [48-50] as well as silicon-germanium (SiGe) [51,52], are well-established, and have been heterogeneously integrated on the SOI platform [51-53]. Spin-on EO polymers have been used on the SOI platform as well [54-56]. Each of these approaches has its benefits and shortcomings. Silicon optical modulators can be directly formed on SOI wafers using CMOS-compatible processing, but at the cost of limited dynamic electrical extinction [57,58] and linearity [59]. III-V EA modulators also usually present low extinction ratios [60] and generally have larger cross-sections than the silicon plasma dispersion modulators, leading to much larger bending radii. The reliability of polymer EO modulators has been a concern, although stable high temperature operation has recently been demonstrated [61].

A detailed comparison on the technical pros and cons of all these different platforms and predictions on their commercial success and potential market share is beyond the scope of this work; this paper focuses on compact LN modulators.

Section 2.2 describes the fabrication of compact LN EO modulators. Section 2.3 reviews the state of the art and touches upon digital and analog system requirements. Section 2.4 addresses the design of such modulators. Section 2.5 outlines advances required for commercial viability and potential applications, and Section 2.6 presents our concluding remarks.
2.2 Waveguide Platforms and Their Fabrication

Cross-sectional schematics of the major modern LN waveguide platforms developed in recent years and used for modulators are shown in Fig. 2-1. A schematic of conventional diffused waveguides in bulk LN single crystals (Fig. 2-1(a)) is also shown.
Figures 2-1(b), (c) and (d) depict three approaches for forming thin-film waveguides on thermally-exfoliated thin-film LN on SiO₂. They are proton-exchange, rib-loading with a different material, and dry etching of LN, respectively. These thin-film LN wafers are commercially available in 75-mm diameter on both LN and Si substrates. We expect that these thin film LN wafers will likely be available in 150 mm diameter in the near future – single-crystalline LN wafers are commercially available up to 150 mm, and the bonding technology is sufficiently mature.

A different approach, enabled by the maturation of thermally exfoliated LN thin film technology, is shown in Fig. 2-1(e). Here, sub-micrometer-thick platelets of LN are bonded on SOI using special transfer techniques, which do not damage the thin platelets. The Si on LN platform, shown in Fig. 2-1(f), employs a different approach of patterning thin films of silicon on bulk LN substrates. Both single-crystalline and amorphous thin films have been utilized, as discussed later. Finally, Fig. 2-1(g) shows an approach based on mechanical thinning or polishing. A patterned LN wafer is adhesive-bonded to a Si wafer. The LN substrate is mechanically thinned down to form the thin film. In the following, the fabrication of compact modulators on these platforms is discussed.

2.2.1 Substrate Fabrication

The first step towards realizing compact EO modulators and other devices using LN is the ability to slice thin films of single crystal LN from bulk LN wafers and bond them to transparent low refractive index substrates, while maintaining the EO property of LN. This
approach has provided superior ferroelectric thin film quality compared to other approaches, such as molecular beam epitaxy [62], pulsed laser deposition [63], sputtering [64], chemical vapor deposition [65], and sol-gels [66]. Since LN is anisotropic, the crystal orientation of a wafer is of paramount importance to realize the desired EO effect. LN wafers are commercially available with many different orientations. Among them, X, Y and Z-cut wafers are important for photonic applications.

Figure 2-2: Variation of projected range and longitudinal straggle with helium ion implantation energy.
The workhorse of forming thin films of LN, exploited in the approaches of Figs. 2-1(b)–(e), is helium (He) ion implantation. A crystalline LN surface is bombarded with He ions at a specific angle, energy, and dose. The ions lose their energy to the LN crystal, through nuclear collisions and electronic excitation, and stop at a particular penetration depth, where they damage and thereby physically weaken the crystal. This depth is characterized by a variety of statistical measures. Its average and deviation are called the projected range and longitudinal straggle, respectively. The dependence on He ion energy is shown in Fig. 2-2, estimated using a Monte-Carlo simulation package [67]. The projected range provides an initial estimate of the final thin-film thickness, while the longitudinal straggle is indicative of the size of the implanted or damaged layer. There are two methods to forming thin films of LN using He-ion implantation, as follows.

2.2.2 Crystal Ion Slicing

The first method based on ion implantation, called crystal ion slicing (CIS), was established in the late 1990s. A single crystal LN wafer is implanted with He ions at a few MeV, annealed, and wet-etched in hydrofluoric acid, to detach a single crystal free-standing LN thin film. Rapid thermal annealing is used to recover the material properties of LN which are degraded after the implantation step [68]. CIS is suited for LN films around 10-μm thick. The spatially non-uniform exposure to the wet etchant across a die results in an undesired non-uniformity in film thickness.
2.2.3 Thermal Exfoliation

Following the initial success of CIS in forming free-standing films, a second method using thermal shock slicing or thermal exfoliation has been established for die-scale and wafer-scale bonding of thin films of LN on to different substrates (Figs. 2-1(b), (c), and (d)). Thermal exfoliation is suitable for forming sub-micrometer-thick films, which are much thinner than the CIS films. The most successful approach using thermal exfoliation has been the direct bonding of thin-film LN on to silicon dioxide (SiO$_2$). This method resembles the Smart Cut™ process commercialized for silicon-on-insulator (SOI) wafers [69]. The first demonstrations of thin-film LN directly bonded to SiO$_2$ on LN substrates were die-scale [70]. Wafer-scale demonstrations soon followed [71]. Sometimes, these wafers are called lithium niobate on insulator (LNOI).

Arguably, the wafer-scale demonstration of thin film LN bonded to oxidized Si substrates is technologically more interesting. The advantages of silicon substrates over LN include cost, potential compatibility with silicon photonics, as well as relaxation of processing conditions of LN-based devices themselves. For example, the extremely low thermal conductivity of LN makes thermal cycling of the material challenging. Silicon substrates, in contrast, are very versatile and can easily handle thermal cycles. Also, processing issues associated with high levels of pyroelectric charges are diminished by eliminating bulk LN substrates.
Figure 2-3: (a)-(c) Summary of wafer-scale thin-film lithium niobate on silicon dioxide fabrication steps. The substrate can be silicon as shown here, or lithium niobate [72]. Reproduced with permission. Copyright 2017, John Wiley and Sons, Inc.; (d) A 3” thin film wafer of lithium niobate bonded to a 4” substrate wafer of oxidized silicon [73]. Reproduced with permission. Copyright 2013, The Optical Society.

Thin-film LN wafers on oxidized Si substrates were first reported by CREOL researchers in 2013 [73]. A major challenge that made this milestone elusive for years was the large thermal expansion coefficient mismatch between LN and Si, rendering the bonding of LN thin films at elevated temperatures infeasible. Progress in methods for room-temperature bonding has alleviated this issue. The wafer-scale fabrication steps for thin-film on Si substrates are
summarized in Fig. 2-3. An ion-implanted LN donor wafer is bonded to a SiO\textsubscript{2} layer, which is thermally grown on Si substrate (in the aforementioned case of thin-film LN-on a SiO\textsubscript{2} buffer on LN substrates, plasma-enhanced chemical vapor deposition (PECVD) is typically used to deposit SiO\textsubscript{2} on the LN substrate). Next, the bonded wafers are annealed at 200 to 220°C to thermally exfoliate the desired thin film of LN from the donor wafer. Similar to CIS, the high temperature annealing step here is crucial for recovering the EO and nonlinear properties of the LN thin film. Hence, after exfoliation, the temperature is increased to 400-500°C to mitigate implantation-induced material degradation. Finally, the LN thin film surface is subjected to a chemical mechanical polish (CMP) to improve the surface quality of the film, yielding surface roughness < 1 nm. The thickness of the SiO\textsubscript{2} layer, the depth of the ion implantation, and the thin film material polished away in the last step, are all independent parameters, offering excellent control over the final thicknesses of the LN thin film and the SiO\textsubscript{2} lower cladding.

A somewhat different approach uses benzocyclobutene (BCB) [74,75] as a polymer adhesive for die-scale bonding instead of direct bonding to SiO\textsubscript{2}. Chips of LN, cleaved from a donor LN wafer implanted with He ions, are bonded to BCB coated LN chips. The post-bond annealing is similar to that for direct bonding to SiO\textsubscript{2}, however, the last step of the anneal is at a lower temperature of 300°C [76,77]. The anneal temperature is one downside of this approach. BCB limits the highest temperature of the post-bonding anneal, which is crucial for the recovery of the implantation induced material degradation, where higher temperatures are desirable. The reliability of polymer-bonding is another drawback. Thus, direct-bonding on SiO\textsubscript{2} layers is preferred, and most of the recent work on thin film LN uses SiO\textsubscript{2} as the lower cladding insulator.
Thin-Film Lithium Niobate Bonded on Top of SOI

Wafer-scale bonding of LN to silicon has been pursued since the late 1990s [78,79], i.e., around the same time as CIS. About a decade later, thin film platelets of LN were bonded to SOI waveguides [80-83], bringing together LN-Si bonding and CIS (Fig. 2-1(e)). An ion-implanted LN wafer is heated to thermally-exfoliated platelets of thin-film LN and annealed. These platelets are then bonded, directly, or using BCB, on top of a SOI microring resonator, to form the hybrid Si-LN platform. More recently, centimeter-size thin films of LN on a LN substrate have been bonded to SOI dies singulated from patterned SOI wafers [84] (Fig. 2-4).
2.2.5 Silicon on Single-Crystalline LN Wafers

There are two approaches to forming the Si on LN platform of Fig. 2-1(f) [85-87]. The first method is based on bonding unpatterned SOI to bulk single crystalline LN [85,86]. The substrate and the buried oxide of the SOI are etched away, leaving behind a layer of single-crystalline Si on LN. The second approach uses a direct deposition of amorphous Si on a LN substrate [87]. In either case, the higher refractive index of silicon provides optical confinement in the platform upon patterning.

Figure 2-5: Micrograph and scanning-electron-microscope image, along with the corresponding optical mode simulations, for (a) high loss [90], and (b) low loss [92], proton exchanged waveguides in thin film LN. The drastic reduction in PE area reduces the propagation loss. Reproduced with permission. Copyright 2015, The Optical Society.
2.2.6 Mechanical Thinning

To achieve the platform depicted Fig. 2-1(g), a combination of polymer adhesive bonding followed by mechanical polishing is employed [88]. Stripes are plasma etched onto a bulk single-crystalline LN wafer, which is then bonded, patterned side-down onto a Si wafer using an ultraviolet (UV) curable adhesive layer. After curing, the LN substrate is mechanically thinned down, followed by tuning the thickness by dry etching, to form waveguides [88].

![Figure 2-6: Scanning electron microscope images of different rib-loaded thin-film LN waveguides using (a) tantalum pentoxide [73]. Reproduced with permission. Copyright 2015, The Optical Society; and (b) silicon nitride [102]. Reproduced with permission. Copyright 2016, IEEE. Micrographs of chalcogenide loaded (c) Mach-Zehnder and (d) microring modulators being tested [96]. Reproduced with permission. Copyright 2015, The Optical Society. (e) Detailed electrode structure and a grating coupler of a microring modulator from (d).]
2.3 Waveguide Fabrication

In this section, some of the different approaches that have been pursued towards forming compact LN waveguides on the wafer platforms discussed above are reviewed.

2.3.1 Proton Exchange and Annealed Proton Exchange

The PE method is well-established for forming waveguides in bulk LN wafers [39,40]. PE relies on the replacement of Li$^+$ ions in LN with hydrogen ions (H$^+$ or protons) to locally increase the extraordinary refractive index and provide optical confinement. PE results in the formation of a complex series of distinct crystallographic phases of the form Li$_{1-x}$H$_x$NbO$_3$. These phases are often accompanied by scattering loss, and degraded nonlinear and EO performance. When PE is followed by a controlled anneal, the process is called annealed proton exchange (APE) [41]. Annealing helps mitigate some of the undesired effects of PE [89]. Both PE and APE have been used to form waveguides in thin film LN [90,91] with losses ranging from 11 dB/cm to 16 dB/cm for PE, and 0.6 dB/cm for APE. More recently, a very short PE time has been used to realize a small exchange depth [92], resulting in low loss waveguides (0.2 dB/cm) without a post-PE anneal (Fig. 2-5). These waveguides present micron-scale cross sections, at the cost of high bending radii, as discussed in Section 2.4.
Figure 2-7: Scanning-electron-microscope images of different argon-etched thin-film LN waveguide structures in chronological order of reporting: (a) [103]. Reproduced with permission, 2008; (b) [105]. Reproduced with permission. Copyright 2014, The Optical Society; and (c) [106]. Reproduced with permission, 2017. The improvement in sidewall roughness over time is evident, culminating in 0.4 dB/cm propagation loss demonstrated in (c).

2.3.2 Rib Loading

Arguably, the most straightforward way to form waveguides on a thin film of LN is to deposit a different dielectric or semiconductor on the thin film. The dielectric film is then patterned to form a rib, which loads the LN thin film. The refractive index of the rib-loading material should be closely matched that of LN to maximize the confined optical energy in the LN layer. This approach has been demonstrated using a handful of materials, such as tantalum pentoxide (Ta$_2$O$_5$) [73,93,94], titanium dioxide (TiO$_2$) [95], chalcogenide glass (ChG), e.g.,
Ge$_{23}$Sb$_7$S$_{70}$ [96-98], and silicon nitride (SiN) [99-102] (Fig. 2-6). The immediate benefit of rib-loading is the ease of processing, e.g., ChG and SiN are easier to etch than LN and offer smooth etched sidewalls for low waveguide propagation loss. Another advantage is that rib-loading is applicable to any LN crystal cut. The reported propagation loss of rib-loaded thin-film LN waveguides is summarized in Table 2-1.

<table>
<thead>
<tr>
<th>Rib material</th>
<th>Loss (dB/cm)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tantalum pentoxide</td>
<td>5</td>
<td>[73]</td>
</tr>
<tr>
<td>Titanium dioxide</td>
<td>5.8</td>
<td>[95]</td>
</tr>
<tr>
<td>Chalcogenide glass</td>
<td>1.2</td>
<td>[97]</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td>1</td>
<td>[99-101]</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td>7</td>
<td>[102]</td>
</tr>
</tbody>
</table>

2.3.3 **Dry Etching**

As mentioned, LN has traditionally been difficult to chemically dry-etch [103]. Isotropic wet etching is not compatible with forming small waveguide cross-sections. Alternatively, dry
etching assisted by argon, and argon milling, have been extensively investigated for patterning LN in both bulk single-crystalline, as well as thin-film wafers (Fig. 2-7) [104,105]. Historically, etched thin film LN waveguides have suffered from high propagation losses. In one recent demonstration, though, low-loss waveguides (0.4 dB/cm) have been realized [106]. However, this particular demonstration is only on Z-cut LN, where the re-deposition of material from the dry etching is expected to be different from X- and Y-cut. Nonetheless, this encouraging report on etching Z-cut LN is an important milestone towards realizing low-loss X- and Y-cut LN waveguides using dry etching.

Figure 2-8: Transfer functions for (a) phase, (b) Mach-Zehnder, and (c) microring modulators.
2.3.4 Thin-Film Lithium Niobate Bonded on Top of SOI

There is no LN-related waveguide processing when forming waveguides by bonding LN thin films on top of SOI waveguides, i.e., the entire burden of waveguide formation is on the SOI end of the processing. SOI waveguides with thin film LN bonded on top with losses of 4.3 dB/cm have been reported [84]. Due to the high refractive index of Si compared to LN, bending radius is often sacrificed for optical mode overlap with the EO LN film.

2.3.5 Silicon on LN

The main feature of the silicon-on-LN platform (Fig. 2-1(f)) is the elimination of SiO₂ cladding layers. This is particularly advantageous in the mid-wave infrared wavelengths, where SiO₂ is optically lossy. Mid-infrared modulation (at 3.4 μm wavelength) has been demonstrated using crystalline Si thin films bonded on LN substrates [85]. The reported waveguide propagation loss is as ~ 2.5 dB/cm. Further processing optimization has led to 0.8 dB/cm in microrings [86]. Depositing amorphous Si on LN substrate is easier than bonding crystalline SOI and removing the substrate. The tradeoff is a higher propagation loss of ~ 3 dB/cm [87].

2.3.6 Mechanical Thinning and Other Methods

Modulators formed using mechanically-thinned LN waveguides adhesive-bonded to silicon (Fig. 2-1(g)) have reported waveguide losses ~ 1 dB/cm [88]. Other waveguide structuring methods, such as femtosecond laser writing [107] and optical grade dicing [108], are not discussed here, since have not been used to form modulators in thin film LN.
Figure 2-9: Low-frequency optical extinction ratio for MZ and microring modulators. The OER for certain ring modulators, when not explicitly mentioned, has been extracted from voltage tuning measurements.

2.4 Performance of Thin Film LN EO Modulators

The performance of three types of electrooptic modulators, namely the phase, Mach-Zehnder (MZ), and microring types, shown in (Fig. 2-8), is discussed in this section.

2.4.1 Optical Extinction Ratio

The optical extinction ratio (OER) quantifies the optical power extinction offered by a modulator in the off state, relative to the on state at low frequencies (DC to a few MHz). The OER of a MZ and a microring modulator can be discerned as the ratio of the maximum to minimum value of the photoreceiver output. An ideal symmetric MZ modulator presents infinite OER. However, fabrication imperfections, such as deviations from 50:50 power splitting and combining, and loss-imbalance between the arms of the MZ modulator, lead to finite OERs. The
OER for an EO microring modulator is determined by the passive spectral response of the microring, which in turn depends on the coupling coefficient between the bus waveguide and the microring, the propagation loss in the microring, and the excess loss at the coupler.

The specific application of the modulator determines the acceptable OER range. Above 20 dB OER is required for long-haul communications and over 30 dB is desirable in certain switching applications, while short-reach transmission can tolerate lower OER.

Figure 2-10: (a) Fabry-Perot reflections of a thin-film LN phase modulator [110]. Reproduced with permission. Copyright 2016, The Optical Society; (b) Resonance of a microring modulator [97]. Reproduced with permission. Copyright 2015, The Optical Society. Theoretical fits to measured data for both (a) and (b) are sufficient to extract propagation loss.

A summary of OER for thin-film LN EO modulators is presented in Fig. 2-9. This includes all the various platforms discussed in Section 2.2, as well as COTS LN MZ modulators. Similar charts are shown for other figures of merits in the following subsections. In all cases, an empty column signifies that the corresponding metric has not been reported for that particular
platform. It is observed from Fig. 2-9 that, in the case of the OER, rib-loaded (Fig. 2-1(c)) and Si-on-LN (Fig. 2-1(f)) thin-film platforms offer the best performance and are on par with COTS LN modulators.

Figure 2-11: Waveguide loss for different modulator demonstrations. Some microring modulator data is omitted because the loss in a microring is often increased, i.e., the quality factor is decreased, in order to increase modulation bandwidth. Thus, it is not indicative of the quality of the platform employed.

1 These loss values are on waveguides per se, not MZ modulators, but with processing conditions similar to those used in COTS modulators.

2.4.2 Optical Loss

Some loss values (propagation loss) were mentioned in Section 2.2.2. Optical loss, an important metric, is reviewed and discussed here in more depth. The optical loss of a MZ modulator can be considered to have various contributions and associated parameters. The overall insertion loss of the interferometer is an important system parameter that depends on
coupling loss and propagation loss. Coupling loss depends on the mode overlap between the input light field and the waveguide mode, and the quality of the waveguide facet. The propagation loss depends on material absorption, sidewall scattering induced loss, and metal induced absorption associated with the overlap of the edges of the optical mode with the metal electrodes. Another important component is the loss imbalance between the two MZ arms, which degrades the extinction ratio, and may affect the chirp. This includes scattering from undesired contaminants and fabrication defects.

Optical loss for a microring modulator can be split up similarly. The on-chip insertion loss here includes the propagation loss in the bus waveguide and in the microring region, as well as the less significant loss of the directional coupling region. Obviously, the propagation loss in the microring has a significant impact on the optical quality factor, i.e., it influences the limit of the modulation speed of the microring.

The optical loss of a straight waveguide, such as a phase modulator, can be extracted from Fabry-Perot reflections (Fig. 2-10(a)). Alternatively, microrings can be used as well (Fig. 2-10(b)). A summary of waveguide propagation losses of the variously discussed technologies is presented in Fig. 11. The data has been limited to demonstrations of modulators. The rib-loading platform (Fig. 2-1(b)) offers the lowest propagation loss of ~ 1 dB/cm among modulators, although it is still higher than the ~ 0.2 dB/cm values in COTS devices.
2.4.3 Half-wave Voltage and Tunability

The half-wave voltage, $V_\pi$, also called the switching voltage, is the voltage required to toggle a MZ modulator between the on and off states. For a phase modulator, it is the voltage required to accumulate a $\pi$-phase shift over the device length, $L$. The half-wave voltage-length product, $V_\pi L$, is a figure of merit that is often used to qualify the design of the MZ modulator, since it is independent of the device length, $L$. The tunability, in pm/V, is the analog of $V_\pi$ for microring modulators, which represents the spectral shift of an optical resonance of the microring modulator per volt applied to the electrodes. The $V_\pi$ and tunability determine which electrical drivers are suitable to drive a modulator, and whether amplifiers are necessary.
Figure 2-12 summarizes the trend of $V_{\pi}$ and $V_{\pi}L$ values among compact LN EO MZ modulators. The rib-loaded devices [73,97,99,102] have the lowest $V_{\pi}$ of $< 3$ V, comparable to COTS MZ modulators, but with much shorter lengths. The ion-milled and the rib-loaded variations of the thin-film LN on SiO$_2$ lower cladding approach (either on LN or Si substrates) offer the lowest $V_{\pi}L$ to date on any LN-based technology. This is because the high optical confinement facilitates the placement of the bias electrodes in close proximity of each other without incurring metal-induced optical loss.

Figure 2-13: Tunability of LN microring modulators.

In comparison, the ion-milled devices in [111] have 42% lower $V_{\pi}L$ than the rib-loaded device in [99] (1.8 vs. 3.1 V.cm). This $V_{\pi}L$ reduction corresponds well with the 37% reduction in electrode gap (3.5 vs. 5.5 μm), which is trivial to implement in rib-loaded structures since both types of waveguides offer similar lateral confinement and bending loss, as discussed later (Fig. 2-19). It is not clear whether the aggressive electrode proximity in [111] may have contributed to the higher loss of 3 dB/cm vs. 1 dB/cm in [99] (Fig. 2-11). Figure 2-13 similarly presents the tunability for microring modulators. In this case, the LN-on-SOI technology has demonstrated
the best performance, most likely because of the Z-cut oriented thin film. No high-speed measurements have been carried out on these particular Z-cut devices to date, as follows.

![Diagram](image)

Figure 2-14: Examples of frequency responses of compact LN EO modulators: (a) MZ type [99]. Reproduced with permission. Copyright 2016, The Optical Society; and (b) microring type [111]. Reproduced with permission.

2.4.4 Modulation Bandwidth and Frequency Response

The 3-dB electrical modulation bandwidth is the frequency at which the electrical response of a calibrated photodetector (Fig. 2-15) measuring the modulated output wave drops to half of its low-frequency value. The frequency response is often complicated by acoustic waves in the LN waveguides and acoustic resonances in substrates, and clamping and unclamping of the LN structure, all of which lead to ripples, potentially larger than 1 dB, occurring at frequencies as large as a few GHz, depending on the physical structure. Figure 2-15 tabulates the measured 3-dB bandwidths in various state-of-the-art devices. Among them, the SiN rib-
loaded LN thin-film approach on Si substrate [99] has demonstrated the highest bandwidth of ~33 GHz to date. Design considerations for higher bandwidths are presented in Section 2.4.

![Figure 2-15: 3-dB modulation bandwidth for both MZ and microring modulators.](image)

1 Estimated from optical sideband measurements. This particular MZ modulator has been tested up to 110 GHz.

### 2.4.5 Digital Transmission

Digital data transmission has evolved into using a wide variety of higher order modulation formats [32,33]. So far, however, thin film LN EO modulators have been used only for non-return to zero (NRZ) on-off keying (OOK), i.e., intensity modulation with direct detection. While higher order formats enable higher aggregate transmission bit rates for the same baud rate, the simplicity of detection for OOK makes it an attractive choice for data centers. We expect that higher order formats will be demonstrated on compact LN thin film modulators in the future.
Transmission rates for OOK in thin film LN EO modulators are presented in Fig. 2-16. Evidently, the reported data is sparse for these measurements. Also, since electrical extinction ratio, the length of the pseudorandom bit sequence used, and other factors are important for a complete picture of digital transmission, we refer the reader to the relevant references provided in the figure for further experimental details.

![Figure 2-16: Comparison of OOK data rates for various compact LN modulators.](image)

2.4.6 **Linearity and Dynamic Range**

The linearity of the transfer function of a modulator around a particular operating or bias point is central to the analog performance of the modulator. The nonlinear distortion present in an analog link is comprised of the nonlinearity of the modulator and the rest of the link (sources, amplifiers, detectors, RF spectrum analyzers, and any other components). The most straightforward way to quantify the distortion is by measuring intermodulation products. For two in-band modulation tones of frequencies $f_1$ and $f_2$, the in-band intermodulation distortion (IMD) tones are usually the third-order intermodulation (IMD3) tones at $2f_1 - f_2$ and $2f_2 - f_1$. If the
bandwidth is over an octave, second-order distortion tones, such as \( f_1 + f_2, 2f_1, \) and \( 2f_2 \) become important. These effects are cubic and quadratic, respectively. The spurious-free dynamic range (SFDR) is the signal-to-noise ratio at the output at the frequency of a fundamental input RF tone when the IMD products are equal in power to the noise at the output, for a two-tone input of identical power.

Figure 2-17: (a) IMD3 measurements for a LN on SOI microring modulator, along with a benchmark COTS LN MZ modulator for comparison [81]; (b) IMD3 SFDR for compact LN EO modulators.

A typical IMD3 measurement is shown in Fig. 2-17(a) [83], while a comparison of SFDR for compact LN EO modulators is shown in Fig. 2-17(b). There are only two reports in this
regard for the novel compact structures reviewed here, with SFDRs in the 90 to 100 dB.Hz$^{2/3}$ range. Evidently, the performance of these early reports are comparable to the COTS counterparts.

It is noted that the SFDR of a modulator is only one of the many metrics required to evaluate an analog link. However, it is the only feature of the link which cannot be improved by amplification before and after the link. We refer the readers to excellent reviews on the linearity of analog links [112] and microwave photonics [113,114].

2.5 Design

The design of compact LN modulators is discussed here for $X$-cut thin-film LN modulators. Similar guidelines can be established for $Z$-cut modulators.

2.5.1 Waveguide and Low Frequency Design

As seen throughout this chapter, there are many approaches that have been utilized to form waveguides for the modulators in thin film LN. In this section, rib-loaded, ion milled, and PE single-mode waveguides are analyzed. For the purposes of optical design, the approach of thin-film $X$-cut LN bonded on top of SOI (Fig. 2-1(e)) can be treated as a specific case of rib loading a thin film of LN, though from the bottom and with a non-index-matched material, i.e., Si. Similarly, waveguides formed by mechanical thinning are optically identical to ion-milled waveguides.
Assuming a longitudinally uniform structure, the low frequency $V_\pi$ for a symmetric push-pull-configuration [99] MZ modulator is

\[
V_\pi = \frac{\lambda n_{\text{eff}}}{\pi n_e^2 \Gamma},
\]

(2-1)

where $n_{\text{eff}}$ is the effective index of the waveguide mode and $n_e$ is the extraordinary material index of LN. $\Gamma$ is an overlap integral parameter given by

\[
\Gamma = \frac{\iint \frac{E(x,y)}{V} r_{33}(x,y) E_1 \cdot E_1^* dx dy}{\iint E_1 \cdot E_1^* dx dy},
\]

(2-2)

where $E(x,y)/V$ is the RF frequency electric field per volt applied to the electrodes, and $E_1$ is the electric field of the optical mode. It is important to note that $E(x,y)/V$ has units of 1/length. For a pair of ideal parallel plates, it is the inverse of the separation between the plates. The integral in the numerator is performed only over the extent of the EO material (since $r_{33} = 0$, elsewhere), while the denominator is over the entire transverse cross section. $V_\pi$ depends on the electric field per applied volt, and the overlap of the electric field with the intensity of the optical mode in the EO material – these can be tuned through optical and electrical design, as well as the device length.
Figure 2-18: Effect of the refractive index of the rib loading material on waveguide effective index and the modal power confinement in the LN slab, for the combination of rib (height × width) and LN (slab height) dimensions indicated in the legend.

Generally, well-confined compact optical modes are desirable. This is due to a number of reasons – they have, for instance, small bending radii, which enable dense photonic routing, essential for any large-scale integration. An immediate example is the reduction in the size of Y-junctions and microring modulator radii. Furthermore, the gap between the electrodes can be
decreased as the confinement of the optical mode increases. This leads to a reduction in $V_\pi$, evident in (8).

Figure 2-19: Bending loss per 90° bend in dB for different platforms. SOI waveguides are shown as a benchmark. The LN-on-SOI waveguide presents the smallest bending losses, but only when ~ 30% of the optical power is confined in the LN cladding film, while the rest is in the SOI waveguide core (data extracted from [84]). The two rib-loaded waveguides show bend radii below 20 μm when width of the rib material is varied between I (2.4 μm) and II (1.2 μm). The PE waveguides (shown separately) present high bending radii due to the small exchange depth used for obtaining low loss (data extracted from [92]).
Figure 2-18 shows the variation of the effective index of the fundamental transverse-electric (TE) mode with the index of the rib loading material. The physical dimensions are indicated in the legend of Fig. 2-18, and the simulations were carried out using an eigenmode solver (COMSOL™). While practical aforementioned examples include Ta₂O₅, ChG glass, SiN, and Si, the entire range of indices from 1.44 (SiO₂) to 3.48 (Si) can, in principle, be covered using plasma-enhanced chemical vapor deposition of silicon oxynitride, SiN, silicon rich SiN, and amorphous Si. The theoretical discussion here is limited to practical indices, ranging from 1.7 to 3.5.

Control over the optical effective index is a crucial aspect of velocity matching for RF design, discussed later. At the same time, the fraction of the intensity of the optical mode in the LN (Fig. 2-18) also affects the $V_\pi$. It is evident that, the aforementioned issues of etching LN and propagation loss notwithstanding, ion-milled LN and PE waveguides offer less control over the effective index, limited by the material refractive index. However, over 95% of the light is confined in LN in these cases.

Bending losses are simulated using eigenmode simulations in COMSOL™. The loss per 90° bend is tabulated in Fig. 2-19 for waveguide structures representative of LN on SOI, rib-loaded, and PE-LN. The LN-on-SOI waveguide exhibits low bending loss for ~5 μm bending radius, but sacrifices modal overlap with the electrooptically-active LN top cladding (~30% overlap). The rib-loaded structure is similar to those of Fig. 2-18 with a 300-nm-thick LN slab and a rib index of 2.2. Ion-milled waveguides (not shown) present bending loss similar to rib-loaded waveguides for the same bending radius and LN slab thickness. The rib-loaded
waveguides show both small effective areas and tight bending radii. The PE waveguides clearly offer small waveguide areas, and have demonstrated low propagation losses, but they have very high bending radii. The data for LN on SOI and PE-LN can be found in [84] and [110], respectively.

Next, there is an inherent tradeoff between metal-induced propagation loss and the $V_\pi$, mediated by the electrode gap and the optical confinement. The more tightly-confined the waveguide, the smaller the electrode gap, the higher the electric field per applied volt, and the lower the $V_\pi$. However, any further narrowing of the electrode gap after a certain value leads to significant metal-induced optical loss. This critical electrode gap depends on the particular waveguide structure under consideration.

The variation of the average electric field per applied volt is shown in Fig. 2-20. The electric field is averaged over two areas: the area of the rib, and the LN slab area under the rib, which is a good approximation for the well-confined waveguides of interest. Clearly, the RF electric field per applied volt drops sharply, in both the rib and the LN slab, as the dielectric constant, $\varepsilon$, of the rib increases. This can be understood through elementary electromagnetic boundary conditions. However, the consequence of this constraint is that the dielectric constant of the rib material strongly affects the overall $V_\pi$. This adverse impact on $V_\pi$ is very strong for the case of a LN rib (i.e., ion-milled waveguide), as compared to rib materials with lower RF dielectric constants (e.g., SiN). In other words, depending on the refractive indices and mode distribution, the drop of the field per volt associated with the very high RF dielectric constant of a LN rib plays against the higher optical mode overlap with the EO-active material it offers.
Figure 2-20: Average electric field per applied volt as a function of electrode gap and rib dielectric constant for the structure shown above. The top plot presents the average field in LN and the lower plot is the corresponding value in the rib. Depending on the rib index, electrode gaps as low as 3 μm present prohibitively high propagation loss.
Finally, it is important to note that the electrode-induced loss can be used in microring modulators to tune the quality factor and therefore the maximum modulation frequency. This illustrates an additional perspective on the loss-tuning tradeoff compared to the loss-$V_π$ tradeoff. Also noteworthy is that the full optimization of the $V_π$ may also be affected by the RF design discussed in the following subsection.

Before delving into the RF design for MZ modulators, additional requirements for microring modulators are briefly discussed. With small dimensions, microring electrodes can be treated as lumped elements driven as capacitors. The modulation bandwidth is limited by the product of the capacitance ($C$) and total resistance ($R$). Accordingly, a simplified model for the RF half-wave voltage is

$$V_π(ω) = V_π(0)[1 + iωRC],$$

(2-3)

where $V_π(0)$ is the half-wave voltage at DC. A detailed treatment of microring modulators can be found in [115].

### 2.5.2 RF Design

There are many facets to the RF design of traveling-wave electrodes of MZ modulators, which must be managed simultaneously with low frequency and waveguide design. The optical modulation frequency response, $m(\omega)$, is [116,117]
\[
m(f) = \left| \frac{(\Phi_+ + r_L \Phi_-)(1 + r_S)}{\exp(2i\Phi_+) + r_L r_S \exp(-2i\Phi_-)} \right|^2, \tag{2-4a}
\]

\[
\Phi_\pm = \exp(iu_\pm) \sin(u_\pm)/u_\pm, \tag{2-4b}
\]

\[
u_\pm = \pi(n_{RF} \mp n_{opt})fL/c - i\alpha_{RF}L/2, \tag{2-4c}
\]

\[
\Gamma_L = (Z_L - Z_0)/(Z_L + Z_0) ; \Gamma_S = (Z_0 - Z_S)/(Z_0 + Z_S), \tag{2-4d}
\]

where \(n_{RF}\) and \(n_{opt}\) are the RF and optical mode indices, respectively, \(f\) is the RF frequency, \(\alpha_{RF}\) is the RF loss, \(Z_L\) and \(Z_S\) are the load (termination) and source impedances, respectively, and \(Z_0\) is the characteristic impedance of the RF electrodes. \(m(f)\) quantifies the optical frequency response of the modulator. \(\Gamma_L\) and \(\Gamma_S\) are the RF reflections between the termination and the electrodes, and the electrodes and the source, respectively. The 3-dB electrical bandwidth can be estimated from the \([m(f)]^2 = 1/2\) condition.

There are a number of design considerations for high-speed design – velocity matching, impedance matching, and RF loss. Velocity matching is the propagation effective-index mismatch between the RF and optical fields, contained in the \(u_\pm\) terms. The smaller the difference of \(n_{RF}\) and \(n_{opt}\), the higher the modulation bandwidth. The \(Z_L\) and \(Z_S\) impedances are typically 50 \(\Omega\). Though frequency-dependent, the characteristic impedance of the electrodes is then designed to be as close to 50 \(\Omega\) as possible, to minimize electrical reflections at the RF input and from the terminating impedance. Finally, the RF loss can be decomposed into a sum of metal and dielectric loss. The higher the RF loss, the lower the modulation bandwidth.
The RF electrode design comprises of a fine balance between the above three factors in conjunction with the limitations imposed by the aforementioned low-frequency and waveguide design considerations. The RF index and characteristic impedance can be modeled by finite element and boundary element methods, among others.

An immediate benefit of using thin-film LN is that velocity matching is much more straightforward than in COTS low-index-contrast counterparts. LN has a much higher RF dielectric constant than the square of its optical index, resulting in a much higher $n_{RF}$ compared to $n_{opt}$. COTS LN MZs have managed to work around this by techniques such as using SiO$_2$ buffer layers and very thick electrodes to shift the RF mode upwards. However, this consideration is diminished significantly for thin film LN because of the reduced thickness of LN and the lower dielectric constant of the surrounding SiO$_2$ ($\varepsilon \sim 3.9$). Thus, the thin film LN electrodes can be $\sim 1$ μm tall, unlike the $\sim 10$ μm or more for COTS MZ modulators.

In the limit of negligible RF reflections (i.e., good impedance matching), the modulation response is simplified to [118]

$$m(f) = \exp\left(-\alpha_0 \sqrt{fL}/2\right) \left[\sinh^2\left(\frac{\alpha_0 \sqrt{fL}}{2}\right) + \sin^2(\pi \nu f L)\right]^{1/2},$$

(2-5)

where $\nu = (n_{RF} - n_{opt})/c$ is the velocity mismatch, and $\alpha_0$ is the metal RF loss parameter at 1 GHz.
Figure 2-21: EO $S_{21}$ roll-off in dB for a range of velocity mismatch and RF loss for the following pairs of frequency and electrode length (a) 40 GHz and 2 cm; (b) 70 GHz and 2 cm; (c) 100 GHz and 2 cm; (d) 40 GHz and 10 cm. The 3-dB modulation bandwidth is marked with a black contour line in each plot.

This latter form lends itself to easier analysis than (11). The reduced modulation with increasing RF loss and velocity mismatch is evident in (12). The velocity mismatch has a sinusoidal contribution to the numerator and a quadratic contribution to the denominator. The RF
loss scales as a decaying exponential in the numerator, and a quadratic in the denominator. Equation (2-5) has been used to quantify the bandwidth-length tradeoff [118], i.e., the decrease in RF bandwidth with increasing device length. This is clear in (12), where the effects of velocity mismatch and RF loss are both scaled by the device length. Thus, an increase in any of \( v, \alpha_0, \) and \( L \) will diminish the modulation and hence the bandwidth.

Here, general design guidelines for velocity mismatch and metal RF loss in the presence of good impedance matching are established. The EO \( S_{21} \) roll-off is plotted in Figs. 2-21(a)-(c) at frequencies of 40, 70, and 100 GHz for 2-cm-long electrodes. Figure 2-21(d) provides a benchmark at 40 GHz and 10 cm. The two lengths are chosen to facilitate a comparison between shorter thin-film and longer COTS LN MZ modulator, when both are set up for a DC \( V_\pi \) of 1 V. Evidently, the compact devices can yield much higher modulation bandwidths with comparatively relaxed design tolerances, even up to 100 GHz, for low voltage operation.

2.6 Outlook

As reviewed in Section 2.3, the performance of compact thin film LN modulators is now on par with COTS LN MZ modulators in several key figures of merit. 3-dB modulation bandwidths up to 33 GHz [99] and operation up to 110 GHz [88] have been independently confirmed in MZ modulators, along with 30 GHz bandwidth in microring modulators [111]. In addition, low switching voltages and good extinction ratios have been established. Potential applications of this emerging technology include communications in optical interconnects, terrestrial and submarine systems, RF-photonics, millimeter wave imaging, and electric field
sensing. However, there are some milestones on the road to commercial viability that have yet to be achieved.

The first milestone is packaging. The compact modulator demonstrations so far have yet to be equipped with optical and RF packaging. RF-compliant packaging has the challenge of not perturbing the modulator response and is a complicated task. Furthermore, perhaps all demonstrations so far have utilized some form of optical alignment stages for optical coupling. Such systems may be susceptible to drift over time. This has obviated the study of thermal drift, DC drift and reliability. These are crucial aspects of modulator performance for real-world deployment. It is expected that work on these fronts will come to fruition soon.

There is further device optimization to look forward to. As established in Section 2.4.2, the design requirements for achieving 100 GHz modulation bandwidth at low switching voltages (~ 1 V) are well within those of COTS LN modulators. It is expected that such high- and low-power devices will be realized in the near future.

In the meantime, there are many exciting possibilities heralded by the realization of compact LN modulators. Perhaps the most exciting commercial application is expected to be in data centers and high-performance-computing. With the ever-increasing data rate requirements, the use of on-off keying and direct detection in these infrastructures will likely be replaced by the use of higher-order modulation formats, aided by forward-error correction and other digital signal processing techniques. There is room for growth across the entire spectrum of core-to-core to inter-data-center interconnects. In a similar vein, metro- and long-haul-terrestrial and submarine telecommunication may evolve into using denser WDM grids, potentially aided by
frequency combs, to address increasing data rates. Higher-order modulation formats and coherent detection might be employed up to certain transmission lengths. Compact thin-film LN modulators are indeed promising candidates for such applications. Their small footprint renders them attractive for high-density on-chip integration. Their high extinction ratio, compared to the other modern compact modulators mentioned in Section 2.1, is attractive as well for all the above applications. They also have potential applications in forming miniaturized compact ultrafast versions of the LN optical switches demonstrated around the 1990s and onwards.

With the anticipated improvements in linearity, compact LN modulators are promising candidates for analog links. RF-photonic down converting links have recently been demonstrated in-flight [119]. The adoption of optical-fiber-based interfacing in an aircraft can potentially lead to significant weight reduction by eliminating coaxial cables. Similar considerations apply to naval vessels.

Millimeter waves offer tremendous potential for imaging applications, based on their penetration through smoke, fog and clouds. There has been good progress in millimeter-wave beam formation and imaging using LN modulators [120]. Fully integrated implementations of these systems in the future may benefit in efficiency and sensitivity enhancements from the low switching voltages and high bandwidths that are anticipated of compact LN modulators. Along these lines, compact LN devices have already been utilized as compact electric field sensors [121], and there is room left in device optimization for better performance. Compact high-sensitivity electric field sensors may be exploited in medical applications, as a part of point-of-care monitoring systems, and in electromagnetic field sensing for the armed services. Finally
and on a completely different note, compact LN MZ modulators have been investigated at visible wavelengths [122], potentially for the on-chip control of trapped ions.

2.7 Conclusion

The technology of compact LN modulators has matured tremendously over the last several years and is becoming well-established for numerous applications, both, in the near future, and, in the long term. These devices, which are miniaturized versions of commercial-off-the-shelf LN modulators, can be densely integrated on silicon with low switching voltages and promising digital and analog performances. With advances in packaging and reliability studies, these devices may soon evolve into a formidable contender for a variety of evolving applications in data centers, high performance computing, digital and analog telecommunication links, sensors, and imaging, among others.

2.8 References


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CHAPTER 3: HETEROGENEOUS MICRORING AND MACH-ZEHNDER MODULATORS BASED ON LITHIUM NIOBATE AND CHALCOGENIDE GLASSES ON SILICON


Abstract— Thin films of lithium niobate are wafer bonded onto silicon substrates and rib-loaded with a chalcogenide glass, Ge$_{23}$Sb$_7$S$_{70}$, to demonstrate strongly confined single-mode submicron waveguides, microring modulators, and Mach-Zehnder modulators in the telecom C band. The 200 μm radii microring modulators present 1.2 dB/cm waveguide propagation loss, $1.2 \times 10^5$ quality factor, 0.4 GHz/V tuning rate, and 13 dB extinction ratio. The 6 mm long Mach-Zehnder modulators have a half-wave voltage-length product of 3.8 V.cm and an extinction ratio of 15 dB. The demonstrated work is a key step towards enabling wafer scale dense on-chip integration of high performance lithium niobate electro-optical devices on silicon for short reach optical interconnects and higher order advanced modulation schemes.

3.1 Introduction

The advent of the optical interconnect has been driven by the fundamental loss and speed limitations of traditional copper interconnects at short communication links [1]. Optical modulation is an essential functionality of optical interconnects. For integration into short-haul
communication systems, optical modulators will be required to satisfy certain stringent criteria – high extinction ratio, large modulation bandwidth, and low insertion loss. Furthermore, low drive power and small device footprint will be significant factors in the integration of multiple modulators on a single chip for advanced higher-order modulation schemes that enable faster data transmission. It is also desirable to have modulators on silicon substrates for potential integration with silicon photonics and electronics. Platforms on silicon substrates have been pursued towards satisfying these requirements.

All-silicon (Si) optical Mach-Zehnder modulators (MZMs) and resonant microring modulators (MRMs), based on the well-established Silicon–on–Insulator (SOI) technology [2] have been heavily investigated in the telecom wavelengths [1,2]. Silicon lacks intrinsic second-order nonlinearity ($\chi^{(2)}$), essential for electrooptic modulation based on Pockels effect. Hence, all-Si modulators typically rely on the free-carrier plasma dispersion effect, where modulation of the free carrier concentration in a doped silicon waveguide modulates the complex refractive index, inducing an optical phase shift [3], and an inextricable change in the optical absorption. An inherent tradeoff exists between the modulation bandwidth and the extinction ratio (ER) of the modulators [1]. For example, all-Si modulators operating at 50 Gb/s have been demonstrated with an ER of 5.6 dB [4], as have modulators at 10 Gb/s with an ER of 18 dB [5,6]. All-Si phase modulator sections exhibit losses ranging from 1–4 dB/mm leading to high on-chip insertion loss above 1.9 dB and 3.5 dB in the off and on states, respectively, and modulation efficiencies between 1–3 V.cm [4,5,7,8]. Reed et al. [7] review recent advances in carrier-depletion all-Si modulators. All-Si MRMs afford low drive power and device footprint by virtue of their resonant
nature. However, this resonant nature reduces the reliability of obtaining the desired resonant operation wavelength using CMOS compliant fabrication, due to the very small fabrication tolerances of the devices [9].

![Diagram](image)

Figure 3-1: Schematic of the new platform depicting the chalcogenide (ChG) rib, lithium niobate (LN) core slab, lower optical cladding of silicon dioxide (SiO2), silicon substrate (Si), and the gold metal electrodes for: (a) Microring modulators; (b) Mach-Zehnder modulators.

Other approaches on silicon that have been explored include silicon-organic hybrid (SOH) integration [10] and photonic crystal modulators [11]. While the aging and stability of the organic polymers used in SOH platforms is still under study, high performance signaling at 160 Gb/s has been achieved using 16-state quadrature amplitude modulation (16 QAM) [10]. The SOH modulators had 18 GHz bandwidth, 1.3 V.cm modulation efficiency, and were 1.5 mm long [10]. Photonic crystal modulators on silicon have demonstrated extinction ratios above 10 dB at 1 Gb/s bandwidth [11]. Alternatively, heterogeneous integration of electroabsorption (e.g., SiGe and InP) and electrooptic (e.g., lithium niobate (LN)) modulators on silicon substrates has
been pursued [6]. In particular, LN exhibits strong electrooptic effect and is an excellent candidate for heterogeneous integration on silicon.

Unlike all-Si modulators, conventional LN modulators do not suffer from bias-induced loss and low ER, and can attain zero to negative chirp for increasing fiber dispersion tolerances [12]. Also, high extinction ratios above 20 dB, and wide modulation bandwidths (up to 100 GHz [13]) render these devices viable for long-haul telecommunication systems. In-diffusion of titanium into bulk LN wafers [12] and annealed proton exchange [14] are two methods used to define conventional LN stripe waveguides for MZMs. However, these conventional diffused LN waveguides suffer from low index contrast. This leads to low optical confinement in both the horizontal and vertical directions, and large half-wave voltage length products. A typical LN MZM is a few cm long, with a \( V_\pi \) of 3–6 V. Integrating multiple conventional LN MZMs for higher order modulation schemes while retaining low drive power would require long device modules, i.e., a larger device footprint. These limitations make conventional LN modulators too costly and bulky for short-range datacom applications.
Figure 3-2: COMSOL™ simulations of the Mach-Zehnder modulators: (a) Optical TE mode profile at 1550 nm – the thin gold stripes are the 100-nm-thick regions of the gold electrodes; (b) RF field distribution at 10 GHz – the regions marked Au are the gold metal electrodes. The chalcogenide (ChG) rib is shown with a white outline.

An ideal modulator platform would possess a strong reliable electrooptic effect, and be integrable onto a silicon substrate. In one approach towards this goal, an ion sliced film of LN is bonded as the top cladding onto an all–Si waveguide [15,16,17]. The electrooptic modulation is
due to the overlap of the evanescent tail of the guided mode with the LN cladding. The fraction of the guided optical power present in the LN cladding is as high as 42% for TM, and 11% for TE polarizations [16]. A shortcoming of this LN top-clad approach is the instability of the bonding based on free-standing structures [15] and the unreliability of the bonding based on polymers [16,17]. A reliable bonding approach, that directly transfers crystalline silicon from a SOI die onto bulk LN, has been successfully demonstrated at telecom [18] and mid-infrared [19] wavelengths.

As elaborated in Section 3.2, heterogeneous integration of highly confined thin films of LN on silicon wafers coated with a thermal silicon dioxide (SiO₂) cladding layer addresses the challenge of vertical confinement in LN. Another long-standing challenge for achieving tight, laterally confined LN waveguides has been the difficulty of etching the hard material. To circumvent this, the LN can be rib-loaded with a material whose refractive index matches that of the LN such that most of the optical energy still resides in the LN core waveguide region. Tantalum pentoxide, Ta₂O₅, has been proposed for this purpose, and optical resonators and MZMs have been demonstrated on the heterogeneous platform and characterized at low frequencies [20]. Selective oxidation of tantalum forms the waveguide ribs with reasonable propagation loss, around 5 dB/cm [21,22]. In the present effort, another type of index-matched material, Ge₂₃Sb₇S₇₀ chalcogenide (ChG), is used. The advantages over Ta₂O₅ include ease of processing and propagation loss as low as 0.42 dB/cm in submicron waveguides [23], which immediately reduces the on-chip optical insertion loss by 4 dB. Also, demonstrated here are LN MRM with grating couplers on Si substrates. The MZMs described in this work have an on-chip
insertion loss of 1 dB, and this can be reduced by further optimizing the ChG processing. Figure 3-1 shows a schematic of the MZMs and MRMs fabricated on the new platform introduced in this work. Finally, the MZMs on Si are characterized at radio frequencies (RF) for the first time.

3.2 Design

A 400-nm-thick film of Y-cut LN bonded to a 2 μm thick layer of SiO2 on a Si substrate forms the slab region of the ridge optical waveguide. The LN thin films are rib-loaded with a 0.35 μm × 1.3 μm strip of index-matched chalcogenide to form single-mode waveguides at 1550 nm wavelength, as depicted in Fig. 3-2(a). Bending losses are found to be negligible for this geometry at the 200 μm bend radius of the MRMs. The crystal orientation of the lithium niobate thin film is chosen to utilize the highest electrooptic coefficient of LN, viz., $r_{33} = 31$ pm/V. Thus, the z-axis of the LN crystal is aligned along the horizontal RF electric field created by the lateral metal electrodes, shown in Fig. 3-2(b). The MRMs are designed for a tunability of 3.8 pm/V, while accounting for the tensor nature of the electrooptic coefficient, $r$. COMSOL™ simulations confirm that ~60% of the TE optical mode resides in the LN core region, and predict a $V_{π}L$ of 3.4 V.cm for an electrode gap of 5.5 μm. The ~60% confinement in LN is much higher than the aforementioned value of 11% for TE mode in LN thin films bonded on SOI waveguides [16].

The lower $V_{π}L$ affords a lower drive voltage, and therefore lower drive power. It also permits smaller device lengths, which not only reduce the device footprint, but can also potentially increase the theoretical modulation bandwidth achievable [24,25]. This is expected based on theoretical studies showing that for the same bandwidth-length product, higher
modulation bandwidth is attainable in devices with shorter lengths [25]. Once this platform is fully developed, it can potentially offer significantly faster data transmission compared to commercially available lithium niobate modulators. The metal electrode vias and pads are designed to minimize the velocity mismatch [24] between the RF modulation field and the optical signal, while maintaining a characteristic impedance as close as possible to 50 Ω.

Grating couplers were designed using finite element simulations, following the standard guidelines reported in the literature [26,27,28]. The grating period and fill factor were varied to couple the guided mode to a free space Gaussian mode with a mode size of 17.5 μm × 5.2 μm. Due to the limited range of thicknesses available for the silicon dioxide lower cladding and LN layers, a less than optimal structure was achieved. The remaining un-coupled power in the waveguide was 30% of the guided mode. The combined loss due to the mismatch between the coupled free space mode and optical fiber mode, the uncoupled light in the waveguide, and the light that is diffracted toward the substrate results in a calculated loss of 6.2 dB per coupler. Measured results showed a coupling efficiency of 10 dB for each coupler, which was likely due to reflections from the facets of the fibers. Higher coupling efficiencies may be pursued by optimizing the thicknesses of the silicon dioxide cladding and the LN layer.
Figure 3-3: (a) Measured transmission spectrum (blue) around one under-coupled microring resonance, and the corresponding theoretical fit (red) (b) Measured transmission spectrum (blue) around one critically coupled MRM resonance and the corresponding theoretical fit (red); (c) Measured transmission power spectrum of the critically-coupled MRM devices; (d). Optical modulation (green) following the electrical drive signal (blue) at sub-kHz frequencies. The drive signal clipping observed is a measurement artefact from the limitation of the measurement range of the oscilloscope used, and doesn’t affect the extraction of any parameters from the measured data.
3.3 Fabrication

According to the design and dimensions described above, $Y$-cut LN thin films were transferred onto thermal SiO$_2$ cladding layers on silicon substrates using ion implantation and room temperature bonding, as described in detail elsewhere [20,29]. ZEP 520-A was spin-coated on the die, and patterned by electron-beam lithography by a Leica EBPG5000+ writer, followed by the evaporation of 100 nm of gold and lift-off to form the metal electrode base. Next, the die was covered with the index-matched Ge$_{23}$Sb$_7$S$_{70}$ ChG layer deposited by electron-beam evaporation, which was patterned using electron-beam lithography, and dry-etched using inductively-coupled plasma reactive-ion etching (ICP-RIE) to form the rib-loaded region and achieve single-mode waveguides, microrings, and grating couplers. The refractive index of the ChG film was measured to be 2.22 at 1550 nm using prism coupling. It is noted that the RIE process was based on our recently developed dry etching recipes, which have resulted in a record-low propagation loss of 0.42 dB/cm in submicron ChG waveguides on Si [23]. After a 2 μm thick benzocyclobutene (BCB) top-cladding was spun and cured, the gold vias and pads, each about 2 μm thick, were patterned by subsequent photolithography and dry etching, and grown using electroplating.

3.4 Characterization

The MRMs were characterized by coupling light into the grating couplers from a semiconductor laser, tunable from 1530 to 1565 nm. Grating couplers were preferred over end-butt coupling in this case due to the smaller footprint they offer the compact devices. The
Microring resonators demonstrate a propagation loss of 1.2 dB/cm and a loaded quality factor $Q$ of $1.2 \times 10^5$ at 1560 nm wavelength, as extracted from numerical fitting to the measured transmitted power spectrum, shown in Fig. 3-3(a). These devices have a 200 μm radius, and are under-coupled to minimize the coupling loss. The corresponding unloaded $Q$ is $1.3 \times 10^5$. The propagation loss of 1.2 dB/cm in the LN waveguides rib-loaded with ChG is significantly lower than the Ta$_2$O$_5$ counterparts with a loss of 5 dB/cm [20]. The critically-coupled MRMs have a lower loaded $Q$ of $8.6 \times 10^4$, an unloaded $Q$ of $1.26 \times 10^5$, at a 200 μm radius, and a maximum potential extinction ratio of over 15 dB, seen in Fig. 3-3(b) and Fig. 3-3(c). The low frequency DC coupled response is plotted in Fig. 3-3(d). The measured modulation is 0.4 GHz/V (3.2 pm/V, which is close to the designed value of 3.8 pm/V), at an extinction ratio of 13 dB. The triangular drive signal used was amplified by a voltage amplifier to capture the response of the modulator across an entire resonance notch.

Figure 3-4: (a) Sub-kHz response of a MZM with a 5.5 μm electrode gap – the blue triangular waveform is the drive signal divided by 10, the green curve is the observed modulation. The MZMs are strongly overdriven to accurately extract the $V_\pi$. (b) Sub-MHz modulation of a different MZM with a 7 μm electrode gap. Both electrodes are 6 mm long.
The MZMs were characterized by coupling light, from the tunable laser source, in and out of the MZM chips by end-butt coupling using lensed fibers, i.e., there are no grating couplers incorporated for the MZMs with large footprints. The modulated output signal was fed directly into a DC coupled photodetector. The MZMs present an on-chip optical insertion loss of 1 dB in both the on and off states, which is lower than all-Si modulators discussed in Section 3.1. A $V_{\pi}L$ of 3.8 V.cm and a 15 dB extinction ratio at 1550 nm were measured at low modulation frequencies, as shown in Fig. 3-4(a), for MZMs with an electrode gap of 5.5 μm. The AC coupled response around a 1 MHz modulation frequency of another fabricated MZM with a wider electrode gap of 7 μm is given in Fig. 3-4(b), where the $V_{\pi}L$ is measured to be 6.4 V.cm. Ground-signal-ground probes connected to a Short-Open-Load-Thru (SOLT) calibrated Agilent vector network analyzer (VNA) were used to measure the $S$ parameters of the electrodes, shown in Fig. 3-5. The travelling wave coplanar waveguide electrodes were found to have a sufficiently low reflection ($S_{11}$), and the 3-dB bandwidth of the electrodes is 5.6 GHz, determined from the electrical transmission, $S_{21}$. A characteristic impedance around 42 Ω and a microwave propagation effective index of 2.3 were extracted from further analysis of the $S$ parameters. The electrical bandwidth was limited by the impedance mismatch between the 42 Ω MZM electrodes and the 50 Ω probes and VNA ports, and by the electrode loss due to the quality of the electroplating. The microwave propagation index was sufficiently close to the optical propagation index of 2.1 for the device to not be limited exclusively by group velocity mismatch [24]. The high frequency electrooptic modulation was measured using the VNA in conjunction with a high-speed photodetector, with a cut-off frequency of 7 GHz. The input electrical port of
the MZM was connected to the VNA, and the coplanar waveguide electrodes were terminated using a standard 50 Ω impedance. The high-speed photodetector was connected to the other port of the VNA.

![Graph showing electrical S-parameters S11 (blue) and S21 (black), and electrooptic modulation parameter EO S21 (red), viz., limited by the 7 GHz photodetector cut-off.]

Figure 3-5: Electrical S-parameters $S_{11}$ (blue) and $S_{21}$ (black), and electrooptic modulation parameter $EO \ S_{21}$ (red), viz., limited by the 7 GHz photodetector cut-off.

The electrooptic response, $EO \ S_{21}$, in Fig. 3-5 is limited to ~ 7 GHz, which is the bandwidth limit of the detector. The $EO \ S_{21}$ response is reasonably flat between 2 to 7 GHz. However, the 3-dB bandwidth is found to be 1 GHz from the electrooptic $S_{21}$. The observed initial 3-dB frequency drop at ~ 1 GHz, followed by the non-monotonic response from 2 to 7
GHz, could possibly be explained by acousto-optical interactions, and acoustic resonances confined by the coplanar waveguide electrodes [17,30,31]. This behavior has been observed in other thin film LN modulators as well [17], and can be alleviated by a slight roughening of the LN surface [32].

3.5 Summary

Compact electrooptic microring resonator modulators and Mach-Zehnder modulators were fabricated and characterized on lithium niobate thin films rib-loaded with chalcogenide glasses at 1550-nm wavelength range. With a propagation loss of 1.2 dB/cm, and extinction ratios of 13 dB, the microring modulators operate at 0.4 GHz/V. The Mach Zehnder modulators operate with 15 dB extinction ratios, and a $V_{π}.L$ of 3.8 V.cm. These Mach Zehnder modulators offer much smaller device footprint and lower $V_{π}.L$ than conventional lithium niobate optical modulators and extinction ratios comparable to them. As this platform matures, it is expected that these improvements will enable the dense on-chip integration of electrooptic modulators for higher order advanced modulation schemes, leading towards heterogeneous integration into optical interconnects on silicon.

3.6 References


CHAPTER 4: HIGH-PERFORMANCE AND LINEAR THIN-FILM LITHIUM NIOBATE MACH-ZEHNDER MODULATORS ON SILICON UP TO 50 GHZ


Abstract—Compact electrooptical modulators are demonstrated on thin-films of lithium niobate on silicon operating up to 50 GHz. The half-wave voltage length product of the high-performance devices is 3.1 V.cm at DC, and less than 6.5 V.cm up to 50 GHz. The 3-dB electrical bandwidth is 33 GHz, with an 18 dB extinction ratio. The third-order intermodulation distortion spurious free dynamic range is 97.3 dBHz$^{2/3}$ at 1 GHz and 92.6 dBHz$^{2/3}$ at 10 GHz. The performance demonstrated by the thin film modulators is on par with conventional lithium niobate modulators, but with lower drive voltages, smaller device footprints, and potential compatibility for integration with large-scale silicon photonics.

4.1 Introduction

The last decade has seen a pronounced increase of interest in optical interconnects [1,2] and integrated RF photonics [3,4]. Optical modulation, digital and analog, respectively, is a key function for progress in both of these fields. Optical modulators on silicon (Si) substrates are desirable to leverage compatibility with Si electronics and large-scale integration capabilities of
the silicon photonics technology [5]. With this aim in mind, one type of modulator that has been widely pursued is the all-silicon integrated modulator [6,7], on the silicon-on-insulator (SOI) platform, based on the free-carrier plasma dispersion effect [8]. High data transmission rates up to 50 Gb/s have been demonstrated but with low extinctions ratios below 7.1 dB [9-12]. On the other hand, conventional lithium niobate (LN) modulators, traditionally used in RF photonic systems, have demonstrated high performance analog modulation [13,14]. However, these modulators are bulky and not compatible with silicon substrates, and thus not suitable for economical large-scale on chip integration. The limitations of all-silicon and LN modulators have driven the integration of a handful of different material systems on silicon for optical modulation. Some of these include silicon-organic hybrid [15], and heterogeneously integrated electroabsorption and electrooptic modulators on silicon [16,17].

Most recently, there has been a spurt of interest in the heterogeneous integration of thin film LN on silicon substrates [18-24]. Our approach has been to rib-load thin films of LN on oxidized silicon with a refractive-index-matched dielectric to form submicron optical modulators [18-20]. In these works, the related processes developed for low-loss index-matched tantalum pentoxide [25,26], chalcogenide glass [27], as well as silicon nitride, have been used, respectively, for rib loading the devices, but with limited modulation bandwidths, and no characterization of intermodulation linearity. An alternative approach has been to bond thin slabs of LN onto prefabricated Si waveguides [21-24].
The work presented in this chapter establishes the performance of submicron LN-on-Si Mach-Zehnder (MZ) modulators as on-par with conventional lithium niobate counterparts that are commercially available. The half-wave voltage length product, $V_{\pi}L$, and device footprint demonstrated in this work are significantly lower than that of conventional LN modulators, with comparable extinction ratios, electrical bandwidth and intermodulation spurious free dynamic range.

4.2 Fabrication

MZ modulators in push-pull configuration with 8-mm arm lengths were fabricated. Conventional LN MZ modulators typically have 3-cm and longer electrode arms. Similar to our pioneering work on the fabrication issues [18], ion implantation and room temperature bonding are used to transfer 400-nm thick films of Y-cut LN on to a 2-μm thick layer of thermally-grown...
silicon dioxide on a Si substrate. This in-house process forms the slab region of the ridge optical waveguide. Rib-loading with an index-matched material avoids the challenges of etching LN. As mentioned, we have previously used tantalum pentoxide [18] and chalcogenide [19] ribs.

Here, we employ silicon nitride due to the ease of processing. Accordingly, a 0.5-μm thick layer of silicon nitride (SiN) is deposited using plasma-enhanced chemical vapor deposition (PECVD). The SiN is deposited at 750 mTorr pressure and 300 °C temperature, using a mixture of 2% silane and nitrogen, flowing at 2000 and 10 sccm, respectively. The low-frequency plasma is driven at 60 W. The refractive index of the thin film of SiN is 1.93 at 1550 nm, measured using a prism-coupler commercial setup. 1.3-μm-wide strips of SiN are patterned using electron beam lithography (EBL) to form single-mode optical waveguides at 1550 nm by rib-loading the LN thin film. Then, a 2 μm thick layer of benzocyclobutene (BCB) is spun and cured as the top optical cladding. Vias, 5 to 10 μm wide, are etched through the BCB layer and electroplated with gold. Metal pads, 8 to 14 μm wide and 2 μm tall, are formed above the vias by gold electroplating to complete the fabrication of the traveling-wave metallic electrodes.

4.3 Design

A simulation of the optical transverse-electric (TE) mode performed in COMSOL™ is shown in Fig. 4-1(a). Around 70% of the optical mode is confined in the LN slab region. Compared to reported values of a typical conventional titanium-diffused LN waveguide [28], the optical mode area is reduced by ~ 24 times, i.e., from about 2 μm by 6 μm (half-intensity widths) [28] in conventional diffused LN waveguides to 0.5 μm by 1 μm in this work.
An important benefit of this increased confinement is a significant reduction in the critical bending radius (< 200 µm in our approach [19]) compared to the diffused waveguides (> 5 mm [29]). Thus, there is negligible optical loss induced in the gentle bends used to form the Y-junctions of the MZ modulators. Additionally, the EBL patterning of the waveguides ensures that the tips of the Y-junctions are defined very sharply, thereby avoiding any loss at the junctions. The submicron waveguides on LN afford a lower $V_{π,L}$ due to the increased optical confinement and good optical-RF field overlap, leading to lower drive voltages and smaller device lengths compared to conventional LN modulators.

The highest electrooptic (EO) coefficient of LN, $r_{33} = 31$ pm/V, is utilized by aligning the z-axis of the LN crystal along the horizontal radio frequency (RF) electric field created by push-pull coplanar waveguide (CPW) travelling wave electrodes. The high-speed performance of travelling wave electrode modulators depends on matching the characteristic impedance of the CPW electrode at radio frequencies to that of the source and load (50 Ω), while minimizing both the velocity mismatch between the optical and RF waves, and the loss of the RF wave [30-32]. Thus, the CPW electrodes are designed to maintain a characteristic impedance as close as possible to 50 Ω. The simulations for the electric field characteristics of the CPW electrodes are carried out in COMSOL™ at radio frequencies ranging from 1 GHz to 10 GHz. The characteristic complex impedance, $Z$, of a CPW electrode at a particular radio frequency, $ω$, follows that of a conventional CPW transmission line. Thus, $Z$ is comprised of resistive (R), inductive (L), conductive (G), and capacitive (C) elements, all per unit length, often referred to as the RLGC model for a transmission line [33]. Each of these components can be further split
up and calculated based on different physical regions of the modulator structure. This is particularly important for the more involved capacitances often encountered in silicon optical modulators [34], but relatively unimportant for this work. The frequency-dependent RLGC transmission line parameters are conveniently derived from the RF electromagnetic field simulations run in COMSOL™ [33].

The RF-dependent velocity mismatch between the RF and optical waves, and the RF propagation loss can both be minimized by an appropriate design of the CPW electrodes that balances the three-way tradeoff between velocity mismatch, RF loss, and characteristic impedance for high-speed performance. The RF wave index and propagation loss can be directly extracted from the RF electric field simulations. An additional constraint on the design is that the electrode gap across each waveguide arm of the modulator must be wide enough to not introduce metal induced optical loss, which would increase the on-chip insertion loss and degrade device performance.

An instance of the RF electric field at 10 GHz, simulated in COMSOLTM, is shown in Fig. 4-1(b). Similar to conventional LN modulators, the electric field is somewhat sharper at the edge of the electrodes than in the middle of the 5.5-μm-wide electrode gap. However, this does not detract from the increase in optical confinement and the decrease of the electrode gap, and the subsequent drive voltage reduction, as supported by the $V_{\pi}$L values presented in this work. The reduction in drive voltage could be further enhanced if more of the optical mode is buried in LN than the aforementioned value of 70%. However, this would entail etching the LN, which thus far has not proven to be a viable approach for low loss submicron waveguides.
Alternatively, the rib-loading, as in the structure presented in this work, could be altered to push the optical mode further down into the LN. This would simultaneously result in a decrease in the lateral optical confinement, thus increasing the electrode gap required to avoid metal induced optical loss in the waveguide, and thereby defeating the purpose of further lowering the drive power. This tradeoff between lateral optical confinement and the confinement of the mode in the LN ties in with the tradeoffs involved in designing the CPW electrodes through the electrode gap. The particular electrode shape and structure chosen in this work is not a unique solution to balancing these tradeoffs, and more optimized structures can potentially yield improved performance.

4.4 Characterization

Light from a tunable continuous-wave (CW) semiconductor laser was fed through a polarization controller and coupled into and out of the LN-on-Si MZ modulators using end-butt fiber coupling. For low-frequency characterization, a DC coupled photodetector was used to capture the optical response of the modulator. $V_{\pi}L$ of 3.1 V.cm and extinction ratio of 18 dB were measured at 1550 nm, as presented in Fig. 4-2.
To obtain the high-frequency response of the modulator, the electro-optic S parameter (EO $S_{21}$) of the MZ modulator was measured from 10 MHz to 50 GHz. A ground-signal-ground (GSG) probe was used to launch the RF signal onto the carefully designed and fabricated coplanar travelling wave electrodes, which were terminated using a standard 50 $\Omega$ impedance. One port of a 50-GHz vector network analyzer (VNA) was used as the electrical signal source. A bias tee was used to set the modulator at quadrature. The modulated optical output was fed through an erbium-doped fiber amplifier to a 70-GHz-bandwidth high-speed photodiode, which was connected to the second port of the VNA. The VNA was calibrated using Short-Open-Load-Thru (SOLT) standards. The electrical return loss ($S_{11}$) is below 10 dB up to 50 GHz and the
electrical transmission ($S_{21}$) is smooth up to 50 GHz. The electrical EO bandwidth of the MZ modulator is 33 GHz, as shown in Fig. 4-3. The $EO \ S_{21}$ has a slight peak near 5 GHz, similar to behavior observed in some conventional LN modulators [35], and remains reasonably flat up to 50 GHz with an electrical roll-off of ~ 6 dB, indicating the potential for operation beyond 50 GHz. As plotted in Fig. 4-4, the RF $V_{\pi L}$ was extracted from the measured low frequency $V_{\pi L}$ and $EO \ S_{21}$ [36], and evidently it is below 6.5 V.cm up to 50 GHz.

![Figure 4-3: Measured $S$ parameters of the MZ modulators, namely, electrical transmission and reflection ($S_{21}$ and $S_{11}$) and electrooptic transmission ($EO \ S_{21}$). The (eoe) signifies that the electrooptic response $EO \ S_{21}$ is electrical. Evidently, the 3-dB electrical EO bandwidth of the devices is 33 GHz.](image-url)
The third order intermodulation distortion (IMD3) spurious free dynamic range (SFDR) was measured to quantify the linearity of the LN-on-Si MZ modulators biased at quadrature from 1 GHz to 10 GHz. Two RF tones, separated by 10 MHz, were combined and launched using a GSG probe onto the MZ modulator electrodes. The modulated optical output was fed to a 20-GHz-bandwidth photodiode, which was connected to a 26 GHz RF spectrum analyzer (RFSA). The results are summarized in Fig. 4-5. The noise floor of the RFSA varies from -149 dBm/Hz at 1 GHz to -145 dBm/Hz at 10 GHz. The measured IMD3 SFDR is 97.3 dBHz$^{2/3}$ at 1 GHz,
96.6 dBHz$^{2/3}$ at 5 GHz, 93.6 dBHz$^{2/3}$ at 8 GHz, and 92.6 dBHz$^{2/3}$ at 10 GHz. The decrease in the SFDR at higher frequencies is partly due to the degradation of the RFSA noise floor. The SFDR was measured with less than 1 mW of optical power in the modulator. Previously, SFDR values above 110 dBHz$^{2/3}$ have been reported in prior work on conventional LN modulators [37-39]. These have typically relied on higher optical powers and lower RFSA noise floors, around -160 dBm/Hz or lower, leading to higher SFDR. In contrast, the overall SFDR in this work was limited by the noise floor specification of the RFSA used, which was above -150 dBm/Hz. Increasing the optical power in the modulator, and using a different RFSA with a lower noise floor would potentially lead to higher SFDR.
Figure 4-5: Third order intermodulation distortion spurious free dynamic range: (a) 97.3 dBHz$^{2/3}$ at 1 GHz; (b) 96.6 dBHz$^{2/3}$ at 5 GHz; (c) 93.6 dBHz$^{2/3}$ at 8 GHz, and (d) 92.6 dBHz$^{2/3}$ at 10 GHz.

4.5 Summary

In summary, high-performance LN-on-Si compact modulators have been demonstrated for optical interconnect and RF-photonic applications. The results demonstrate the coming-of-age of thin film lithium niobate modulators, demonstrating performance on par with commercial lithium niobate modulators, but with lower drive voltages, smaller device footprints, and
potential compatibility with silicon photonics. The operating range of 50 GHz and the reported spurious free dynamic range values are both limited by the equipment available for characterization and can be further improved.

4.6 References


CHAPTER 5: SECOND-HARMONIC GENERATION IN INTEGRATED PHOTONICS ON SILICON


Abstract— This chapter presents the recent progress on integrated second-order nonlinear waveguides on silicon substrates for second-harmonic generation. In particular, demonstrations of thin-film lithium niobate, III–V compound semiconductor and dielectric waveguides integrated on silicon substrates are reviewed. For completeness, the fundamentals of the nonlinear optical processes involved are briefly introduced. Methods demonstrated for phase matching, eg, periodic poling and mode-shape modulation, in the compact integrated devices are discussed. Finally, an outlook for how integrated photonics may benefit from the progress in this field is provided.

5.1 Introduction

Optical three-wave mixing [1,2] has been pursued for the generation of coherent light from the ultraviolet to the infrared since 1961 [3-22]. The phenomenon of three-wave mixing occurs in transparent non-centrosymmetric materials that exhibit a sufficiently strong nonlinear response to intense coherent radiation. Waves of often broadly separated frequencies, commonly referred to as the pump, signal, and idler, with angular frequencies $\omega_p$, $\omega_s$, and $\omega_i$, are coupled to each other, leading to frequency conversion. Second-harmonic generation (SHG), sum- and
difference-frequency generation (SFG and DFG), spontaneous parametric down conversion (SPDC), optical parametric oscillation (OPO), and optical parametric amplification (OPA) are some typical three-wave mixing processes. These were originally demonstrated based on bulk crystals in bench top configurations [3-16], and subsequently in integrated waveguides [17-22]. Optical phase matching is required in these processes to compensate for the dispersion of the interacting waves to ensure efficient energy transfer [23]. Thus, phase matching is one of the key factors that ought to be engineered in waveguide implementations of three-wave mixing. A significant advantage of using waveguides is the increase in the nonlinear overlap between the interacting waves, leading to an increase in the nonlinear efficiency [24]. In particular, SHG, where two pump photons of frequency $\omega$ are converted to a single signal photon at frequency $2\omega$, has received significant attention, due its many applications, e.g., frequency stabilization and imaging microscopy. This review paper will largely use SHG to elucidate the progress made in second-order nonlinear integrated photonics on silicon.

### 5.2 Nonlinear coupled-mode equations

Before delving into the existing integrated photonic solutions for second-order nonlinear optics on silicon, we present a theoretical formulation of SHG, which is a special case of three-wave mixing with $\omega_p = \omega_s = \omega_i/2$. Clearly, the following formulation can be readily extended to other three-wave mixing processes. Dropping the subscript notations for the involved angular frequencies, the nonlinear polarization response at the idler frequency $2\omega$, $P_{2\omega}$, is given by [1,23]

$$P_{2\omega} = 2dE_\omega E_\omega,$$  

(5-1)
where $E_{\omega}$ is the pump electric field at frequency $\omega$, and $d$ is the nonlinear tensor, equal to half the second-order nonlinear susceptibility tensor, $\chi^{(2)}$. We utilize the local normal-mode expansion (LNME) [25], which is based on using the local eigenmodes of a spatially varying waveguide.

The normalized field amplitudes of the second harmonic (SH) signal $a_{2\omega}(z)$, and the pump $a_{\omega}(z)$, at frequencies $2\omega$ and $\omega$, respectively, satisfy the following coupled-mode equations in a periodic waveguide [25]

\[
\frac{d}{dz}a_{2\omega}(z) = -i(a_{\omega}(z))^2 e^{i\Delta \beta z} f(z) - \frac{\alpha_{2\omega}}{2} a_{2\omega}(z) \tag{5-2a}
\]

\[
\frac{d}{dz}a_{\omega}(z) = -ia_{\omega}(z)a_{2\omega}^*(z)e^{-i\Delta \beta z} f^*(z) - \frac{\alpha_{\omega}}{2} a_{\omega}(z) \tag{5-2b}
\]

where $\alpha_{2\omega}$ and $\alpha_{\omega}$ are the waveguide propagation losses at frequencies $2\omega$ and $\omega$, respectively, and $\Delta \beta_0$ is the phase mismatch between the signal and the pump waves, averaged over one period of propagation length. $f(z)$ is a locally varying nonlinear coupling of the propagation equations that captures all the effects of the modulation of the waveguide, and has the form [25]

\[
f(z) = \sqrt{2\mu_0 \epsilon_0} \left( \frac{\mu_0}{\epsilon_0} \right)^{1/2} \exp \left[ -i \frac{1}{\epsilon_0} \frac{[2\beta_{\omega}(z) - \beta_{2\omega}(z)] + \Delta \beta_0}{\Delta \beta_0} d \zeta \right] \Gamma(z), \tag{5-3a}
\]

\[
\Gamma(z) = \frac{\int \int \int E^{2\omega}(x,y,z) [E^{\omega}(x,y,z)]^* dx dy}{\left( \int \int \int \left| E^{2\omega}(x,y,z) \right|^2 dx dy \right)^{1/2}}, \tag{5-3b}
\]

where $\beta_{2\omega}(z)$ and $\beta_{\omega}(z)$ are the local propagation constants, $n_{\text{eff}}^{2\omega}(z)$ and $n_{\text{eff}}^{\omega}(z)$ are the local effective indices, and $E^{2\omega}(x,y,z)$ and $E^{\omega}(x,y,z)$ are the local transverse mode field profiles of
the signal and pump waves, respectively. As mentioned, $d(x,y,z)$ is the second-order nonlinear $d$ tensor that mediates the nonlinear process.

![Figure 5-1](image)

Figure 5-1: The coupled-mode equations presented in Eqs. (2a) and (2b) are simulated for $\eta_0$ of 50 %/(W.cm²) (solid traces) and 1000 %/(W.cm²) (dashed traces). The critical impact of $\eta_0$ for low CW input power applications (10 mW in this example) is visible in the pump depletion achieved in the higher $\eta_0$ trace.

The origin of $\Delta\beta_0$ lies in the dispersion of the effective index of the waveguide, which has contributions from the material dispersions of the core and cladding materials, and the dispersion
due to the optical confinement offered by the waveguide [26,27]. This leads to different phase
velocities for the pump and SH waves. Efficient SHG requires a mitigation of $\Delta \beta_0$ by inducing an
appropriate $z$ dependent variation in $f(z)$. Phase matching, i.e., the compensation of the different
phase velocities, is crucial for achieving high-efficiency nonlinear frequency conversion. The
term quasi-phase matching (QPM) is used when this compensation is periodic. The accepted
measure of the efficacy of the phase matching is the normalized conversion efficiency, which is a
figure of merit of the waveguide itself, independent of the input power and the mode of
operation, pulsed or continuous wave (CW). It is calculated, in units of $1/(\text{W.cm}^2)$, as

$$\eta_0 = \left( \frac{1}{\Lambda} \int_0^\Lambda f(z) \exp\left[i z \left(-2\pi q / \Lambda + \Delta \beta_0\right)\right] dz \right)^2$$  \hspace{1cm} (5-4)

where $\Lambda$ is the period along the propagation length, and $q$ is an integer chosen to
minimize $\Delta \beta_0 - (2\pi q / \Lambda)$. This amounts to calculating the Fourier series expansion of $f(z)$ and
choosing the coefficient that best cancels out $\Delta \beta_0$ in the phase. As an illustration, the evolution of
the pump and the SH signals is simulated in Fig. 5-1. Two different values of $\eta_0$, 50 $\%/(\text{W.cm}^2)$
(solid traces) and 1000 $\%/(\text{W.cm}^2)$ (dashed traces), are used as examples. These roughly
correspond to a traditional (section 5.3) and a novel integrated (section 5.4.1) nonlinear
waveguide for SHG. The input CW pump power is 10 mW for both cases, which is
representative of a typical integrated photonic laser source. A strong increase in frequency
conversion with an increase $\eta_0$ is clearly seen.
Several materials have been used for three-wave mixing in bulk crystals using free-space Gaussian beams. Table 5-1 lists some key materials, along with their largest nonlinear coefficient, normalized to the $d_{33}$ coefficient of lithium niobate (LN), viz., 30 pm/V. Lithium niobate is chosen as the benchmark, since it is perhaps the most heavily used material in this field. Included in Table 5-1 are some III-V compound semiconductors. Nonlinear waveguides have been able to utilize only a few of these materials, due to limitations in material processing and phase matching.

<table>
<thead>
<tr>
<th>Material</th>
<th>$d_{ij}/d_{33,\text{LN}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiNbO$_3$</td>
<td>1</td>
</tr>
<tr>
<td>KH$_2$PO$_4$</td>
<td>0.014</td>
</tr>
<tr>
<td>KD$_2$PO$_4$</td>
<td>0.014</td>
</tr>
<tr>
<td>β-BaB$_2$O$_4$</td>
<td>0.073</td>
</tr>
<tr>
<td>LiTaO$_3$</td>
<td>0.867</td>
</tr>
<tr>
<td>AlN</td>
<td>0.033</td>
</tr>
<tr>
<td>GaN</td>
<td>0.260</td>
</tr>
<tr>
<td>GaAs</td>
<td>12.3</td>
</tr>
</tbody>
</table>
The approaches used for phase matching in integrated photonic waveguides can be largely classified into two categories. The first well-established category is QPM, and is outlined in sections 5.3 and 5.4. The second category relies on minimizing $\Delta \beta_0$ (to zero) through modal dispersion, i.e., engineering the dispersion of the waveguide by choosing suitable materials for the core and cladding and an appropriate waveguide geometry. Some examples that utilize this approach are outlined in section 5.5. The following sections review some particular waveguide implementations of $\chi^{(2)}$ optics, with an aim of emphasizing the prominent pursued approaches, rather than forming an exhaustive chronological list.

### 5.3 Periodically poled lithium niobate (PPLN)

The most popular approach to phase matching has been QPM. Periodically-poled lithium niobate (PPLN) waveguides, based on QPM, represent the most successful implementation of $\chi^{(2)}$ waveguides [17-22]. LN offers high nonlinear coefficients and a broad transmission window [1]. QPM is realized through the periodic reversal of the crystal domain of LN, which is also a ferroelectric material. Called periodic poling, the process induces a reversal in the sign of certain coefficients of the $d$ tensor, which are then chosen to mediate the nonlinear frequency mixing. PPLN has led to numerous successful demonstrations of three-wave mixing. High-power conversion in SHG has been demonstrated as well (Fig. 5-2) [28,29]. Periodic poling has also been demonstrated in other ferroelectrics and polymers [17,18].

However, conventional PPLN waveguides are not readily compatible with modern integrated photonics. These waveguides are formed in LN single crystal wafers by the diffusion
of metals, such as titanium [30], or protons [31]. They offer low refractive index contrast, with weak optical confinement, large waveguide cross-sections (~10\(\mu\text{m}^2\)), and large bending radii. In contrast, modern integrated photonics is largely based around oxidized silicon substrates, with tightly confined dry etched waveguides of submicron cross-section. While dry plasma etching and wet etching have been pursued as alternative approaches to defining large LN waveguides [32,33], these methods have not yet been successfully demonstrated for small compact waveguides. The incompatibility of conventional PPLN waveguides with silicon substrates has driven the pursuit of thin film PPLN waveguides on silicon, as follows.

Figure 5-2: (a) Cross-section of a PPLN wafer after etching in hydrofluoric acid to enhance visibility of the poled regions. The vertical stripes correspond to alternating poled domain orientations [28]. (b) SHG from 1064 nm to 532 nm (green) using a PPLN waveguide, with 42% single-pass internal power conversion. Figures reproduced from [28]. © The Optical Society.
5.4 Thin-film lithium niobate on silicon

The ideal solution to realizing efficient $\chi^{(2)}$ nonlinearities on silicon lies in forming hybrid compact LN waveguides on silicon. Such an approach aims at combining the benefits of conventional PPLN, i.e., the material properties of LN, with the benefits of modern integrated photonics, i.e., compact waveguides on robust and inexpensive silicon substrates. This has been realized by our group using thin-film LN on silicon [34]. Bulk single crystal LN wafers are bonded at room temperature onto oxidized silicon substrates after ion implantation, and are
thermally sliced to form thin films of LN, as illustrated in Fig. 5-3. Tightly-confined waveguides are formed by rib-loading these thin films with refractive-index-matched materials. Rib loading entirely circumvents the requirement of etching the LN to induce lateral confinement, since LN is a very hard material to dry etch, especially for low-loss submicron cross-section waveguides. Previously, we have developed materials such as tantalum pentoxide, and chalcogenide glass ribs in order to achieve low-loss waveguides [35-37], and used the hybrid waveguides to demonstrate optical modulators [34,38,39]. More recently, we have used silicon nitride (SiN), which is well-established for waveguiding applications, due to its broad transmission window and ease of processing, to demonstrate optical modulators [40], PPLN [41] (section 5.4.1), and mode-shape modulation, a specific variant of grating-assisted QPM, in thin film LN on silicon [42], as described in more detail in section 5.4.2.

5.4.1 Thin-film PPLN on silicon

Compact PPLN waveguides are formed on silicon using the thin film bonding and SiN bonding described above [41]. The Y-cut LN slab is 400 nm thick, bonded onto a 2000-nm-thick SiO$_2$ lower cladding layer on a silicon substrate, rib loaded by a SiN rib that is 2000 nm wide and 400 nm tall (Fig. 5-4(a)).
The poling period is determined to be ~ 5 µm through eigenmode simulations for TE polarized SHG, with a TE pump at 1580 nm (Figs. 5-4(b) & (c)). Including propagation loss, the normalized conversion efficiency is estimated to be 1400 %W^{-1}cm^{-2}, with a mode overlap integral of 2.3 µm^2. The increase in optical confinement yields an increase in nonlinear power conversion, as indicated in Fig. 5-5. The submicron PPLN waveguides offer a consistent increase in frequency conversion (around an order of magnitude) relative to conventional PPLN for low input powers. Depending on the power level, conventional PPLN would require propagation lengths greater than four times that of thin film PPLN for a given power conversion. Additionally, at high input powers thin film PPLN offers high efficiency power conversion in less than 1 cm of length, even at higher propagation losses. The fabricated waveguides are pumped using a pulsed source and the SHG signal is measured on an optical spectrum analyser as shown in Figs. 5-6(a)-(c), phase matching around a fundamental wavelength of 1580 nm. The quadratic nature of the nonlinear SHG process is confirmed (see Fig. 5-6(d)).
Figure 5-5: Numerical simulations for CW SHG power using PPLN waveguides – (a)&(b), For low input powers (100 µW), thin film PPLN consistently presents stronger SHG than conventional PPLN. (c)&(d), Thin film PPLN offers ~ 50% power conversion at higher CW input powers (1 W) in less than 1 cm of propagation, regardless of propagation loss, while conventional PPLN solutions require longer lengths. Figures reproduced from [41]. © The Optical Society.

Figure 5-6: (a) Measured frequency-doubled signal from thin film PPLN around 788 nm. (b) Output spectra, displaced by 60 dB, for increasing input pump powers (bottom to top). (c) SHG traces with input average powers of 1.67, 0.87 and 0.31 mW. (d) Quadratic dependence of the 788 nm signal power on the input pump power with a slope of 1.91 on a log scale. Figures reproduced from [41]. © The Optical Society.
5.4.2 Mode-shape modulation in thin film LN on silicon

As an alternative to the intensive fabrication requirements of obtaining high-fidelity periodic poling, we have recently also demonstrated mode-shape modulation, a variant of grating-assisted QPM in thin-film LN waveguides [42], shown in Figs. 5-7(a)&(b). The waveguide is comprised of a 600-nm-thick LN slab, which is rib-loaded by a grating waveguide of SiN. The periodicity of the grating is fixed by the extent of the lateral sinusoidal variation of the grating, as determined through simulations using an eigenmode solver. The pump and harmonic eigenmodes are shown in Fig. 5-7(c) at a grating width of 1095 nm. The periodic spatial variation of the eigenmodes induced by the lateral grating induces a periodic spatial variation in $f(z)$. In particular, the nonlinear growth of the SH field is driven by the first-order term in the Fourier series expansion of $f(z)$, which cancels out the $\exp(i\Delta\beta_0 z)$ phase terms in Eqs. (2a) and (2b), while the constant term in the series expansion results in fast oscillations of the SH field, shown in Fig. 5-7(d). The normalized SHG conversion efficiency is extracted to be $0.8\text{W}^{-1}\text{cm}^{2}$. The deleterious impact of increasing waveguide propagation loss is also illustrated in Fig. 5-7(d). Measurements on the fabricated waveguide are shown in Figs. 5-7(e)&(f).
Figure 5-7: (a) Sinusoidal SiN grating (exaggerated in magnitude for visibility) on top of a LN thin film. (b) Micrograph image of a fabricated waveguide. (c) intensity profiles of the fundamental and second-harmonic TE modes of the waveguide at a grating width of 1095 nm; (d) Numerical simulation of SHG conversion efficiency for different propagation losses. The inset shows oscillations of the amplitude which aren’t visible in the main figure. (e) Output spectrum of the waveguide; and (f) SHG around 784 nm. Figures reproduced from [42].

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While the normalized conversion efficiency of conventional PPLN is somewhat higher (~40%W⁻¹cm⁻²), this approach circumvents the challenges of achieving high-fidelity periodic poling in thin film LN, and is broadly applicable to materials which cannot be poled. The
physical dimensions of the waveguide grating strongly influence the SHG process. The thickness of the LN thin film influences the grating induced waveguide propagation loss through the amount of scattering encountered by the waveguide modes. The Fourier series coefficients of $f(z)$ also depend on this. Additionally, the extent of the grating also affects the nonlinear conversion. A stronger grating increases the nonlinear coupling. However, a stronger grating also increases the propagation loss. Therefore, a delicate balance is required between the propagation loss and $f(z)$.

5.5 Other approaches to $\chi^{(2)}$ waveguides on silicon

A few other approaches which have been explored towards realizing second order nonlinear waveguides on silicon are reviewed in this section.

5.5.1 $\chi^{(2)}$ in III–V compound semiconductors and dielectrics on silicon

As noted in Table 5-1, GaAs has a very high second-order nonlinear coefficient. However, implementing efficient phase matching in GaAs waveguides has been elusive. For instance, poling techniques are not applicable since the material is not ferroelectric. Other techniques, such as orientation patterning, grating-assisted quasi-phase matching, and modal phase matching have been pursued instead with varying degrees of success [43-46]. However, none of these techniques has been investigated on silicon substrates for second-harmonic generation to date. It is noted that recently, thin-film AlGaAs-on-insulator nanowaveguides on indium phosphide substrates have been demonstrated for third-order nonlinear optics [47]. It is
expected that such waveguides will be realized on silicon substrates in the future, and second-order nonlinear effects can be realized on them by adapting guidelines already established for typical AlGaAs nanowaveguides [48].

Nonetheless, aluminium nitride (AlN) is a III-V compound semiconductor recently pursued for SHG on silicon [49-51]. Prior to the pursuit of waveguides, the \( \chi^{(2)} \) response of sputtered AlN thin films was confirmed via optical reflection measurements for SHG [52]. However, these thin films are typically polycrystalline. Therefore, the effective \( \chi^{(2)} \), as confirmed by SHG measurements, is often limited to a few pm/V. This naturally limits the conversion efficiency. Nevertheless, when used in a doubly resonant high quality factor microring configuration, in one particular case, AlN has yielded impressive SHG conversion efficiency (Fig. 5-8(a)), as high as 2300 %/W [51].

Another III-V compound semiconductor that has been investigated for SHG on silicon is gallium nitride (GaN). [53,54] Crystalline GaN thin films have been transferred to oxidized silicon via bonding, backside removal, and chemical-mechanical polishing, and patterned to form waveguides and microrings (Fig. 5-8(b)) [53]. Aided by its crystalline nature, the GaN thin films exhibit a higher \( \chi^{(2)} \) than the polycrystalline AlN thin films. However, the quality factor of the GaN microrings is lower than the AlN counterparts, resulting in an overall lower conversion efficiency, as seen in Fig. 5-8(c) [53].
In contrast to III-V compound semiconductors, an interesting dielectric in which SHG has been demonstrated is silicon nitride (SiN) [55-57]. SiN has been very successfully used for demonstrating $\chi^{(3)}$ nonlinear optical effects, such as supercontinuum generation in straight waveguides and frequency comb generation in microring resonators [58-61]. A $\chi^{(2)}$ response can be elicited in SiN through applying strain, due to its heteropolar bonds. Silicon dioxide (SiO$_2$) claddings have been used to break the symmetry of SiN (Fig 5-8(d) and 5-8(e)) [55], and electric
field induced second harmonic generation (EFISHG) has been demonstrated, as well [56]. However, the performance of SiN waveguides for SHG has been limited by the low nonlinearity itself. It is important to note that, several recent reports suggest that the $\chi^{(2)}$ response of SiN is influenced not only by strain and interface effects, but also defects and the overall material composition [62-66].

Each of the above three platforms have relied on modal phase matching, where the phase velocities of the pump and SH modes are engineered to be equal. In essence, the dispersion due to the optical confinement of the interacting waveguide modes nullifies the dispersion of the core and cladding materials. Higher order waveguide modes are used for higher frequency modes due to the normal dispersion of the constituent materials [55,56,67-69]. However, the use of higher-order modes compromises the nonlinear mode overlap and thus the nonlinear conversion efficiency.

5.5.2 $\chi^{(2)}$ in silicon waveguides

Silicon waveguides using the silicon-on-insulator (SOI) platform are well-established as building blocks for large-scale integrated photonics [70]. The crystalline structure of silicon exhibits centrosymmetry, where the $\chi^{(2)}$ tensor is zero in the dipole approximation. While this rules out SHG in bulk single-crystalline Si, SHG has repeatedly been observed when the crystal symmetry of Si is broken at a surface [71-75]. More recently, SHG has been studied and reported in strained Si waveguides [76-79]. Initially, the $\chi^{(2)}$ response was attributed to the strained Si core of the waveguides (Fig. 5-9) [76]. However, recent investigations have concluded that the
actual $\chi^{(2)}$ response from the silicon itself is likely significantly smaller than previous estimates [80-85]. These waveguides typically have SiN cladding layers that break the crystal symmetry in the Si waveguides. It has been accordingly argued that the majority of the nonlinear response originates from the SiN cladding layer and not the Si core [83]. At this moment, it is fair to state that the physical origin of the $\chi^{(2)}$ response in silicon waveguides is still debatable, and requires further investigation. The resolution of this uncertainty is expected to help analyse the maximum achievable $\chi^{(2)}$ response, which may be extracted from silicon waveguides using this approach.

Figure 5-9: (a) Schematic of silicon waveguides on insulator with a SiN cladding layer to impart strain. (b) Micrograph image and scanning electron microscope (SEM) image of the strained Si waveguide facets. (c) Spectral variation of the SH power generated with the strained Si waveguides. Figures reproduced from [76], © Nature Publishing Group.

An alternative approach to SHG in Si uses EFISHG, where a d.c. electric field at zero frequency interacts with the strong $\chi^{(3)}$ nonlinear tensor of Si to enable SHG [85,86]. EFISHG has demonstrated high effective $\chi^{(2)}$ values in Si, at the cost of high propagation losses, which limit overall device performance. The Si EFISHG waveguides also consume electrical power, compared to all the aforementioned approaches, which are essentially passive devices and do not
consume any electric power. The d.c. electric field is applied across $p$-$i$-$n$ junctions at very high reverse bias voltages, likely close to breakdown.

In addition to the discussed complications of the aforementioned approaches on Si, the transmission and absorption limitations of silicon also become relevant. The bandgap of silicon limits light generation to around 1.1 µm at the lower wavelength edge. Additionally, strong two-photon and free-carrier absorption effects below 2.2 µm [70] limit the spectral windows at which Si could be optically pulse-pumped for frequency generation. On the other hand, the heterogeneous approaches of Sections 5.4.1, 5.4.2 and 5.5.1 benefit from the material properties and prior comprehensive characterization of the employed nonlinear material. This comes at the cost and complications of the heterogeneous integration process. At present, the overall nonlinear device performance offered by heterogeneously integrated materials trumps the performance achieved so far in silicon waveguides. However, the performance of the silicon waveguides may still potentially be improved, perhaps even to the point of competing with the performance of heterogeneously integrated solutions.

5.6 Outlook

Several schemes for second-order nonlinear optics have been established in waveguides on silicon. Each of these schemes presents trade-offs between performance and different aspects of fabrication. Realizing the full potential and benefit of these solutions would involve the integration of different optical functionalities on a common substrate, preferably silicon. This can
be achieved through the heterogeneous integration of different materials on the same silicon chip [87], where each material system is already established for a particular set of functions. This is the overarching approach commonly employed for integrating active laser sources on silicon photonic chips. Numerous other waveguide devices have been realized using this approach as well [87]. While the dense integration of multiple functions on a photonic chip has been repeatedly demonstrated, the pursuit of integrated systems which utilize $\chi^{(2)}$ is much more nascent. One can easily envision frequency referencing, photon pair generation, and tunable optical parametric oscillators as some $\chi^{(2)}$ functionalities which could be integrated with existing on-chip laser sources. Difference frequency generation could be used in conjunction with on-chip mode-locked lasers to generate mid-infrared light for spectroscopic applications.

Regardless of the details of the particular physical configuration employed, all of these are exciting developments realized in the last several years. The variety of these implementations can only assist in the pursuit of new densely integrated complex photonic systems on a chip, which would not have been possible without the introduction of the $\chi^{(2)}$ response onto silicon.

5.7 References


CHAPTER 6: SECOND-HARMONIC GENERATION IN PERIODICALLY POLED THIN-FILM LITHIUM NIOBATE WAFER-BONDED ON SILICON


Abstract— Second-order optical nonlinear effects (second-harmonic and sum-frequency generation) are demonstrated in the telecommunication band by periodic poling of thin films of lithium niobate wafer-bonded on silicon substrates and rib-loaded with silicon nitride channels to attain ridge waveguide with cross-sections of ~ 2 µm². A nonlinear conversion of 8% is obtained with a pulsed input in 4 mm long waveguides. The choice of silicon substrate makes the platform potentially compatible with silicon photonics, and therefore may pave the path towards on-chip nonlinear and quantum-optic applications.

6.1 Introduction

Quasi-phase matching (QPM) for three-wave mixing has enabled progress in fields such as telecommunications [1] and quantum optics [2,3]. Numerous three-wave optical mixers on-chip have been investigated towards high performance integration with material systems such as silicon and III-V compounds. Silicon (Si) lacks intrinsic second-order nonlinearity ($\chi^{(2)}$), essential for efficient nonlinear three-wave frequency mixing, due to its centrosymmetric
crystalline nature. Nonlinear effects demonstrated on the silicon-on-insulator (SOI) platform are thus typically based on third-order nonlinearity ($\chi^{(3)}$), which is significantly weaker than nonlinear mixing driven by the $\chi^{(2)}$ tensor. Furthermore, important three-wave mixing nonlinear effects such as second-harmonic generation (SHG) are conveniently realized using $\chi^{(2)}$ nonlinearity, and are much more difficult to implement using $\chi^{(3)}$ nonlinearity. SHG has been pursued in III-V waveguides [4,5]. However, these attempts are limited by high optical propagation losses and difficulties of poling.

It is well-known that lithium niobate (LiNbO$_3$ or LN) possesses one of the highest $\chi^{(2)}$ values and a broad transmission window [6]. Z-cut bulk periodically-poled lithium niobate (PPLN) waveguides have thus been established as the method of choice for implementing QPM for efficient three-wave mixing [7]. The in-diffusion of titanium into bulk LN wafers [8] and annealed proton exchange [9] are two methods used to define conventional LN stripe waveguides for QPM. However, these conventional diffused LN waveguides suffer from low index contrast and typically work only for transverse-magnetic (TM) waveguide modes. This leads to poor optical confinement, large mode sizes, and poor overlap between different optical modes for three-wave mixing, such as the fundamental and second-harmonic modes involved in SHG and sum-frequency generation (SFG). PPLN waveguides have been reported in the past on bulk Z-cut [10] and X-cut [11-13] LN with normalized nonlinear conversion efficiencies around 40 %W$^{-1}$cm$^{-2}$ [10-12] in telecom wavelengths. One approach to integrate LN on Si is metallic bonding using gold, where ~10 µm thick films of LN are bonded after poling on Si, with conversion efficiencies around 80 %W$^{-1}$cm$^{-2}$ [14]. Recently, there has been an interest in poling
X-cut thin film LN [15,16]. One effort based on thin film X-cut PPLN on a LN substrate has demonstrated a nonlinear conversion efficiency around 160 %W⁻¹cm⁻² [16].

Figure 6-1: (a) Schematic of the device depicting the silicon nitride (SiN) rib, the lithium niobate (LN) slab, the silicon dioxide (SiO₂) lower cladding, the silicon (Si) substrate, and the metal poling electrodes. The SiO₂ top cladding is excluded for clarity; (b) & (c) COMSOL™ simulations of the fundamental TE waveguide modes at the pump wavelength (1580 nm) and the second harmonic wavelength (790 nm).

Evidently, the most widely used QPM devices based on bulk PPLN are not directly compatible with state-of-the-art integrated photonics on silicon substrates or suffer from low efficiency due to large optical mode size. Hybrid submicron waveguides of LN integrated onto silicon substrates would be the ideal solution for introducing efficient $\chi^{(2)}$ photonics on silicon. We have previously solved the challenge of obtaining tightly confined LN waveguides by ion implantation and slicing of thin films of LN heterogeneously integrated onto an oxidized silicon substrate, and rib loading the films with index-matching materials [17,18]. Different materials, such as tantalum pentoxide and chalcogenide glass have been previously developed for low loss [19-21] and used for rib loading the house-made LN thin films for demonstrating optical
modulators [17,18]. Another index-matching alternative material with a wide transmission window used by us for modulators is silicon nitride (SiN) [22].

Figure 6-2: Numerical simulations for the generation of second harmonic (S.H.) power using PPLN waveguides across different input CW pump powers and propagation losses for varying effective mode overlap areas: (a) and (b) For an input power of 100 µW, there is about an order of magnitude improvement in nonlinear conversion for submicron waveguides, even for propagation lengths up to 4 cm, irrespective of propagation loss; (c) and (d) For an input power of 1 W, the nonlinear conversion offered by submicron PPLN waveguides is ~ 50% in less than 1 cm of propagation, even at a relatively high loss of 1 dB/cm, while conventional PPLN solutions require much longer lengths.

A schematic of the PPLN on Si device with SiN ribs presented in this work is shown in Fig. 6-1(a). Using this structure, the first integration of a locally-poled PPLN wavelength converter on a silicon substrate is demonstrated. Unlike previous PPLN on Si efforts [14], the poling in this work is performed locally after wafer bonding, offering greater flexibility than directly bonding pre-poled LN on Si. Besides, the present ion-slicing approach [17,18] avoids metallic bonding and the high optical loss associated with it.
Figure 6-3: Major fabrication steps (a) Y-cut LN on Si substrate; (b) First lithography and etching of LN; (c) Metal electrode deposition; (d) Lithography and etching to completely define the periodic electrodes; (e) Poling of LN on Si with periodic domain reversal; (f) SiN rib definition by PECVD, lithography, and etching to form the ridge waveguide. Not shown in this figure is the final deposition of a SiO₂ top cladding by PECVD.

6.2 Design

The slab region of the ridge optical waveguide is formed by bonding a 400-nm-thick film of Y-cut LN to a lower cladding 2-μm-thick layer of SiO₂ on a Si substrate. The crystal orientation of the LN thin film is chosen to utilize the highest nonlinear coefficient of LN, viz., \( d_{33} = 30 \text{ pm/V} \) [6], for the transverse-electric (TE) waveguide modes. The z-axis of the LN thin film is thus aligned along the electric field of the TE mode. Waveguides are formed by rib-loading the LN thin films with strips or channels of SiN (Fig. 6-1(a)). COMSOL™ simulations
are used to determine the poling periodicity required for the QPM of the SHG process with a pump wavelength in the telecommunication band, based on the dimensions of the SiN strips. The SiN ribs are 400 nm tall and 2,000 nm wide, resulting in a poling period around 5 μm for TE polarized pump and harmonic light. Around 65% of the pump and 90% of the second harmonic fundamental TE optical modes are confined in the LN thin film. The modes, simulated with COMSOL™, are shown in Figs. 6-1(b) and (c). The simulated value of the normalized conversion efficiency is around 1400 %W⁻¹cm⁻² for including propagation loss, with a mode overlap integral around 2.3 μm² at a pump wavelength of 1,580 nm. DC electric field simulations run in COMSOL™ are used to determine the duty cycle of the poling electrodes, targeting a 50% duty cycle in the distribution of the electric field along the propagation axis. It is noteworthy that the final duty cycle that is obtained for the reversed domains is also a function of the poling time [23]. The high optical confinement leads to significantly enhanced nonlinear interaction, thereby reducing the device length required for nonlinear conversion. This is verified in Fig. 6-2, where the generated second harmonic power is numerically simulated across a wide range of effective mode overlap areas for different input continuous-wave (CW) power levels and propagation losses. The figure indicates a clear increase in nonlinear power conversion with increasing modal confinement for shorter propagation lengths, irrespective of the propagation loss.

6.3 Fabrication

Similar to our prior works on optical modulators [17,18], ion implantation and room-temperature bonding are used in-house to transfer Y-cut LN thin films onto thermal SiO₂
cladding layers on silicon substrates in accordance with the design and dimensions described above. The fabrication steps are depicted in Fig. 6-3. Electron-beam lithography on a Leica EBPG5000+ writer, followed by dry etching using inductively-coupled plasma reactive-ion etching (ICP-RIE), was used to define the boundaries of the periodic electrodes. The dry etch was engineered to produce a pronounced LN side wall angle around 70°. This ensured good contact between the subsequent metal deposition and the LN sidewall for the entire depth of the LN film. The electrodes are sufficiently far away (> 3 μm) from the waveguide code (SiN rib) to avoid metallic loss of the optical waves. Metal poling electrodes with a 30% duty cycle (based on the COMSOL™ DC simulations discussed above) and 9 μm separation were fabricated using electron beam evaporation of 100 nm of chromium, lithography, and dry etching. The dies were poled across the etched ridges by applying high voltage pulses to the poling electrodes using contact probes at room temperature. Next, the SiN rib layer was deposited using plasma enhanced chemical vapor deposition (PECVD). This was patterned using electron-beam lithography, and dry-etched to form the rib-loaded region. Finally, a 2-μm-thick SiO₂ top cladding was deposited using PECVD, and the dies were diced and polished.
Figure 6-4: Top-view SEM of a poled LN mesa after etching in hydrofluoric acid. The domain duty cycle is seen to be uniform and close to 0.35 based on the differential etching of the polar surfaces of LN.

During poling, the electric field was ramped up to ~ 40 kV/mm, with voltages around 350 to 400 V, for 10 ms and ramped down slowly to prevent back-switching of the inverted domains [23]. The high electric field was used to ensure the onset of nucleation and subsequent domain reversal. Domain merging was avoided by using three identical pulses and limiting the pulse duration to 10 ms [24]. The domains are expected to be poled entirely through the LN film based on the high poling field, the long pulse duration, and the deep LN etching for the poling electrodes. The quality and uniformity of the poling was confirmed after characterization by wet etching in hydrofluoric acid, shown in Fig. 6-4. This was in keeping with the differential etching of the positive and negative z-axis of LN [25], where the negative z surface etches faster than the positive z surface, and confirms successful poling.
6.4 Characterization

Obviously, the ultimate proof for successful poling is demonstration of nonlinear optical processes that require QPM. The fabricated 4-mm long thin film PPLN waveguides were optically characterized by coupling light in and out of the chips by lensed fibers. The input was a mode-locked fiber laser operating at a MHz repetition rate amplified by an erbium-doped fiber amplifier, followed by a polarization controller. The propagation losses at the pump and second harmonic wavelength are < 1 dB/cm, obtained by analyzing the insertion loss across a number of waveguides. The material absorption of the SiN rib material is < 1 dB/cm and < 0.2 dB/cm at the fundamental and second harmonic wavelength respectively, measured on a Metricon prism-coupling system. The coupling loss measured per facet at the pump wavelength is ~ 10 dB. The coupling loss at the second harmonic wavelength is marginally higher due to the multimode nature of the lensed fibers used. The coupling losses can be potentially reduced by the use of appropriately-designed input and output waveguide tapers, or the use of free-space lensed input and output coupling.
Figure 6-5: (a) Autocorrelation and (b) optical spectrum, of the pulsed input to the PPLN waveguide; (c) Output of a reference unpoled waveguide; (d) Output of a poled waveguide, with a frequency doubled signal around 788 nm.

Figure 6-5(a) shows the autocorrelation of the input pulse. The input pulse is around 500 fs wide, sitting on a 7 ps wide pedestal. While the pedestal lowers the peak power of the input and generated output pulse, it is sufficiently wide to diminish the effects of pulse walk-off induced by group-velocity mismatch induced in the 4 mm long devices [26-29]. Group-velocity-induced walk-off can reduce the conversion efficiency, depending on the waveguide length and the pulse widths. The optical spectrum of the input pulse is shown in Fig. 6-5(b). The output after the PPLN samples was fed directly to an optical spectrum analyzer. An optical power meter was
used alternatively to monitor the output power after the waveguide. The optical spectrum recorded for the reference unpoled waveguide is shown in Fig. 6-5(c), with no evidence of harmonic generation. The poled waveguide phase-matches near a fundamental wavelength of 1,580 nm. The output optical spectrum is shown in Fig. 6-5(d), with a clear frequency doubled signal generated around 788 nm.

The average second-order nonlinear conversion efficiency of the device is extracted to be 8% by integrating the input and output average power. This effective efficiency includes contributions from any phase-matched second-order process, i.e., primarily SHG, although SFG could have considerable contribution too. It is practically difficult to differentiate the weight of each effect, due to the pulsed nature of the input source. Similarly, it is difficult to extract the normalized conversion efficiency in %/W.cm² using the present data. That is because it requires detailed numerical modeling based on the relative contributions of SHG and SFG in addition to the input and output temporal profiles [26-29].

Optical spectra, displaced by 60 dB, recorded at decreasing input pump powers, are plotted in Fig. 6-6(a). Figure 6-6(b) shows the generated output signals of the 1st, 4th, and 7th traces, from the top, plotted in Fig. 6-6(a). The slight asymmetry of the spectrum in Fig. 6-6(b) could be attributed to the asymmetry of the contribution of SHG to the generated signal. The quadratic nature of the generated signal is seen in Fig. 6-6(c), where the average integrated output power is plotted against the average integrated input power on a logarithmic scale from the traces in Fig. 6-6(a). A linear fit to these measurements yields a slope of 1.91, which is very close to the slope of 2 expected for low propagation loss.
Figure 6-6: (a) Optical spectra for decreasing input pump powers (top to bottom), displaced by 60 dB. The input power for each trace can be read in part (c); (b) Optical spectra around the generated output signal wavelength of 3 of traces in part (a) with input average powers of 1.67, 0.87 and 0.31 mW, respectively; (c) A straight line fit of slope 1.91 on a logarithmic scale shows the quadratic dependence of the output signal on the input pump.

6.5 Conclusions

The first compact heterogeneous periodically-poled thin film LN waveguides on silicon substrates have been fabricated and characterized. A nonlinear conversion of 8% has been obtained with a pulsed input. These devices are 4 mm long and the cross-sections are significantly smaller than traditional PPLN wavelength converters. The compact size along with the use of a silicon substrate demonstrates the compatibility of efficient $\chi^{(2)}$-based nonlinear photonic devices with silicon photonics for potential on-chip nonlinear and quantum-optic applications.
6.6 References


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CHAPTER 7: SECOND-HARMONIC GENERATION IN SINGLE-MODE INTEGRATED WAVEGUIDES BASED ON MODE-SHAPE MODULATION


Abstract— Second-harmonic generation is demonstrated using grating-assisted quasi-phase matching, based on waveguide-width modulation or mode-shape modulation. Applicable to any thin-film integrated second-order nonlinear waveguide, the technique is demonstrated in compact lithium niobate ridge waveguides. Fabricated devices are characterized with pulsed-pumping in the near-infrared, showing second-harmonic generation at a signal wavelength of 784 nm and propagation loss of 1 dB/cm.

7.1 Introduction

Optical three-wave mixing [1,2], utilizing the second-order nonlinearity ($\chi^{(2)}$) of non-centrosymmetric materials, has enabled the generation of coherent light over a wide range of frequencies from the ultraviolet to the infrared in different material systems. Efficient three-wave mixing processes, such as second-harmonic generation (SHG), sum- and difference-frequency generation (SFG/DFG) and spontaneous parametric down conversion, require optical phase matching, which is a compensation between the different wavevectors of the interacting
waves. Nonlinear frequency conversion is anticipated to be significantly more efficient in integrated nonlinear waveguides than in bulk nonlinear crystals, due to an increase in the nonlinear overlap between the interacting waves [2,3]. Consequently, several approaches have been explored for optical phase matching for frequency conversion using three-wave mixing in waveguides. Arguably, the most popular approach has been quasi-phase matching (QPM), where the phase mismatch between the interacting waves is periodically compensated. The most successful implementation of QPM has been in periodically-poled lithium niobate (PPLN) waveguides [4-6].

An alternative poling-free implementation for integrated QPM uses periodic gratings [7-10]. Grating-assisted quasi-phase matching (GA-QPM) mimics the concept and benefits of the more established periodic-poling method, but with more relaxed fabrication demands and, of course, applicability to materials that cannot be inherently poled. Generally, a net nonlinear gain for GA-QPM based frequency conversion is achieved via periodic spatial perturbation of waveguide geometrical parameters, for example mode-shape modulation, exploited in this work. This is in contrast to periodic poling, in which the sign of the nonlinearity is entirely and periodically reversed in the crystal. Previous demonstrations of GA-QPM include GaAs [8,9] and titanium-diffused lithium niobate (LiNbO₃ or LN) waveguides [10]. A similar approach has also been previously applied to four-wave mixing in integrated silicon waveguides [11].

Meanwhile, our team has pioneered a platform for thin-film LiNbO₃ [12]. The advantages of the thin-film technology, compared to conventional titanium-diffused waveguide, is the high-contrast waveguides formed by bonding 300 to 600 nm of LiNbO₃ (with a refractive index of ~
2.16) on a silicon dioxide (SiO₂ with an index of ~ 1.48) bottom-cladding layer and rib-loading it with an index-matching material (e.g., silicon nitride, SiN), for lateral confinement. High-performance electrooptic modulators [13,14] and PPLN waveguides for SHG [6] have been demonstrated on the platform.

In this chapter, a variation of GA-QPM is applied to our thin-film LiNbO₃ waveguides technology to achieve SHG. The approach, which may be also called mode-shape modulation (MSM), relies on periodically modulating the width of the SiN rib on top of the LiNbO₃ thin film. The width modulation conveniently provides QPM, while the challenges etching or poling are avoided (see Fig. 7-1(a)). Thus, the nonlinear effect is exclusively obtained from the modulation of the nonlinear mode overlap integral between the fundamental (pump) and generated second-harmonic (SH) waves, and mediated by the refractive index perturbation. Another advantage over the aforementioned works on GaAs and titanium-diffused waveguides is the shallow etching of the thin (400 nm) SiN rib layer, thanks to the tight mode confinement of the high-contrast waveguides. To avoid grating-induced losses from coupling into higher order modes, a ridge waveguide structure is adopted, utilizing a sinusoidal width perturbation in the rib, which is kept in single-mode operation for both the pump and SH wavelengths.

7.2 Fabrication

The fabricated waveguides are formed by depositing a 400-nm-tall rib of SiN on a 600-nm thin film of X-cut LN, surrounded by SiO₂ bottom and top clads. The width of the SiN rib sinusoidally varies from 855 nm to 1095 nm, with a period around 5.5 μm, as dictated by the
phase mismatch, according to COMSOL™ simulations. Only the SiN film is patterned, i.e., the LN film is unetched to avoid etch-induced losses [6,12-14], as shown in Fig. 7-1(a). Thus, there is no spatial perturbation of the $d$ tensor, and the nonlinear effect is exclusively due to the width modulation of the SiN rib. The design is phase-matched for transverse-electric (TE) modes, thus ensuring that the SHG process is mediated by the largest nonlinear coefficient of LN, viz., $d_{33}$. An optical micrograph of the top view of a fabricated waveguide is provided in Fig. 7-1(b). The transverse TE modes of the pump and SH waves at a grating width of 1095 nm are shown in Figs. 7-1(c) and (d).
Figure 7-1: (a) Concept of the GA-QPM ridge waveguide used in this work, showing the longitudinally varied waveguide width following a sinusoidal pattern (exaggerated in its magnitude for visibility). The minimum and maximum width of the grating are also indicated; (b) top-view optical micrograph of a fabricated waveguide; and (c) and (d) intensity profile of the fundamental and second-harmonic TE modes of the waveguide at a grating width of 1095 nm.
7.3 Design and simulation

The GA-QPM thin film LN waveguides are numerically investigated using the local normal-mode expansion (LNME) [15], where the eigenmodes of the local spatial structure of the waveguide are used for the expansion. The corresponding coupled-mode equations for the normalized field amplitudes during SHG assume the form

$$\frac{d}{dz}a_{2\omega}(z) = -i(a_{\omega}(z))^{2} e^{i\Delta\beta_0} f(z) - \frac{\alpha_{2\omega}}{2} a_{2\omega}(z),$$  \hspace{1cm} (7-1a)  

$$\frac{d}{dz}a_{\omega}(z) = -i a_{\omega}(z) a_{2\omega}^{*}(z) e^{-i\Delta\beta_0} f^{*}(z) - \frac{\alpha_{\omega}}{2} a_{\omega}(z),$$  \hspace{1cm} (7-1b)  

where $a_{2\omega}(z)$ and $a_{\omega}(z)$ are the normalized field amplitudes of the signal (SH) and the pump at frequencies $2\omega$ and $\omega$, respectively, and $\alpha_{2\omega}$ and $\alpha_{\omega}$ are the corresponding averaged waveguide propagation losses. $\Delta\beta_0$ is the phase mismatch between the signal and the pump waves, averaged over one period. $f(z)$ is a nonlinear coupling coefficient that captures the effect of the periodic modulation of the waveguide on both the transverse field overlaps at $\omega$ and $2\omega$. Further details can be found in Ref. 15.

The quadratic SHG process is simulated for the aforementioned waveguide dimensions. The normalized SHG conversion efficiency is presented in Fig. 7-2, and is a figure of merit of the nonlinear waveguide, and is independent of the input optical power, and the mode of operation (pulsed or continuous wave (CW)). $f(z)$ is evaluated numerically using an eigenmode
solver by Lumerical Solutions. The first-order term in the Fourier series expansion of \( f(z) \) cancels out the \( \exp(\pm i \Delta \beta_0 z) \) phase terms in Eqns. (7-1a) and (7-1b), hence driving the nonlinear growth of the SH field, while the constant term in the series expansion results in fast oscillations of the SH field. The propagation loss is varied from 0 to 5 dB/cm, illustrating the effect of propagation loss on the SHG process. The inset in Fig. 7-2 displays the fast oscillations of the SH field amplitude.

Figure 7-2: SHG conversion efficiency versus propagation length for the MSM numerical simulation for different propagation loss values. The inset presents the associated normalized SH field amplitude along with the oscillations that are present but too small to be discernible in the main figure.
The normalized CW conversion efficiency is extracted to be \( \sim 0.8 \ %W^{-1}cm^{-2} \). A similar evaluation of the nonlinear effect using 500-fs-long transform-limited hyperbolic secant pulses for the pump yields the same conversion efficiency by adapting the analytical model described in Ref. 16 for grating-assisted quasi-phase matching. The group-velocity mismatch-induced pulse walk-off leads to SHG pulse durations around 4 ps in 5 mm long waveguides for the 500 fs input. It is stressed, however, that this theoretical estimation is based on the assumption of transform-limited input pulses, which may not necessarily be applicable to the input source employed in the experiments (Fig. 7-3(a)).

It is noted that while the above simulated efficiency is lower than what has been achieved in PPLN (\( \sim 40 \ %W^{-1}cm^{-2} \)), the challenges of periodically poling thin-film devices in terms of required short periodicities and applicability of the proposed technique to \( \chi^{(2)} \) material systems that cannot be poled must be stressed.

Finally, we remark that the physical dimensions of the waveguide strongly influence the nonlinear SHG process. Varying the height of the LN film affects both the grating-induced waveguide propagation losses, \( a_{2\omega}(z) \) and \( a_{\omega}(z) \), and the magnitude of the first Fourier series coefficient of \( f(z) \) that drives the nonlinear process. The extent of the width modulation has a similar effect on these factors. A larger width modulation increases the strength of the nonlinear coupling coefficient, but at the cost of increased propagation losses. Thus, a balance must be maintained between the propagation losses and the Fourier series coefficients of \( f(z) \).
Figure 7-3: (a) Pulsed pump input spectrum and autocorrelation (inset); (b) OSA trace of the output; and (c) SH signal generated around 784 nm.
7.4 Characterization

The 4.9-mm-long waveguides were characterized by pulsed-pumping at a 100 MHz repetition rate with a 500 fs pulse duration source, with a 7 ps pedestal (see inset of Fig. 7-3(a)). The spectrum is centered at 1560 nm, with an average power of 84 mW (Fig. 7-3(a)). The source light was coupled on and off the chip through lensed fibers, with an estimated coupling loss of 6.5 dB/facet. A fiber-based polarization controller was used at the input to align the polarization in the horizontal direction, corresponding to the Z-axis of the LN film and the TE mode of the waveguide. The output light from the waveguide was collected and fed to an optical spectrum analyzer (OSA) to determine the phase-matching wavelength for a given period. Based on the total fiber to fiber insertion loss of 13.5 dB at the pump wavelength, a low propagation loss of 1 dB/cm is estimated, due to the low loss from the SiN grating and not etching the LN layer for lateral confinement. An OSA trace, showing the generated SH signal at 784 nm, is shown in Figs. 7-3(b) and (c), with a peak power spectral density of -33.3 dBm/nm for the signal. The pump shows a power spectral density of -16 dBm/nm at the corresponding phase-matched wavelength of 1568 nm, indicating a penalty of -17.3 dB from the SHG process. Differences between the coupling efficiency for the pump and signal waves into the tapered fiber may influence this value slightly. A plot of integrated pump power versus integrated output power at the harmonic tone, shown in Fig. 7-4, confirms the quadratic relationship consistent with the SHG process, with a slope of 2.18 for a straight-line fit.

The generated signal at 784 nm has a linewidth of ~ 2.2 nm. Such a narrow linewidth is governed by the phase matching conditions of any involved nonlinear processes, primarily SHG.
Due to the broad spectrum of the input pulse, it is also possible that there is a degree of contribution from sum-frequency generation (SFG). Meanwhile, it should be noted that the harmonic tone cannot be generated by mode-matching processes, since the waveguide design is single-mode at both the pump and signal wavelengths.

![Graph of integrated pump power vs. signal power](image)

Figure 7-4: Measured pump power vs. signal power, showing the quadratic slope of 2.18 (fitted line).

Assuming the aforementioned 4 ps SHG pulse widths for a transform-limited input source, and accounting for only the corresponding spectral region of the pump, it is possible to extract a very crude nonlinear conversion efficiency of ~ 1 %/(W.cm²) from the presented data.
However, an accurate estimate of the experimental conversion efficiency would require good understanding of the spectral phase of the input pulse measured by methods such as frequency-resolved optical gating (FROG). This complication is in addition to the aforementioned possible contribution from SFG. Future investigations with a CW input will allow attaining a more accurate experimental normalized conversion efficiency for the reported method.

It should be finally discussed that the conversion efficiency could be increased by employing a higher-refractive-index rib-loading material to allow faster compression of the mode. Additionally, there may be more optimized alternative width modulation patterns, which can simultaneously achieve low grating-induced losses and high SH conversion efficiency.

7.5 Conclusion

In conclusion, waveguide width or mode-shape modulation is employed to obtain poling-free quasi-phase matching in thin-film lithium niobate. Second harmonic generation is demonstrated at a signal wavelength of 784 nm, utilizing near-infrared pulsed pumping. A low propagation loss of $\sim 1 \text{ dB/cm}$ is measured. This implementation is directly applicable to other conventional second-order nonlinear integrated waveguide platform, notably material systems such as compound semiconductors which cannot be periodically poled.

7.6 References


CHAPTER 8: RANDOM QUASI-PHASE MATCHING ON A NANOPHOTONIC HETEROGENEOUS SILICON CHIP

The contents of this chapter have been accepted for presentation at the 2018 Conference on Lasers and Electro-optics (CLEO) as: A. Rao, T. Sjaardema, G. C.-Gonzalez, A. Honardoost, M. Malinowski, K. Schepler, and S. Fathpour, “Random Quasi-Phase-Matching on a Nanophotonic Heterogeneous Silicon Chip.”

Abstract—Grating-assisted random quasi-phase-matching is demonstrated in unpoled thin-film lithium niobate waveguides on a silicon substrate via second-harmonic generation from near-infrared to visible wavelengths.

8.1 Introduction

The efficiency of nonlinear optical three-wave mixing, such as second-harmonic generation (SHG), depends on phase matching (PM), which is basically a conservation of momentum between the interacting waves. Typical PM schemes include birefringent PM, and quasi-phase-matching (QPM). However, PM intrinsically limits the conversion bandwidth of the nonlinear interaction. Previously, random quasi-phase-matching (rQPM) has been investigated as a means to realize nonlinear conversion in materials which cannot be phase-matched, and to circumvent the bandwidth limitation imposed by PM schemes [1,2]. For example, rQPM in bulk polycrystalline zinc selenide has been used for mid-infrared difference frequency generation [1] and for optical parametric oscillation [2].
Figure 8-1 (a) Schematic of the rQPM thin-film LN on silicon waveguide; (b) Normally distributed grating period variation for 1000 gratings. The mean is 3700 nm, and the three
standard deviations are indicated in the legend; (c) Micrographs of some fabricated rQPM waveguides; (d) Optical spectrum of the pulsed pump; (e) Two representative SHG spectra of the rQPM waveguides, showing enhanced nonlinear conversion bandwidth; (f) Quadratic dependence of the SHG power on the pump power in three waveguides of varying length, decreasing from 4 to 0.4 mm; and (g) Linear dependence of nonlinear conversion with propagation length at two different pump powers (60 and 80 µW).

8.2 Design and fabrication

In this chapter, we demonstrate SHG using rQPM in nanophotonic waveguides, as an alternative to more conventional PM schemes employed in waveguides, such as QPM and modal dispersion engineering [3]. Our waveguides are made of thin-film lithium niobate (LN) on a silicon substrate, which provides superior optical confinement compared to conventional LN waveguiding approaches [3-5]. We use grating-assisted quasi-phase-matching (GAQPM) for implementing rQPM. GAQPM relies on a physical modulation of the width of a nonlinear waveguide to induce a local spatial variation of the second-order nonlinear overlap integral [5]. When the periodicity of the sinusoidal modulation is chosen randomly, rQPM is realized, as depicted in Fig. 8-1(a), where the periods, \( \Lambda_i \) are sampled from a Gaussian distribution. The partially etched ridge waveguides are formed by etching 300 nm of LN from a 600-nm-thick LN slab. A range of waveguide grating widths, ranging from 20 to > 100 nm, modulating 1100-nm-wide ridge waveguides were fabricated. The mean of the grating period, \( \Lambda \), is equal to the SHG coherence length (3700 nm). The Gaussian distribution of the grating period is visualized in Fig.
8-1(b). Micrograph images of some of our fabricated rQPM waveguides with different grating widths are shown in Fig. 8-1(c).

8.3 Characterization

SHG around 775 nm is measured using a picosecond pulse width pump source at 1550 nm and an optical spectrum analyzer (Fig. 8-1(d)). Two representative SHG spectra are plotted in Fig. 8-1(e), which confirm the enhancement of the SHG bandwidth, by nearly an order of magnitude, compared to our previous results on SHG using conventional PM schemes in similar thin-film LN waveguides [4,5]. The quadratic dependence of the rQPM-based SHG on pump power is shown in Fig. 8-1(f). The linear dependence of generated power on propagation length is an important signature of the rQPM process [1]. This is verified by measuring the SHG from waveguides of different lengths, as presented in Fig. 8-1(g).

8.4 Conclusion

These results demonstrate the viability of using random quasi-phase-matching in nanophotonic waveguides. The approach can be easily extended to waveguides in other platforms for broadband frequency conversion, notably including those material systems in which phase-matching is not viable, such as polycrystalline materials and compound semiconductors.
References


CHAPTER 9: PHOTON PAIR GENERATION ON A SILICON CHIP USING NANOPHOTONIC PERIODICALLY-POLED LITHIUM NIOBATE WAVEGUIDES


Abstract— This chapter presents a new class of photon pair sources on a silicon chip. The source is based on nanophotonic periodically poled lithium niobate waveguides and presents MHz rate pair generation.

9.1 Introduction

There has been a pronounced increase of interest in realizing high efficiency integrated photonic sources to generate quantum states of light in the past decade. The most attractive substrate of choice remains silicon for such nonlinear devices, for its potential compatibility with large-scale silicon photonics [1]. In general, there are two major mechanisms employed for integrated photon pair generation – spontaneous four-wave mixing (SFWM) [2], and spontaneous parametric down-conversion (SPDC) [3]. Traditionally, and with better performance, photon pair sources use SPDC in either free space or integrated photonic configurations. Tightly confined integrated photonic configurations yield an increase in the
nonlinear overlap over their free space counterparts, which results in an enhanced nonlinear interaction. With this feature in mind, periodically poled lithium niobate (PPLN) waveguides have been used for numerous demonstrations in quantum optics. These waveguides benefit from the superior intrinsic material properties of lithium niobate (LN) – high optical nonlinearity and broadband transparency. However, they suffer from large mode sizes compared to modern integrated photonic waveguides, and the bulk LN substrate is not directly compatible with silicon photonics.

9.2 Nanophotonic PPLN source

Merging the benefits of PPLN with modern integrated photonics, we demonstrate correlated photon pair generation using nanophotonic periodically poled lithium niobate waveguides on a silicon chip. A patterned silicon nitride rib on top of a thin film of LN forms the core of the high index contrast waveguides [1]. Silicon dioxide constitutes the upper and lower claddings. This scheme has been previously used for the demonstration of different nanophotonic components, such as electrooptic modulators, and nonlinear frequency converters [4,5]. Periodic electrodes are employed for periodic domain reversal of the thin film LN (Fig. 9-1(a)). The source is quasi-phase-matched for a type–0 interaction, i.e., all interacting waves, shown in Fig. 9-1(b) and (c), are transverse-electric (TE) polarized.
Figure 9-1 (a) Schematic of nanophotonic periodically poled lithium niobate waveguide on silicon; (b) & (c) TE polarized optical mode simulations for spontaneous parametric down converted photon pairs and the pump, at 1584 nm and 792 nm.

9.3 Characterization

A Ti-sapphire laser centered at 792 nm, with 81.8 MHz repetition rate, and < 0.5 ps pulse-width, is coupled into the integrated photon pair source. The generated telecom band photon pairs are extracted using a lensed fiber. The residual pump light is filtered using anti-reflection coated silicon dies. Two fiber coupled tungsten–silicide superconducting nanowire single photon detectors [6] are used after a 50:50 beam splitter in a Hanbury Brown-Twiss configuration. Figure 9-2 shows singles and coincidence rates for a series of pump powers coupled into the waveguide. The on-chip pair generation rate is estimated to be ~ 1 MHz/mW by subtracting twice the optical transmission loss (in dB) from the output of the chip to the detectors. Normalized coincidence measurements for characterizing the coincidence-to-accidental ratios at different powers are shown in Fig. 9-3.
Figure 9-2 (a) Singles rates at detectors 1 and 2; (b) Measured photon pair coincidence rate at detectors; (c) Estimated photon pair generation rate on-chip.

Figure 9-3 (a)–(c) Correlation histograms showing photon-pair coincidences, measured at pump powers of 7, 14, and 28 μW. The coincidence-to-accidental ratios are around 15, 10, and 6, and are artificially low because the signal and idler are not deterministically separated.

9.4 Conclusion

The presented results are a promising demonstration of miniaturized nanophotonic PPLN waveguides. Short-term improvements in our source will include reduced coupling loss at waveguide facets. In the medium-term, the enhanced optical confinement in conjunction with the compatibility with silicon substrates implies that the novel source could be utilized to form high-
efficiency quantum photonic circuits on silicon. The platform can also benefit from seamless integration with LN electrooptic modulators, with applications ranging from on-chip manipulation of complex entangled states to quantum metrology [7,8].
9.5 References


CHAPTER 10: SPECTRAL RESOLUTION OF SECOND-ORDER COHERENCE OF BROADBAND BIPHOTONS


Abstract— The second-order coherence of biphoto pairs is spectrally resolved using a time-of-flight fiber spectrometer. Spectrally resolved coincidence-to-accidental ratios of over 300 are measured using a thin-film lithium niobate waveguide source on a silicon chip.

10.1 Introduction

The study of the coherence properties of photon states, using correlation functions, is vital to our understanding of the physics of quantum states of light [1,2]. The coherence of many different physical systems, such as spontaneous parametric down-conversion and four-wave mixing sources, heralded-photon sources, and lasers, has been studied using correlation functions. Of the many entangled photon states, broadband biphotos are basic building blocks for realizing high-dimensional states, and for extending the capabilities of photonic quantum metrology. In this work, we spectrally resolve the second-order coherence \(g^{(2)}\) of broadband biphotos using time-of-flight spectrometry, realizing a measurement of \(g^{(2)}(\omega_i,\omega_s)\), for signal, \(s\), and idler, \(i\), frequencies.
Figure 10-1 (a) Schematic of the time-of-flight fiber spectrometer: SNSPD – superconducting nanowire single photon detector; TCSPC – time correlated single photon counter; (b) Construction of $g^{(2)}(\omega_i,\omega_s)$ in analogy to $g^{(2)}$; (c) Joint spectral intensity (JSI); and (d) $g^{(2)}(\omega_i,\omega_s)$ for increasing input pump powers (left to right).
10.2 Experiment

The time-of-flight spectrometer is depicted schematically in Fig. 10-1(a). The source is a novel thin-film lithium niobate (LN) waveguide on silicon, which has the advantages of compact mode-size and integrability compared to traditional LN sources [3,4]. The source is pumped by a Ti-sapphire laser and the output is passed through a long optical fiber of known length and dispersion after the pump is filtered out. The fiber leads to a 50:50 fiber splitter, which splits the degenerate idler and signal photons. The two outputs of the splitter are connected to tungsten-silicide superconducting nanowire single-photon detectors (SNSPDs) [5]. The time-of-flight through the optical fiber is measured by the SNSPDs and time-domain histogram electronics, and mapped to the photon wavelength through the dispersion of the optical fiber. The spectral density of the degree of second-order coherence is constructed in analogy to the construction of the $g^{(2)}$ from coincidence measurements. The joint spectral intensity (JSI) corresponds to the area of the zero delay coincidence peak in a $g^{(2)}$ measurement, and the background, $B(\omega_i,\omega_s)$, is constructed by averaging over several (~ 100) delayed spectrally dispersed coincidence measurements, similar to the averaged area of the non-zero delay coincidence peaks, as indicated in Fig. 10-1(b). $g^{(2)}(\omega_i,\omega_s)$ is experimentally formulated as

$$
g^{(2)}(\omega_i, \omega_s) = \frac{JSI(\omega_i, \omega_s)}{B(\omega_i, \omega_s)}. \quad (10-1)
$$

The JSI of the source is shown in Fig. 10-1(c), and the spectral resolution of $g^{(2)}$ is shown in Fig. 10-1(d), for three distinct input pump powers. We measure spectrally resolved coincidence-to-accidental (CAR) ratios over 300 (Fig. 10-1(d).)
10.3 Conclusion

The approach presented in this chapter amounts to a simultaneous characterization of all possible spectrally filtered configurations of a typical $g^{(2)}$ measurement, because the JSI and spectral background can be separately integrated over a desired signal and idler frequency range to replicate such spectrally filtered $g^{(2)}$ measurements. Our spectral resolution of the measure of second-order coherence may also have an impact on how application-specific photon-pair sources, such as heralded-photon sources and broadband frequency-entangled sources are optimized.

10.4 References


CHAPTER 11: CONCLUSION AND FUTURE WORK

This dissertation demonstrates building blocks for integrated photonics on thin-film lithium niobate (LN) – electrooptic modulators, nonlinear frequency converters, and correlated photon-pair sources. The continuation of this work is expected to result in complex modulators for Quadrature Phase Shift Keying (QPSK) and Quadrature Amplitude Modulation (QAM) data transmission, advanced quantum photonic circuits, and heterogeneously integrated nonlinear photonic chips on thin-film LN. Furthermore, the concepts for quasi-phase matching demonstrated in this work can be extended beyond LN, to materials such as zinc selenide (ZnSe) and zinc sulfide.

11.1 Complex modulators for Quadrature Phase Shift Keying and Quadrature Amplitude Modulation

Coherent optical communication takes advantage of encoding information in the phase of light, which is distinct from amplitude modulation, such as On-off Keying (OOK). This can offer reductions in optical transmit power and signal to noise ratio (SNR) requirements, increase receiver sensitivity, remove optical filtering requirements, and enable filtering and signal processing in the electrical domain by down-conversion to baseband.
Figure 11-1 Schematic of an IQ modulator [1].

Figure 11-2 Schematic of modulators required for 16 QAM.
An IQ modulator used for QPSK basically consists of two Mach-Zehnder amplitude modulators and one phase modulator, as indicated in Fig. 11-1. QAM relies on the modulation of both phase and amplitude, enabling the transmission of more bits per symbol. The modulator layout required for QAM is more complex than the IQ modulator, as shown in Fig. 11-2 for 16 QAM. The lower drive voltages, reduced footprints, and tight bending radii previously demonstrated in this work lend themselves to forming low power consumption complex modulators for QPSK and QAM.

11.2 Advanced quantum photonic circuits

Figure 11-3 Schematics of two advanced quantum photonic circuits using thin-film PPLN.

Figure 11-3 shows a proposed architecture for the generation of exotic entangled states such as tripartite Greenberger-Horne-Zeilinger (GHZ) entangled states. Progress on GHZ states is currently hampered by extremely slow generation rates, where the state-of-the-art demonstrations of photonic GHZ states record ~ 10 triplets per minute [2]. The proposed scheme
of Fig. 11-3 (a) can potentially attain ~ kHz GHZ rates, a significant advancement in attaining useful GHZ measurement rates.

11.3 Heterogeneously integrated nonlinear photonic chips

Figure 11-4 Schematic of integrated ChG-LN waveguides. Optical mode profiles of the structure are also shown for fundamental TE input at 1550 nm for different cross-sections ((a)–(d)). The adiabatic mode transition is shown as well. [3]
Figure 11-4 depicts the integration of ChG and LN as an extension of the work previously demonstrated in this dissertation, to form photonic elements which can exploit the high third order nonlinearity of ChG along with the strong second order nonlinear response of LN. This has already been demonstrated for four-wave mixing in the ChG, and future implementations will add second-order nonlinear effects in the LN region, with applications in nonlinear optics and frequency metrology.

11.4 Mid-infrared light generation in zinc selenide waveguides

Mid-IR nonlinear frequency conversion in bulk devices has been quite successful but fiber or waveguide forms have been difficult to fabricate. Recently, semiconductor materials such as orientation patterned GaAs [OPGaAs] have been used for mid-IR generation beyond the ~4 µm transmission wavelength limit of PPLN. Some work has been done to develop waveguide OPGaAs [4,5] but the process is complex and expensive, and is usually accompanied by large passive losses. Like GaAs, zincblende-type ZnSe has 43m point group symmetry. Use of orientation patterned single-crystal ZnSe has been considered for bulk orientation patterned QPM [6] because of its broadband transmission window but with little success due to the difficulty of growing thick (> 500 µm) alternating orientations of single crystal ZnSe. And since the refractive index of ZnSe is isotropic, it cannot be used for birefringent phasematching. However, little has been done to fabricate ZnSe frequency conversion waveguide structures.

We have recently grown a <111> ZnSe film on <100> wet oxide silicon confirming this advantageous property of ZnSe growth. For crystals like ZnSe with 43m point group symmetry,
the difference frequency generation (DFG) nonlinear polarizability generated by pump and
signal beams with polarizations oriented along the [1 1 1] direction is also in the [1 1 1] direction
regardless of crystal rotation about the [1 1 1] axis. Then, quasi-phase matching can be achieved
with mode-shape modulation as we have previously demonstrated with lithium niobate ridge
waveguides in chapter 7. Figure 11-5 shows confirms the <111> orientation of our ZnSe film,
measured by x-ray diffraction. Figure 11-6 confirms the uniformity of this growth via a pole
figure. A scanning electron microscope image, shown in Fig. 11-7, clearly shows the
polycrystalline growth of the ZnSe grains. Future work will focus on waveguides for mid-
infrared generation via DFG.

Figure 11-5 X-ray diffraction, identifying the <111> orientation of the deposited ZnSe film.
Figure 11-6 X-ray diffraction, identifying the $<111>$ orientation of the deposited ZnSe film.
Figure 11-7 Scanning electron micrograph of dry etched ZnSe before resist mask removal.

11.5 References


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