Design of high-bandwidth, low-voltage and low-loss hybrid lithium niobate electro-optic modulators

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Abstract

The past decade has seen significant growth in the field of thin film lithium niobate electro-optic modulators, which promise reduced voltage requirements and higher modulation bandwidths on a potentially integrated platform. This article discusses the state-of-the-art in thin film modulator technology and presents a simplified simulation technique for quickly optimizing a hybrid silicon- or silicon nitride-lithium niobate modulator. Also discussed are the feasibility of creating a 1 V half-wave voltage, 100 GHz bandwidth modulator, and the design specifications for a single hybrid silicon-lithium niobate platform optimized to operate across all telecommunication bands (between 1260 and 1675 nm wavelengths).

1. Introduction

Optical communication systems and networks rely upon electrical-to-optical data conversion. One popular approach to perform this function is to map electrical data onto an optical carrier by driving the laser itself [1], but this sort of direct modulation is intrinsically limited in both modulation bandwidth and extinction ratio, and also suffers from coupling between amplitude and phase modulation [2]. Fortunately, external lithium niobate (LN) electro-optic modulators (EOMs) have been under development since at least 1974 [3]. By 1993, LN was a dominant platform for integrated optics, due in large part to its usefulness as an external electro-optic modulator [4], and continues to be widely used today.

Despite its success, traditional bulk LN EOMs have several drawbacks [3]. Fundamentally, they are fabricated as a standalone technology that can not be easily integrated with modern silicon (Si) electronics and Si photonics, due in part to fabrication considerations (lithium and niobium particle contamination in Si processing equipment) and physical limitations (thermal expansion mismatch limits processing capabilities for heterogeneous integration approaches to around 150°C [5]). This is significant, as the ability to integrate many electrical, optical, and electro-optical components on the same platform can reduce costs, increase throughput, and add device functionality that is not available on a standalone platform, such as monolithically integrated driver circuits and thermal control circuits.

Bulk LN EOMs are also limited in terms of performance; due to the fact that waveguides in bulk LN EOMs are fabricated by Ti indiffusion, the waveguide core is weakly guiding and the resultant optical mode is quite large. This in turn limits the minimum spacing between supply and ground terminals, setting a fundamental limit on the minimum drive voltage for an EOM of a particular length. As will be shown in section 2, in order to build a LN-based EOM with a low drive voltage, the device length must be made long.

To overcome this fundamental limitation, recent research efforts have explored using thin films of LN as the material platform for integrated EOMs [6–13]. The idea of making thin films of LN has been around since the late 1960s [14], but a single-crystal film of LN was not realized until 1998 [15], and not
commercialized until around 2010 by companies such as NanoLN (Jinan Jingzheng Electronics Co., Ltd). Recent efforts towards integrating LN thin films on a silicon-on-insulator (SOI) platform have resulted in modulation bandwidths beyond 100 GHz, although with a high drive voltage around 13 V [8, 16], while work in LN thin films-on-insulator (LNOI) as a standalone platform has resulted in drive voltages as low as 2.3 V with a bandwidth of 80 GHz [9]. These large bandwidth, low-power, chip-scale EOMs have a variety of applications beyond high-speed telecommunication links [17], such as arbitrary waveform generation [18], millimeter-wave imaging systems [19], dual-comb spectroscopy [20], and electro-optic digital-to-analog converters [21].

All of the aforementioned modulators are built in the Mach–Zehnder Interferometer (MZI) configuration, in which case they are characterized by their halfwave voltage-length product \( V_{\pi}L \), and their electrical 3-dB bandwidth (BW). For the remainder of this article, we will also characterize modulators by their active region optical propagation loss, which we require to be low (on the order of 1 dB/cm), although in some cases external amplifiers can be used to boost the optical power. The extinction ratio (ER)—the ratio between the optical power of ‘on’ and ‘off’ signals—of an EOM is significant as well, particularly for quantum communications and low bit-error rate (BER) classical communication links [22, 23], as is the linear loss of the device. All Mach–Zehnder modulator (MZM; that is, EOMs in the MZI configuration) performance metrics are related to the non-linear interaction strength of the material being modulated. The reason LN has been the material of choice for many decades is because it has a relatively large electrooptic coefficient \( r_{33} = 30.8 \text{ pm/V} \) \([24]\), resulting in lower \( V_{\pi}L \) and higher BW, while ER depends on \( V_{\pi} \) as well as fabrication accuracy of the optical waveguide splitters and combiners used to make the interferometer. A similar architecture has been used to fabricate EOMs using GaAs waveguides to achieve a bandwidth of 50 GHz with \( V_{\pi} = 4.8 \text{ V} \) \([25]\), and more recently plasmonic polymer waveguides have been used to achieve bandwidths up to 500 GHz with \( V_{\pi} = 3 \text{ V} \) and a propagation loss of 0.5 dB/\( \mu \text{m} \) \([26]\).

SOI-based MZMs can be fabricated at the wafer-scale in commercial foundries, and have seen widespread use over the past decade. However, SOI EOMs—which rely on the movement of carriers in and out of the optical waveguide to create a phase shift—experience significant levels of propagation loss due to the introduction of these carriers, which results in shorter devices (to maintain a reasonable device insertion loss) and reduced extinction ratios \([27, 28]\). To overcome the limitations of all-Si EOMs, a highly non-linear material can be deposited or bonded onto the Si waveguide layer to form a hybrid waveguide capable of large modulation bandwidths. This is the approach of the Si-LN platform \([29]\). In this integrated platform, waveguides are patterned in the Si layer and a film of LN is bonded over the area of interest. While the LN film can be etched afterwards \([7]\), it is possible to achieve large bandwidth modulation without doing so \([8]\).

There are several as-yet unexplored modulator configurations that could be realized in this hybrid Si-LN platform based on the basic MZM, such as quadrature-amplitude modulators (QAM) \([30]\), pulse amplitude modulators (PAM) \([31]\), pulse position modulators (PPM) \([32]\), and wavelength division multiplexed modulator arrays \([33]\). Each of these modulator configurations can be used to achieve higher modulation rates than what is possible with a basic, non-return to zero (NRZ) modulated MZM, without any added fabrication complexity as far as the integration or processing of LN is concerned, since all the waveguiding is performed in the foundry-fabricated Si layer. In addition to scalability and ease of design and fabrication, these complex devices can be made quite compact on a Si-LN platform. A racetrack ring modulator with a 90° bending radius of only 10 \( \mu \text{m} \) has been demonstrated on the Si-LN platform \([6]\), compared with a minimum bend radius of approximately 10 mm in bulk LN \([35]\), a factor of 10\(^9\) reduction in footprint.

Silicon nitride (SiN) is of interest for hybrid LN-based waveguides as well, particularly for visible wavelength and high-power applications where Si is no longer the ideal material of choice \([36]\). This is because, for wavelengths shorter than 1.1 \( \mu \text{m} \), Si is highly absorbing, whereas SiN can guide light down to a wavelength of about 400 nm. Even at 1550 nm, high optical power in Si waveguides can cause two-photon absorption and free carrier generation. These effects are less significant in SiN waveguides. Since the refractive index of SiN (\( n \approx 2.0 \)) is higher than that of the surrounding cladding material, SiO\(_2\) (\( n \approx 1.44 \)), rib waveguides of SiN loading a LN thin-film can also be used to define waveguides with a small mode cross-sectional area, and efficient MZMs. Although SiN has a lower refractive index than both Si and LN at \( \lambda = 1550 \text{ nm} \) (2.00 for SiN \([37]\), 3.47 for Si \([38]\) and 2.14/2.21 for LN along the extraordinary/ordinary crystal axes \([39]\)), it has still been shown to have a bending loss of 300 \( \mu \text{m} \) in the hybrid SiN-LN region, about 4500 times smaller than the footprint of a bulk LN circular bend.

Both platforms—Si-LN and SiN-LN—are also viable candidate platforms for mid-infrared (MIR) modulators. MIR modulators are of interest for a variety of applications, some of which include free-space atmospheric communication links \([40]\), drug development in the pharmaceutical industry \([41]\), and gas sensors, which rely on absorption spectroscopy and can be used for combustion gas monitoring, air quality...
Figure 1. (a) Wafer-scale vision of integrated hybrid electro-optic modulators. A photograph of an SOI wafer (which was used in making hybrid LN devices) is graphically edited to indicate regions in which an LN film may be bonded, and the gold lines represent possible electrode configurations. (b) Cross-section of the hybrid EOM region. (c) A simulated electro-optic response curve for a hybrid Si-LN EOM. The simulated device’s length is 6 mm, $V_{\pi} = 5$ V, microwave loss $= 0.28 \text{dB/(cm-GHz}^{1/2})$ (lowest reported microwave loss in a LN-based EOM, from reference [34]), and index and impedance are matched.

control, and breath analysis [42]. The hybrid platform can conceivably be integrated with various other MIR devices, such as photonic crystal sensors [43], for complete chip-scale functionality.

1.1. Non-hybrid to hybrid transitions
An important aspect of the hybrid Si-LN or SiN-LN waveguide platform is the fact that the LN is only bonded to a particular region of the SOI die, depicted in figure 1(a). The advantage to this approach is that traditional Si or SiN edge couplers and grating couplers can be used to couple light on and off the chip with high efficiency and in a single etch step. Additional Si or SiN photonic components and structures can be used on the same platform as hybrid Si-LN and SiN-LN photonics, meaning integrated heaters, monolithic CMOS circuits, and even integrated lasers can conceivably be built on the same die as high-speed LN-based EOMs.

This layout does present some challenges, however. The optical mode has to be designed in such a way as to prevent significant loss at the transition from the hybrid LN region to the non-hybrid region. To adiabatically convert between the hybrid region and the non-hybrid region with a Si core waveguide, one can taper the Si waveguide to the widest possible single-mode width. Due to the high refractive index of Si, the optical mode will be tightly confined in the waveguide. Then, the Si waveguide simply passes into or out of the LN region before tapering down to the optimized Si width. This is shown in figure 2(a). There are three sources of loss in this transition: (1) the loss experienced by the optical mode as it propagates through the taper in the non-hybrid region; (2) the reflected (due to an effective index mismatch) and scattered (due to modal mismatch) light from the non-hybrid to hybrid transition below the LN film; (3) light scattered by fabrication imperfections or non-adiabatic behavior (due to the taper being too short or poorly designed) in the hybrid taper. Log-scale mode simulations of the optical field intensity of a Si-LN waveguide are shown in figures 2(b)–(d) before the transition, immediately after the transition, and in the narrow Si hybrid section.

Taper loss in either the hybrid or the non-hybrid region can be optimized with different taper lengths or designs [45, 46]. Losses due to the transition below the LN film, however, require good mode confinement in the Si region. Figure 2(e) shows the maximum width a Si waveguide can have before supporting higher order optical modes. For each Si height and corresponding maximum width, the transition loss from the non-hybrid region into the hybrid region is calculated and shown in figure 2(f). This transition is simulated with an infinitely thick LN film, since a thinner film would actually assist to vertically confine the mode and reduce the transition loss. The transition loss was calculated by performing a power coupling calculation in Lumerical’s MODE simulation software [47], which often simplifies to the product of the mode overlap with the Fresnel transmission coefficient.

SiN-LN waveguides, due to the fact that SiN has a lower refractive index than that of LN, cannot transition as easily from the non-hybrid region into the hybrid region. One way to reduce these transition losses is to use a bi-layer waveguide approach to pass under the LN edge with minimal excess losses [48]. SiN-LN optical modes at various stages of such a transition, along with simulated transition loss data, are shown in figure 3 for a LN film thickness of 400 nm. The transition losses in figure 3(f) were calculated in the same way that transition losses were calculated in figure 2(f). An extra 600 nm of oxide between the upper
edge of the SiN and lower edge of the LN was added to simulate the blue curve in figure 3(f), as shown in figures 3(b) and (c). Without using the bi-layer waveguide approach (in which case the LN is bonded directly to the SiN), the lowest transition loss is about 2.8 dB per edge, and about 0.3 dB per edge with the bi-layer SiN transition. Alternatively, one could terrace the LN film to reduce transition losses for a single-layer SiN transition [49]. The terraced structures in reference [49] achieved a transition loss of only 0.81 dB per transition, low enough for the SiN-LN platform to be a realistic choice for EOM design. Future SiN-LN waveguides could improve on the state-of-the-art transition loss by using high index SiN core waveguides [50].

2. Electro-optic modulator design

An MZM is a common design used to make electro-optic modulators, and will be used as the modulator design of choice for the analysis in this section. The basic design layout of an MZM is shown in figure 4. For hybrid waveguides, the optical waveguide is formed in the core layer. For bulk LN or thin film LN platforms, the optical waveguide is formed in the LN layer itself.

2.1. Bandwidth and drive voltage

Regardless of whether a Si or SiN core waveguide is used, the design process of a hybrid LN-based EOM is the same in the hybrid region: maximize bandwidth while minimizing the drive voltage. The frequency response of a LN-based EOM is, from reference [51]:

\[
m(\omega) = \frac{R_L + R_G}{R_L} \left[ \frac{(Z_L + Z_0) F(u_+) + (Z_L - Z_0) F(u_-)}{(Z_L + Z_0) \exp[\gamma mL] + (Z_L - Z_0) \exp[-\gamma mL]} \right] \quad (1)
\]

where \( R_L \) is the load resistance, \( R_G \) is the generator resistance, \( Z_{in} \) is the RF line input, \( Z_{o} \) is the characteristic impedance of the EOM, \( Z_G \) is the generator impedance, \( F(u_\pm) = 1 - \exp[u_\pm]/u_\pm \),
Figure 3. (a) Top view of an SOI chip bonded to a LN film. Waveguides can be either in Si (as in figure 2) or SiN. (b)–(d) Cross-section of the simulated optical mode intensity for the SiN non-hybrid waveguide, the SiN-LN hybrid waveguide when the SiN is at its maximum width, and the SiN-SiN-LN hybrid waveguide when a bi-layer transition approach is used [48]. The optical intensities are plotted on a log scale out to 5 orders of magnitude. For these simulations, the LN film is 400 nm thick, the lower SiN layer is 100 nm thick, the upper SiN layer is 200 nm thick, and the oxide gap between the lower SiN and the LN is 600 nm thick. The lower SiN is 4750 nm wide in (b), (c) and 1000 nm wide in (d). (e) Simulated plot of the maximum single-mode SiN waveguide width for a range of SiN heights (in the non-hybrid region). (f) Minimum transition loss under the LN, not accounting for tapers, for a range of SiN heights based on the maximum single-mode SiN widths in (d), (e). '0 nm Oxide' (black curve) corresponds to the simulations in (b)–(d) if the LN film were bonded directly to the upper SiN waveguide and no lower SiN waveguide were present. '600 nm Oxide' (blue curve) corresponds to the simulations in (b)–(d), where 600 nm of oxide exists between the upper edge of the SiN and the lower edge of the LN.

Figure 4. Schematic of a Mach–Zehnder modulator in the push-pull configuration. 'GND' refers to the grounded electrodes in the coplanar waveguide (CPW) transmission line design. $Z_G$ is the impedance of the microwave source and $Z_L$ is the impedance of the microwave load, both of which are typically 50 $\Omega$.

\[ u \pm = \pm \alpha_m L + j \frac{\omega}{c} (\pm n_m - n_o) L, \quad \gamma_m = \alpha_m + j \frac{\omega n_m}{c}, \quad L \text{ is the electro-optical interaction length in meters, } \alpha_m \text{ is the RF propagation loss in units of inverse meters, } \omega \text{ is the angular frequency, } c_0 \text{ is the speed of light in vacuum in meters per second, } n_m \text{ is the RF effective index, and } n_o \text{ is the optical group index. The variable } \alpha_m \]
Figure 5. Simulated plots of the loss-limited electro-optic (EO) frequency response of a Pockels effect MZM, based on equation (3). The stated loss values are in units of dB/(cm-GHz\(^{1/2}\)) and are represented by the symbol ‘\(\alpha\)’, and frequency-dependent losses are assumed to follow a \(\sqrt{f}\) relationship. The dashed gray line represents the 3-dB level, which defines the modulation bandwidth of the device. The electro-optic device length is 1 cm in (a) and 2 cm in (b).

can be converted to units of dB/m by multiplying it by 8.686 in equation (1). The microwave impedance as seen from the input side of the transmission line is

\[
Z_{in} = Z_0 \frac{Z_L + Z_0 \tanh(\gamma_m L)}{Z_0 + Z_L \tanh(\gamma_m L)}.
\] (2)

The electrical 3 dB bandwidth of the modulator is the frequency at which \(m(\omega)\) has dropped to half its dc value.

In this article, we are mainly interested in very high bandwidth modulators. The bandwidth of a LN-based MZM is limited by three things: an index (and therefore velocity) mismatch between the microwave and optical waves, an impedance mismatch between the modulator’s characteristic impedance and the load/generator impedances, and the microwave loss of the modulator. In the case where index matching and impedance matching are both achieved and the majority of microwave losses are due to conductor losses in the metal lines, the frequency response reduces to:

\[
m(\omega) = e^{-A(f)} \left| \frac{\sinh(A(f))}{A(f)} \right|,
\] (3)

where \(A(f) = \frac{\alpha_m(\omega)L}{2}\). Equation (3) is significant in the sense that most high-speed modulators to date, on either bulk LN or thin film LN, have solved the index matching and impedance matching problems [8, 9, 34], but the device with the lowest microwave loss continues to be the bulk LN EOM from 1998 in reference [34]. For example, equation (3) is shown in figure 5 for different levels of microwave loss.

The second metric that must be considered when designing an EOM is the drive voltage of the modulator. The figure of merit commonly used for modulators in the MZI configuration is the halfwave voltage-length product, or \(V_{\pi}L\) [48, 52]:

\[
V_{\pi}L = \frac{n_{ef} \lambda_0 G}{2n_e r_{33} \Gamma_{mo}}
\] (4)

where \(n_{ef}\) is the effective mode index, \(\lambda_0\) is the free-space wavelength, \(G\) is the electrode spacing for the modulator (fundamentally limited by the optical mode width), \(n_e\) is the extraordinary refractive index of LN \((n_e = 2.14 \text{ at a wavelength of } 1550 \text{ nm})\), \(r_{33}\) is a component of the electro-optic tensor with the value of 30.8 pm/V [24], and \(\Gamma_{mo}\) is the normalized overlap between the optical field and the microwave field within the LN region, defined as:

\[
\Gamma_{mo} = \frac{G}{V_A} \frac{\int_{LN} |E_0|^2 |E_m| dA}{\int_{\infty} |E_0|^2 |E_m| dA}
\] (5)

In equation (5), \(V_A\) is the applied microwave voltage, \(E_0\) is the optical field, and \(E_m\) is the microwave field. The factor of 2 in the denominator of equation (4) accounts for the fact that an MZM can be operated in the push-pull configuration, where one arm of the MZM is biased with a positive voltage and the other arm is biased with an equal negative voltage, reducing the voltage requirements of the device by a factor of 2.
Ultimately, the limitations on $V_{zL}$ are how small $G$ can be and how close to 1 $\Gamma_{mo}$ can get. The gap $G$ is limited by the width of the optical mode, which is why a thin film platform—where the reduced film thickness naturally results in smaller mode areas—can result in significantly reduced drive voltages.

In bulk LN, $\Gamma_{mo}$ depends entirely on the electrical design, since all of the optical mode is already in LN. However, for hybrid waveguide geometries it is an interesting design challenge to squeeze as much light as possible into the LN film without increasing the width of the mode too much, or any gains in a larger $\Gamma_{mo}$ will be negated by a disproportionately larger electrode gap. It is also worth mentioning that the electrode gap impacts the index mismatch, impedance mismatch, and microwave loss, all three of which dictate the modulation bandwidth of the device.

2.2. EOM design optimization

Unlike bulk LN modulators, hybrid Si-LN and SiN-LN modulators have several additional design parameters that can be tuned to optimize the device. For example, the shape of the optical mode in a bulk LN modulator can only be varied to a small extent due to the fact that the waveguide is created by indiffusing Ti into bulk LN, resulting in a very slight refractive index difference. In the case of hybrid waveguides, the LN film thickness and the core waveguide height and width can be manipulated over a wide range, with the aim of minimizing $V_{zL}$ or maximizing bandwidth.

When designing a hybrid EOM, a useful approach is to first minimize $V_{zL}$, and then make adjustments to maximize bandwidth from there. This is because the bandwidth can be made large by reducing the modulator length or increasing the electrode gap, but in both cases that large bandwidth will not be accessible due to the large drive voltage requirements.

Accurately modeling $V_{zL}$ requires two simulations: one of the optical field and one of the microwave field, followed by a calculation of the overlap between the two fields. Another approach is to calculate the change in refractive index in the LN as a function of microwave field, but this again requires two simulations for each geometry [53], and simulations involving the microwave field can become quite time-consuming due to the small features of the waveguide layers. For example, the optimized optical simulation used to create figure 7 consisted of approximately 110,000 mesh cells, while the optimized microwave simulation used to create figure 6 below consisted of approximately 4,000,000 mesh cells. For microwave simulations performed at 100 GHz, this means the microwave simulation takes somewhere around 700 times longer than the optical simulation [54].

If $\Gamma_{mo}$ can be calculated directly from the optical simulation, then $V_{zL}$ could be calculated with only one optical simulation. One approach to solving for $V_{zL}$ with a single simulation is shown below.

Consider $\Gamma_{mo}$ in equation (5). If the microwave field in the LN region is perfectly perpendicular to the electrodes and uniform everywhere, equation (5) reduces to the optical confinement factor in LN:

$$\Gamma_{LN} = \frac{\iint_{LN} |E_0|^2 \, dA}{\iiint_{\infty} |E_0|^2 \, dA}$$  \hspace{1cm} (6)

The Weighted Mean Value Theorem (WMVT) can be used to determine the relationship between these two expressions. The WMVT states [55]:

$$\int_a^b f(x)g(x)\, dx = f(c) \int_a^b g(x)\, dx$$  \hspace{1cm} (7)

for some $c$ in $[a, b]$ as long as $f$ is continuous on $[a, b]$ and $g$ is integrable and does not change its sign on $[a, b]$. Equation (7) can be extended to two dimensions and applied to equation (5), resulting in

$$\Gamma_{mo} = \frac{G}{V_A} E_m(c, d) \frac{\iint_{LN} |E_0|^2 \, dA}{\iiint_{\infty} |E_0|^2 \, dA}$$  \hspace{1cm} (8)

where $E_m(c, d)$ is a value of the microwave field at some point $(c, d)$. The fraction on the right-hand side of equation (8) is clearly the expression for $\Gamma_{LN}$ from equation (6), and so we can relate $\Gamma_{mo}$ to $\Gamma_{LN}$ by a ratio $R$:

$$R = \frac{G}{V_A} E_m(c, d) = \frac{\Gamma_{mo}}{\Gamma_{LN}}$$  \hspace{1cm} (9)

An approximation for the minimum electrode gap $G$ can be determined entirely from the optical mode simulation as well, since the gap is limited only by the width of the optical mode. (All simulations in this article were performed using Lumerical’s MODE solver.) If the electrodes are made of gold, the imaginary refractive index at $\lambda = 1550$ nm is calculated to be 11.263 [56], resulting in a length-normalized loss value.
of about 400 dB/µm. To keep the optical mode’s propagation loss below 0.1 dB cm⁻¹, the electric field should be below a fraction of 2.5 × 10⁻⁸ that of the maximum electric field, assuming a Gaussian modal distribution. The minimum gap \( G_{\text{min}} \) can then be roughly approximated as

\[
G_{\text{min}} \geq 6w_{\text{eff}},
\]

where \( w_{\text{eff}} \) is the effective width of the optical mode, and is calculated from the effective mode area \( A_{\text{eff}} \) by assuming the mode has a circular distribution:

\[
w_{\text{eff}} = 2\sqrt{A_{\text{eff}}/\pi}
\]

In that case, \( V_\pi L \) can be calculated and optimized from one optical simulation as

\[
V_\pi L = \frac{n_{\text{eff}}\lambda_0}{2n_c^4\varepsilon_{33}} \cdot \frac{6w_{\text{eff}}}{R_{\text{LN}}}.
\]

Equation (12) was determined by combining equation (4) with equations (9) and (10). Imposing a different loss requirement in place of 0.1 dB/cm would change the number ‘6’ in equation (12) to a different value, but would not affect the form of this equation, or the following discussion.

Since \( R \) depends only on the microwave field, it can be parameterized as a function of electrode gap for different LN film thicknesses according to

\[
R(G) = A + B \exp(-CG + DG) - G.
\]

The waveguide core (Si or SiN) geometry and electrode thickness do not significantly impact \( R \); for example, \( R \) was simulated over the range of electrode heights from 0.1 µm to 20 µm and found to vary by only about 2%. Likewise, \( R \) varied by about 1% over the Si parameter ranges in figure 7 for Si-LN hybrid EOMs, and about 2% over the SiN parameter ranges in figure 10 for SiN-LN hybrid EOMs. However, the absolute value of \( R \)—as well as the minimum \( V_\pi L \) and maximum bandwidth—is somewhat different depending on the core waveguide material.

2.2.1. Silicon-lithium niobate

In the case of a Si core waveguide, the \( R \) value for different LN film thicknesses is shown in figure 6(a), where each curve is fitted to equation (13). The values of the fit parameters are provided in figure 6(b) for all LN film thicknesses. For future designers interested in working with films of thicknesses other than those provided here, a linear interpolation of \( R \) can be used to obtain an approximate value.

It is worth mentioning the source of the relationship between \( R \) and \( G \) in figure 6(a). Each curve has a local maximum for some value of \( G \). This is due to two competing effects: first, as the electrode gap becomes smaller, the microwave field intensity increases in the LN film, increasing the overlap with the optical field. Second, as the gap becomes smaller, the orientation of the microwave field in the LN film becomes less horizontal, and it is the horizontal component of the microwave field (since it aligns with the electrooptic
Figure 7. Si-LN core waveguide simulated parameters for three different LN film thicknesses, denoted in bold above each plot: (a) Minimum $V_{\pi}L$. (b) Lithium niobate modal confinement factor ($\Gamma_{LN}$). (c) Effective mode width ($w_{eff}$). No guided modes exist for some Si-LN waveguides with LN height = 800 nm; these are denoted by a gray region in the rightmost plots. There appear to be no slab modes at LN heights of 600 nm or less for the simulated Si dimensions.

coefficient of interest in the x-cut LN film) that is needed to create a large $\Gamma_{mo}$. This is why there is a local maximum for each curve in figure 6(a).

Using equation (12), $V_{\pi}L$ can be calculated with a single optical simulation for each set of geometric parameters. The minimum $V_{\pi}L$, based on the rough approximation for $G$ from equation (11), for each combination of core width, core height, and LN film thickness, is shown in figure 7 for a Si core. Minimum $V_{\pi}L$ is predominantly a function of $\Gamma_{LN}$ and $w_{eff}$; surface plots of both of these parameters are shown in figures 7(b) and (c), respectively.

From figure 7, the minimum attainable $V_{\pi}L$ in a hybrid Si-LN MZM is 2.3 V-cm for a LN film thickness of 400 nm and a Si core that is in the general vicinity of 350 nm wide by 100 nm thick.

To achieve broadband operation, index mismatch between the optical group index and microwave index must be minimized. In the hybrid structure, the optical group index is determined nearly entirely by the dimensions of the waveguide core and the LN film thickness. Likewise, the microwave index is determined nearly entirely by the width, height, and spacing of the electrodes (almost always in the coplanar waveguide configuration) as well as the substrate material. As an example of how index matching is achieved, consider figure 8. In this case, a single set of electrode parameters (electrode gap, height, and center electrode width) have been chosen while the core width/height and LN film thickness are varied. A 50 nm oxide layer between the LN film and the electrodes is included in the simulation as well; this assists with metal-induced optical propagation losses.

In figure 8, the center electrode is 20 $\mu$m wide, all the electrodes are 0.3 $\mu$m tall, and the electrode gap is set to 8 $\mu$m. Adjusting these parameters will affect the index matching plots of figure 8. The substrate used in these simulations is high-resistivity silicon (instead of LN for traditional bulk LN modulators [34]). The simulated microwave mode is at a frequency of 100 GHz.

The microwave index in figure 8 is simulated at a frequency of 100 GHz, and as long as the CPW is non-dispersive the microwave index will not change significantly with frequency. A typical strategy to achieve low dispersion CPW lines without impacting $V_{\pi}L$ is to increase the cross-sectional area of the center electrode [8, 34, 57].
Figure 8. Index mismatch between the optical group index and the microwave index for the Si-LN hybrid waveguide. Note that these plots are on a logarithmic scale to make it easier to visualize the optimal index matching conditions (white).

![Index mismatch plot](image)

Figure 9. (a) Simulated (circles) and fitted (lines) data of $R$ as a function of electrode gap for different LN film thicknesses for the hybrid SiN-LN EOM. (b) table of fit parameters for the curves of (a), corresponding to equation (13) for a hybrid SiN-LN EOM. For all simulations, electrode thicknesses are 0.5 $\mu$m, the center electrode is 20 $\mu$m wide, and the ground electrodes are 100 $\mu$m wide. As in figure 6, the ‘$R$’ in $R^2$ is not the same ‘$R$’ that is used in (a) and equation (12).

| $h_L$ (nm) | $R^2$ | RMSE |
|------------|-------|------|
| 200        | 0.9974 0.9984 0.9999 |
| 400        | 0.9954 0.9962 0.9971 |
| 600        | 0.9934 0.9942 0.9951 |

2.2.2. Silicon nitride-lithium niobate

In the case of a silicon nitride (SiN) core waveguide, the $R$ value for different LN film thicknesses as calculated by our simulations is shown in figure 9(a). As in figure 6, the fit parameters are provided in figure 9(b) and linear interpolation can be used for LN thicknesses not shown here. $R$ is fitted only for different electrode gaps and LN film thicknesses because the width and thickness of the SiN waveguide do not significantly impact $R$. As will be seen in figure 10, $R$ is calculated for LN film thicknesses up to only 600 nm because no guided optical modes exist for 800 nm thick films.

Similarly to section 2.2.1, minimum $V_\pi L$ plots can be simulated for a SiN-LN waveguide structure using equation (12) and the $R$ values of figure 9. The results of these simulations, along with the corresponding $\Gamma_{LN}$ and $w_{eff}$ data are shown in figure 10. The silicon nitride is assumed to have a refractive index of 2.0 at $\lambda = 1550$ nm. If the refractive index of SiN were higher, it is possible to form guided modes with an 800 nm-thick film of LN. This could be done by using, for example, silicon-rich amorphous SiN [58].

From the results of figure 10(a), the lowest $V_\pi L$ achievable for a SiN-LN hybrid waveguide is about 2.9 V-cm for a LN film thickness of 400 nm and a SiN core that is 900 nm wide by 200 nm thick, though the tolerances on the SiN core geometry are quite large due to the fact that its refractive index is lower than that of the LN film. In any case, the best design for low $V_\pi L$—for a SiN-LN or Si-LN hybrid waveguide—is one in which the geometries are small enough to confine the optical mode within the LN film, but not so small that the optical mode expands (which increases the minimum $G$).

As in section 2.2.1, the index mismatch between a simulated microwave mode at 100 GHz and the optical mode as a function of waveguide geometry can be simulated to demonstrate the effects of waveguide geometry on index mismatch. These simulated data are shown in figure 11. In figure 11 the center electrode is 20 $\mu$m wide, all the electrodes are 0.5 $\mu$m tall, and the electrode gap is 8 $\mu$m. Because SiN has significantly lower material dispersion compared to that of Si, and because the refractive index of SiN is much closer to that of LN than is the refractive index of Si, geometric dispersion for the SiN-LN hybrid waveguide is also lowered. Practically, this means the group index of the SiN-LN hybrid waveguide is lower and less dispersive than that of the Si-LN hybrid waveguide, making it easier to match the optical group index with the microwave phase index for a SiN-LN hybrid waveguide than a Si-LN hybrid waveguide.
Figure 10. SiN-LN core waveguide simulated parameters for three different LN film thicknesses, denoted in bold above each plot: (a) Minimum $V_\pi L$. (b) Lithium niobate modal confinement factor ($\Gamma_{LN}$). (c) Effective mode width ($w_{eff}$). No guided modes exist for SiN-LN modes when the LN height is 800 nm.

Figure 11. Index mismatch between the optical group index and the microwave index for the SiN-LN hybrid waveguide. Note that these plots are on a logarithmic scale to make it easier to visualize the optimal index matching conditions (white).

2.3. Microwave design
While the simulated results of figures 8 and 11 assume static electrical parameters to demonstrate the effects of optical waveguide design on index matching, in reality the electrode parameters play an important role when designing a high-bandwidth MZM. The three properties of a microwave signal that impact the MZM bandwidth, from equation (1), are microwave index ($n_m$), characteristic impedance ($Z_0$), and loss ($\alpha_m$). How these parameters change based on electrode geometry are shown in figure 12 for an electrode height of 1 µm. For example, instead of tuning the optical waveguide dimensions to achieve index matching in figures 8 and 11, the microwave index can be adjusted (figure 12(a)) by changing the center electrode width or the electrode gap.

Impedance matching can be done by adjusting the electrode parameters as well. Figure 12(b) shows simulated plots of how the characteristic impedance of the traveling wave structure changes with electrode...
gap and center electrode width (for gold electrodes). Generally, 50 Ω is the target impedance (denoted in figure 12(b) by a horizontal dashed black line) because that is often the impedance of the source generator and most off-the-shelf microwave load resistances. If the impedances are mismatched, some amount of microwave power will be reflected back along the line. If enough power is backreflected due to a poor impedance mismatch, electronic components may be damaged. However, if the characteristic impedance is made to be slightly larger than the load resistance, the bandwidth of the modulator will actually increase slightly [51].

The ever-present limiting factor on a modulator’s bandwidth is microwave loss. Conductor loss due to the presence of the electrodes scales with the square root of frequency, but at higher frequencies the SiO$_2$ buffer layer, the Si substrate, and even the LN film can be sources of a significant dielectric loss that scales linearly with frequency [59]. Hybrid and thin-film LN EOMs provide enough design parameters to achieve good index matching and impedance matching while maintaining a lower $V_\pi L$ than bulk LN EOMs [8, 9], but microwave losses will always be present. Fortunately, microwave losses can be mitigated by choosing low-loss substrates, such as high-resistivity Si instead of low-resistivity Si [8], high-quality oxide buffer layers, and (for THz modulation speeds) stoichiometric LN thin films instead of congruent LN thin films [60]. Microwave loss for various electrode parameters is simulated in figure 12(c).

2.4. Requirements for a 1 V—100 GHz modulator
While wide bandwidth operation on a compact platform has been of interest for the past several decades, recent results prove wide bandwidth EOMs can be fabricated using LN thin films [7–9]. The frequency responses of optimized Si-LN and SiN-LN devices are shown in figure 13. In figure 13(a), the Si-LN hybrid EOM has an electrode height of 1 μm, a gap of 8 μm, a Si feature that is 200 nm wide by 100 nm tall, and a 600 nm thick LN film. In figure 13(b), the SiN-LN EOM has an electrode height of 1 μm, a gap of 8 μm, a SiN feature that is 900 nm wide by 200 nm tall, and a 600 nm thick LN film. In both cases, microwave losses at 100 GHz are around 6 dB/cm, index mismatch is less than 1.5%, and $Z_0$ (averaged across the full simulated frequency range) is approximately 51 Ω. These devices could be further improved by operating at lower wavelengths, partially etching the LN film to reduce the effective width of the optical mode, or adding an oxide buffer layer between the Si or SiN and the LN to reduce the optical group index [7–9].

Given the optimized frequency response curves of figure 13, one can ponder what sorts of modulation bandwidths can be achieved when $V_\pi = 1$ V, the maximum amount of voltage often available from CMOS driver circuits [61]. $V_\pi = 1$ V is an important requirement, because a modulator operated at $V_\pi$ can achieve full extinction ratio and maximum signal-to-noise ratio (SNR).

In the case where—such as in figure 13—index matching and impedance matching have both been achieved or very nearly achieved, the loss-limited bandwidth of a modulator is described by equation (3), which is a function of device length $L$. From equation (12), $L$ is

$$ L = \frac{n_{df} \lambda_0 G}{2 n_{e} r_{33} R T_{LN} V_\pi}, \quad G \geq 6 \cdot w_{df}. \quad (14) $$
Figure 13. (a) Plots of $V_\pi$-limited frequency response curves for $V_\pi$ equal to 1 V (black), 2 V (blue), and 3 V (red) for: (a) the hybrid Si-LN waveguide, where the Si is 200 nm wide by 100 nm thick, the LN film is 600 nm thick, and the optical propagation losses are 3 dB/cm; and (b) the hybrid SiN-LN waveguide, where the SiN is 900 nm wide by 200 nm thick, the LN film is 600 nm thick, and the optical propagation losses are 0.8 dB/cm. The 3-dB electrical bandwidth is shown next to each curve of the same color.

equation (14) can be combined with the expression for $A(f)$ provided in section 2, resulting in the following:

$$A(f) = \frac{\alpha_m(f) n_{\text{eff}} \lambda_0 G}{4r_S r_M \Gamma_{\text{LN}} V_\pi}$$

(15)

where $\alpha_m(f)$ is the linear loss of the microwave mode at the frequency $f$. When $\lambda_0 = 1.55 \, \mu\text{m}$, equation (15) reduces to

$$A(f) = \frac{600 [\text{V}]}{V_\pi} \cdot \frac{\alpha_m(f) n_{\text{eff}} G}{\Gamma_{\text{LN}}}.$$  

(16)

From equation (3), to reach a 3 dB modulation bandwidth of 100 GHz, $A(f)$ must be equal to or less than 0.368 when $f = 100 \, \text{GHz}$, and so

$$\alpha_m(f) \leq \frac{V_\pi}{1630 [\text{Volts}]} \cdot \frac{\Gamma_{\text{LN}}}{n_{\text{eff}} G}.$$  

(17)

keeping in mind that $\alpha_m$ is in units of $[\text{m}^{-1}]$ and can be converted to units of $[\text{dB/m}]$ by multiplying it by a factor of 8.686. In equation (17), $\Gamma_{\text{LN}}$ can be replaced by $\Gamma_{\text{mol}}$. In figure 13, $R$ and $\Gamma_{\text{LN}}$ are limited to about 0.75 and 0.88, respectively, while $n_{\text{eff}}$ and $G$ are typically around 1.95 and 8 $\mu\text{m}$. Using equation (17), these values predict that a maximum microwave loss of about 2.2 dB/cm at 100 GHz is required to achieve $V_\pi = 1$ V at 100 GHz for a LN-based EOM at $\lambda_0 = 1550 \, \text{nm}$. This means, to push the $V_\pi = 1$ V (black) curves in figure 13 out to a bandwidth of 100 GHz, microwave losses need to be reduced from 0.6 dB/(cm-GHz$^{1/2}$) to 0.22 dB/(cm-GHz$^{1/2}$), assuming microwave losses scale as $f^{1/2}$ due to electrical conductor losses [8, 34].

Achieving 0.22 dB/(cm-GHz$^{1/2}$) microwave loss is nontrivial; the lowest microwave loss ever reported for an index-matched and impedance-matched LN-based EOM is about 0.28 dB/(cm-GHz$^{1/2}$) [34], and that device had a much larger $w_{\text{eff}}$ and, thus, $G$. Of course, this does not preclude the possibility of reducing microwave losses. One can imagine depositing thicker and/or higher-quality metal layers to bring down microwave losses, or depositing superconducting films in place of traditional metals. It may even be possible to increase the electro-optic coefficient, and thereby increasing the microwave loss requirement, by using different lithium niobate crystal compositions [62].

In the best-case theoretical scenario where $R = 1$ and $\Gamma_{\text{LN}} = 1$, the maximum allowable microwave loss at 100 GHz increases to 0.33 dB/(cm-GHz$^{1/2}$). Achieving unity or near-unity values for $R$ and $\Gamma_{\text{LN}}$ may be achievable by lightly etching the LN film for enhanced optical mode confinement, or etching grooves into the hybrid structure prior to metal deposition to increase the electrical-optical mode overlap.

This simple analysis suggests it may be possible to achieve a 3-dB modulation bandwidth of 100 GHz with only 1 V operating voltage if microwave losses can be sufficiently reduced.

2.5. Optimal film thicknesses for telecommunications applications

In the scenario where hybrid Si-LN EOMs are used for telecommunications, it is interesting to consider what single combination of Si and LN layer thicknesses are optimal across the full telecommunication wavelength range of 1260–1675 nm. Such an optimized material platform would allow for the integration of EOMs from
the O band (1260–1360 nm) all the way out to the U band (1625–1675 nm) on the same die. It could also provide designers with a standard of performance upon which to build more complex integrated components.

As discussed in section 2.2, one approach to optimizing a hybrid Si-LN EOM is to minimize $V_\pi L$. However, a good hybrid design should also minimize non-hybrid/hybrid transition losses across the 1260–1675 nm window. Because the optical mode at 1675 nm will be the largest—and thus exhibit the largest transition loss—of all the wavelengths being considered for a given geometry (simply based on the fact that 1675 nm is the longest wavelength in the telecom range), that wavelength can be used to determine the minimum Si layer thickness.

A reasonable maximum allowable transition loss of 0.2 dB per transition is used in this analysis. In that case, the smallest Si waveguide height that results in $\leq 0.2$ dB transition loss for a single-mode waveguide is found to be 150 nm, as per the method described in figure 2(f). A plot of minimum transition loss versus wavelength, based on this Si height, is shown in figure 14(a).

Next, to determine the optimal LN thickness, $V_\pi L$ is calculated for a range of Si widths and LN thicknesses at the maximum wavelength ($\lambda = 1675$ nm), shown in figure 14(b). The minimum $V_\pi L$ for this wavelength occurs when the LN film is 400 nm thick. In this case, $V_\pi L = 2.8$ V-cm.

The maximum wavelength can be used here because $V_\pi L$ varies linearly with wavelength, meaning—if all else is kept the same—$V_\pi L$ of an EOM at 1675 nm should be about 33% higher than the $V_\pi L$ of an EOM at 1260 nm. But, the situation is actually more severe than that at longer wavelengths; the electrode gap $G$ is fundamentally limited by the width of the optical mode, which also increases with wavelength. For these reasons, an EOM at the maximum wavelength will determine the best LN film choice.

These simulations result in a Si thickness of 150 nm and a LN thickness of 400 nm. A single-chip designed for the full telecom range can then be designed with a variable Si width defined by photolithography and dependent upon the wavelength of interest. Using these film thickness parameters, a plot of $V_\pi L$ as a function of operating wavelength and Si width is shown in figure 14(c).

$R$ values for a LN film that is 400 nm thick are shown in figure 15(a) at wavelengths of 1260 nm and 1675 nm, and the corresponding fit parameters are provided in figure 15(b). For a LN thickness of 400 nm, $R$ increases by only 2% from 1260 nm to 1675 nm, so $R$ values at $\lambda = 1260$ nm are used at all wavelengths in figure 14(c).

A minimum $V_\pi L$ factor of 1.6 V-cm is found at the minimum wavelength of 1260 nm in figure 14(c). This is not necessarily the minimum value of $V_\pi L$ at that wavelength; instead, it represents the minimum $V_\pi L$ that is achievable on a single chip that can also support acceptable EOMs ($V_\pi L = 2.8$ V-cm at $\lambda = 1675$ nm). At this point, application-specific devices can be designed based on bandwidth, modulation depth, power, and device footprint requirements.

Alternatively, a 600 nm thick LN film can be used for high bandwidth devices at minimal cost to $V_\pi L$. From figure 14(b), the minimum $V_\pi L$ value at a wavelength of 1675 nm increases from 2.8 to 2.9 V-cm when increasing the LN film thickness from 400 nm to 600 nm. With this thicker LN film and the same design approach described in section 2.2 and section 2.3, a maximum modulation bandwidth of 122 GHz is calculated at $V_\pi = 3$ V ($V_\pi L = 3.8$ V-cm). Due to the fact that $V_\pi L$ scales inversely with wavelength, the maximum bandwidth at $V_\pi = 3$ V for any wavelength shorter than 1675 nm will be larger than 122 GHz in a hybrid Si-LN MZM.
Figure 15. (a) R values when LN is 400 nm thick at wavelengths of 1260 nm (blue curve) and 1675 nm (black curve). (b) Table of fit parameters for the curves in (a), using equation (13).

Figure 16. A flowchart depicting the fabrication process for hybrid Si-LN EOMs. The slicing approach is shown on the left branch while the separation approach is shown on the right. Shared steps are shown in the middle.

3. Device fabrication

Unlike bulk LN EOMs, hybrid Si-LN (or SiN-LN) EOMs rely on particular dimensions and tolerances of the material layer geometries. Such accuracy of layer thickness and feature width-spacing were not available 20 or 30 years ago, and even just a decade ago there was a dearth of commercially-available LN thin films. Since then, companies such as NanoLN (Jinan Jingzheng Electronics Co. Ltd.) have provided high quality wafers of lithium niobate-on-insulator (LNOI), accelerating the development of LN thin film-based technologies for researchers and commercial organizations alike.

Over the past few years, two approaches have been developed to fabricate hybrid Si-LN EOMs. We are calling these two approaches ‘Slicing’ and ‘Separation’; the full fabrication process flow for each approach is shown in figure 16, and step-by-step explanations of each approach are provided below.

Both approaches begin by patterning the SOI waveguide layer, whether it be Si or SiN. That layer is then planarized in one of three ways: by providing fill features during the etch (assuming the SOI surface is
sufficiently smooth [29, 63]), depositing and polishing a transparent cladding layer, or spin-coating a polymer cladding layer [64, 65].

In the slicing approach, a second wafer of bulk LN of the desired cut is then implanted with a certain dose and energy (which determines final film thickness) of ions, usually either hydrogen or helium [66, 67]. Next, the implanted bulk LN is bonded to the patterned, planarized SOI. After bonding, the sample is annealed to strengthen the bond as well as to ‘slice’ off the majority of the bulk LN, leaving a thin film whose thickness is determined approximately by the ion implant depth [67, 68]. The exposed, sliced LN film is then planarized to reduce slicing-induced roughness or crystalline damage.

In the separation approach, the planarized SOI is bonded to LNOI and then thermally annealed [5, 66, 69–73]. LNOI consists of a LN thin film pre-bonded to an oxide cladding on a substrate, preferably Si to mitigate thermal stress [74]. The LNOI handle and oxide clad are then removed to expose the backside of the LN film [7, 8].

Finally, in both approaches, electrodes are patterned on the LN film using standard photolithography processes. Both gold and aluminum have been used to create electrodes for LN EOMs [7–9, 34]. Due to its higher conductivity and inertness, gold is the preferred choice for electrodes. However, gold is significantly more expensive than aluminum, and as a result thick gold films—on the order of 500 nm or thicker—require electroplating. This adds an extra step to the fabrication process compared with the fabrication of aluminum electrodes. Although they do oxide, aluminum electrodes which can be made fairly thick (on the order of microns) in a single deposition step, and the oxidation is not significant enough to make the devices inoperable [8].

The Slicing and Separation fabrication approaches will be more or less advantageous depending upon their use cases. For example, the Slicing approach requires more fabrication steps, but if it is developed in-house then custom film thicknesses and areas can be realized. There is also no handle removal process, which can be challenging to realize and result in a lower overall device yield. This may be especially useful for wafer-scale production, where wafer bonding tools are readily available and high throughput is required. However, LN processing would be need to be available, something most foundries do not have at present.

On the other hand, the Separation approach is simpler to implement due to the fact that the LNOI material is already provided by an external supplier, so the only additional challenge for device realization is handle removal, which can be non-trivial. The Separation approach is recommended for applications where low yield is acceptable, such as research and development laboratories.

4. Demonstrated modulator performance

Perhaps the most compelling reason to use any type of lithium niobate modulator—whether it be bulk LN, thin film LN, or hybrid Si-LN—is due to the intrinsically high-speed switching/modulation capabilities of noncentrosymmetric materials exhibiting the Pockels effect. However, there are a couple of ways to describe the modulation speed of an electro-optic modulator that can be easy to confuse. The actual ‘speed’ of the microwave signal transmitting along the modulator is the speed of light divided by the microwave group index, which puts the speed of transmission somewhere around half the speed of light. What’s more important, and what is commonly referred to as modulation or switching ‘speed’ is in fact the bandwidth of the device, and the 3-dB bandwidth in particular (that is, the frequency point at which the response drops below half that of the dc value).

There are two types of 3-dB bandwidth commonly referred to in literature: the electrical 3-dB bandwidth and the optical 3-dB bandwidth. Due to the fact that optical power is converted to electrical current squared at a photodetector, the optical 3-dB bandwidth is equivalent to the 6-dB electrical bandwidth. When referring to the ‘bandwidth’ of an electro-optic modulator, the 3-dB electrical bandwidth is preferred, as it is the 3-dB bandwidth measured out of the photodetector and is therefore the bandwidth from the point of view of an electrical system.

To date, the largest 3-dB electrical bandwidth in a hybrid Si-LN EOM is in a Mach-Zehnder modulator configuration and was shown to extend beyond 106 GHz from reference [8]. The measurement was equipment-limited, but a projection of the measured data suggests the bandwidth could be beyond 200 GHz. Such a high bandwidth was achieved by satisfying the velocity matching and impedance matching constraints outlined in section 2.2 while minimizing microwave losses. The bandwidth was ultimately limited by microwave losses, which are due primarily to the Si substrate and metal electrodes used to guide the microwave signal.

Extremely low drive voltage EOMs have been shown in the Si-LN platform as well. By partially etching the LN film, it is possible to achieve better optical mode confinement in the LN film than is possible by guiding the mode solely with a Si rib. In this case, it is even possible to tapered away the Si rib in the hybrid region as was done in reference [7], where a $V_{\pi} L$ factor of only 1.2 V-cm was achieved in a MZM.
configuration. The large bandwidth of reference [8] and low $V_L\cdot L$ of reference [7] represent the best results, respectively, of any LN-based modulator to date of which the authors are aware.

An alternative modulator technology in the LN thin film platform is ring modulators, which can be made orders of magnitude smaller than conventional MZM, though—as with Si ring modulators—they can only operate near their resonance wavelengths and have limited extinction ratios and bandwidths.

A table of notable LN-based modulators operating at $\lambda = 1550$ nm are shown in table 1. A variety of material platform have been considered and tested. The result of reference [34] represents the highest bandwidth device in bulk LN, and is included as a reference point.

5. Possible future directions

The previous sections mainly discuss MZI EOMs based on the hybrid Si- or SiN-LN material platform at telecommunication wavelengths. As lithium niobate is transparent at wavelengths from 400 nm to 5 $\mu$m [39], the operational wavelength range of the hybrid EOMs can be much broader than the telecommunications spectral range. Visible wavelength EO modulators have a wide variety of applications ranging from visible-light communication [79] and holography [80], to optogenetics [81] and optical biosensors [82]. In addition, as $V_L$ is proportional to the operational wavelength, $V_L$ of EOMs working at visible wavelengths should be much smaller compared to those in the near-infrared regime. Recently, a visible-wavelength EOM was demonstrated with a 10 GHz bandwidth and 1.6 V-cm $V_L$ using the etched LN thin film waveguides [83]. As is mentioned by the authors, the modulation bandwidth in that report can be further improved by optimizing the design of the coplanar transmission lines.

For hybrid EOMs, due to the intrinsic material absorption at wavelengths below 1.1 $\mu$m, Si is no longer a suitable material for the loading waveguide. Instead, SiN can be a promising candidate here since it is CMOS compatible and can provide a relatively high index contrast to the cladding material (i.e. SiO$_2$). Based on this SiN-LN waveguide platform, efficient wavelength converters have been realized [84,85], which convert light from telecommunication bands to visible wavelengths.

Mehta et al have demonstrated a SiN rib-loaded LN thin film hybrid EOM with $V_L$ less than 0.5 V-cm [86] at a wavelength of 674 nm, but bonded SiN-LN modulators are yet to be realized. As mentioned in section 1.1, bonded SiN-LN modulators can experience excess vertical mode transition loss at the hybrid/non-hybrid transition region due to the relatively low material index contrast between the waveguide core (SiN) and the slab (LN). Several novel designs have been brought up to address this problem, such as two-layer SiN tapers [87], terraced transition structures [49], and using thick SiN fabricated based on the photonic Damascene process [88].

Modulators working in the mid-infrared (mid-IR) regime (3–8 $\mu$m) have also been demonstrated in recent years [89, 90], based on bulk LN. The challenge of using the Si-LN platform described here for MIR modulators is the strong intrinsic material absorption of SiO$_2$ at wavelengths beyond 3.5 $\mu$m. Possible solutions include fabricating suspended Si waveguides [91], using Si-on-sapphire waveguides [92], and optimizing the waveguide geometry by minimizing the optical mode overlap with SiO$_2$ [93]. The design considerations discussed in the previous sections ($V_L$ optimization, index matching, impedance matching, and microwave loss minimization) can be readily extended to the visible and mid-IR wavelengths. Therefore, we can expect hybrid Si-LN or SiN-LN EOMs at wavelengths beyond the near-IR regime in the near future.

The biggest advantage of the hybrid platform described here is the potential for integration. The versatility of lithium niobate is highly beneficial for the integration of multi-functional building blocks. Another potential use case is periodically poled LN thin films, which can be used in hybrid MZMs to achieve wider bandwidths, lower $V_n$, and lower chirp [94–97]. Furthermore, the frequency response of the modulators can be tailored with aperiodic inverted domain structures [94, 95]. These modulators can be integrated on the same material platform as hybrid non-linear optical devices, and even fabricated in the same steps. Large arrays of these devices could prove useful for applications requiring multiple modulators or phase shifters on the same die, such as solid-state photonic beam steering [98].

Polarization modulators are also important components in advanced optical communications, and can be used for wavelength multiplexing or demultiplexing [99–101]. Similarly, high operating frequency can be achieved using QPM [101]. In addition, the hybrid structure discussed here brings more design freedom to achieve the phase-matching condition.

In recent years, electro-optical phase modulators based on bulk LN have become more widely used in quantum communication systems for frequency conversion of single-photons [102, 103]. Meanwhile, high quality photon-pair sources have been demonstrated through spontaneous parametric down conversion (SPDC) in periodically-poled and dry-etched LN thin film waveguides [104–106]. In the same way, SPDC can be expected from periodically-poled hybrid SiN-LN waveguides. This will enable the integration of photon-pair sources with electro-optic modulators, which is advantageous to reduce the total insertion loss.
Table 1. Table listing relevant LN-based modulators. SiN = silicon nitride, ChG = chalcogenide, a-Si = amorphous silicon, MIM = Michelson Interferometer Modulator, SFDR = spurious free dynamic range at 1 GHz, $\alpha$ = optical propagation loss, $A$ = device area (only the modulation region), and asterisks indicate values that were estimated when exact numbers were not provided. IL = fiber-to-fiber insertion loss.

| Reference | Year | Platform             | EOM Type | BW (GHz) | $V_\pi$ (V) | $L$ (cm) | ER (dB) | SFDR (dB-Hz$^{2/3}$) | $\alpha$ (dB/cm) | $A$ (mm$^2$) | IL (dB) |
|-----------|------|----------------------|----------|----------|-------------|----------|---------|----------------------|-----------------|-------------|---------|
| [75]      | 2019 | LN Film on SOI       | MIM      | 17.5     | 12          | 0.1      | 38      | N/A                  | 0.3             | 0.08        | 12.4    |
| [7]       | 2019 | LN Film on SOI       | MZM      | 70       | 5.1         | 0.5      | 48      | 99.6                 | 0.98            | 0.41        | N/A     |
| [8]       | 2018 | LN Film on SOI       | MZM      | >106     | 13.4        | 0.5      | 25      | N/A                  | 0.6             | 1.27        | 13.6    |
| [9]       | 2018 | LN Film              | MZM      | 82       | 4.4         | 0.5      | 30      | N/A                  | 0.2             | 2.19        | 10.5    |
| [11]      | 2016 | SiN on LN Film       | MZM      | N/A      | 3.87        | 0.8      | 18      | 97.3                 | N/A             | 0.44        | N/A     |
| [76]      | 2016 | SiN on LN Film       | MZM      | 8        | 2.53        | 1.2      | 13.8    | N/A                  | 7               | 0.96        | >20     |
| [10]      | 2015 | ChG on LN Film       | MZM      | 1        | 6.33        | 0.6      | 15      | N/A                  | 1.2             | 0.36$^*$     | N/A     |
| [6]       | 2015 | LN Film on SOI       | Ring     | 7.5      | N/A         | N/A      | N/A     | 98.1                 | N/A             | N/A         | N/A     |
| [77]      | 2014 | LN Film on SOI       | Ring     | 5        | N/A         | N/A      | 5.2     | N/A                  | N/A             | 0.0007      | 4.3     |
| [78]      | 2014 | a-Si on LN Film      | MZM      | 2.5      | 110         | 0.08     | 20      | N/A                  | 3               | 0.064$^*$    | N/A     |
| [57]      | 2013 | LN Film              | MZM      | 24       | 2.5         | N/A      | N/A     | N/A                  | N/A             | N/A         | N/A     |
| [34]      | 1998 | Bulk LN              | MZM      | 69       | 5.1         | 2        | 20      | N/A                  | N/A             | 4.46$^*$     | 5.6     |
as well as the stability requirements for larger systems. Taken together, the large design freedom along with the various functionalities of this hybrid material platform promise many possibilities. The hybrid EOMs discussed here can be integrated easily with other building blocks such as frequency converters, polarization rotators, as well as entangled photon-pair sources, while sharing the same material platform.

### 6. Conclusion

The electro-optic modulator field is undergoing a revolution thanks to the recent availability of high-quality thin films of lithium niobate. By building modulators on an integrated, thin film platform, lower drive voltages, higher bandwidths, and more compact modulators have been demonstrated [6–9]. Thin films can also be bonded to a variety of substrates for heterogeneous integration without damage to the films themselves [74], a flexibility in fabrication that is not available in bulk LN modulator platforms and could lead to wafer-scale hybrid modulator development.

This review paper covered recent progress in the field, as well as design and fabrication considerations important for development of the hybrid Si-LN or SiN-LN modulator platform. An equation for the halfwave voltage-length product that can be evaluated with a single optical simulation is also presented in section 2.2. Layer thicknesses for a single platform optimized for best performance across the entire telecommunication wavelength range (1260–1675 nm) are suggested in section 2.5, and a sampling of future hybrid technologies at visible and mid-infrared wavelengths are considered in section 5. These recent advances in electro-optic modulators suggest an exciting future of novel device concepts and applications lies ahead.

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