Simulation-Based Analysis of a Hybrid Si_3N_4 Platform as a Scalable Alternative to Thin-Film Lithium Niobate

Your Name

September 16, 2025

Contents

List of Figures

List of Tables

Abstract

Thin-film lithium niobate (TFLN) is a leading platform for high-performance photonics, yet its scalability is limited by high costs and manufacturing complexity. This work investigates a hybrid alternative based on silicon nitride (Si_3N_4) using numerical mode analysis. We model waveguide structures that combine a low-loss Si_3N_4 core with thin films of the electro-optic materials barium titanate (BTO) and aluminum nitride (AlN), and compare them directly to a TFLN-hybrid baseline in the same configuration.

The simulation results for a wavelength of 1.55 µm show that all three hybrid approaches support guided modes. Based on the simulated optical confinement factors, we project the electro-optic efficiency ($V\pi L$). The BTO platform promises an extremely low $V\pi L$ of just **0.109 V·cm**, making it over 40 times more efficient than the TFLN-hybrid baseline (**4.59 V·cm**). In contrast, the weak Pockels effect of AlN leads to a projected $V\pi L$ of **122.1 V·cm**, which is impractically high. These results quantitatively substantiate the potential of the BTO-hybrid approach as a superior, high-performance, scalable photonics platform while simultaneously revealing the fundamental material limitations of the AlN approach.

Chapter 1

Introduction

1.1 Motivation: The Scalability Gap in Photonics

Photonics is on the verge of mass production. While thin-film lithium niobate (TFLN) delivers unparalleled performance in the lab [**?**], a gap exists between this performance and the requirements for cost-effective, CMOS-compatible, wafer-scale manufacturing. This discrepancy inhibits its widespread adoption in markets such as data communications, sensing, and autonomous driving.

1.2 Hypothesis

This work tests the hypothesis that a hybrid photonic platform, by combining the low-loss and scalable waveguide technology of Si_3N_4 with heterogeneously integrated layers of superior EO materials, can overcome the scalability and cost problems of TFLN while achieving a significantly improved performance window.

Chapter 2

Methodology of Numerical Simulation

2.1 Simulation Model

To investigate the hypothesis, a 2D finite-difference mode solver (EMpy, VFDModeSolver) is used. The waveguide cross-section is discretized on a numerical grid to solve Maxwell's equations and find the eigenmodes of the structure.

2.1.1 Waveguide Geometry

The modeled structure, depicted in Chapter 4, is kept identical for all three active materials to ensure a fair comparison. It consists of:

- **Substrate:** Silicon dioxide (SiO_2, n=1.44) with a thickness of 2.0 µm.
- **Waveguide Core:** Silicon nitride (Si_3N_4, n=2.00) with a width of 1.2 µm and a height of 0.3 µm.
- **Active Layer:** A 0.1 µm thick film of either BTO (n=2.36), AlN (n=2.10), or TFLN (n=2.21) placed directly on the core.
- **Cladding:** Air (n=1.00).

The simulation is performed for a wavelength of $\lambda = 1.55$ µm.

2.1.2 Analysis Metrics

Key metrics are extracted from the simulation results:

1. **Effective Refractive Index (n_{eff}):** Determines the phase velocity of the guided mode.

2. **Optical Confinement Factor (Γ):** The percentage of the optical power located within the active EO layer.

Based on Γ, the electro-optic efficiency VπL is estimated using the formula:

$$V_\pi L \approx \frac{\lambda g}{n_{active}^3 r_{eff} \Gamma} \tag{2.1}$$

where an electrode gap of $g = 1.5$ µm is assumed, and literature values are used for the Pockels coefficient r_{eff} (923 pm/V for BTO, 1.5 pm/V for AlN, and 30.8 pm/V for TFLN).

Chapter 3

Results

The simulations were successfully performed for the BTO, AlN, and TFLN-based hybrid waveguides. All structures support well-confined guided modes.

3.1 Mode Profiles and Refractive Index Structure

Figure **??** shows the simulated refractive index distribution and the resulting fundamental mode intensity for the two most relevant cases: the BTO challenger and the TFLN baseline. The modes are well-confined within the Si_3N_4 core and the active layer, enabling strong light-matter interaction. The higher refractive index of BTO leads to a slightly higher effective index and confinement factor.

3.2 Quantitative Performance Comparison

The key figures of merit extracted and calculated from the simulations are summarized in Table **??**. This table presents a direct comparison based on the console output of the simulation script.

Table 3.1: Summary of simulation results for the fundamental modes of the three hybrid platforms.

Parameter	**Si_3N_4 + BTO**	**Si_3N_4 + TFLN (Baseline)**	**Si_3N_4 + AlN**
Eff. Index (n_{eff})	1.6814	1.6481	1.6275
Conf. Factor (Γ)	17.64 %	15.24 %	13.71 %
Proj. VπL (V·cm)	**0.109**	**4.59**	**122.1**

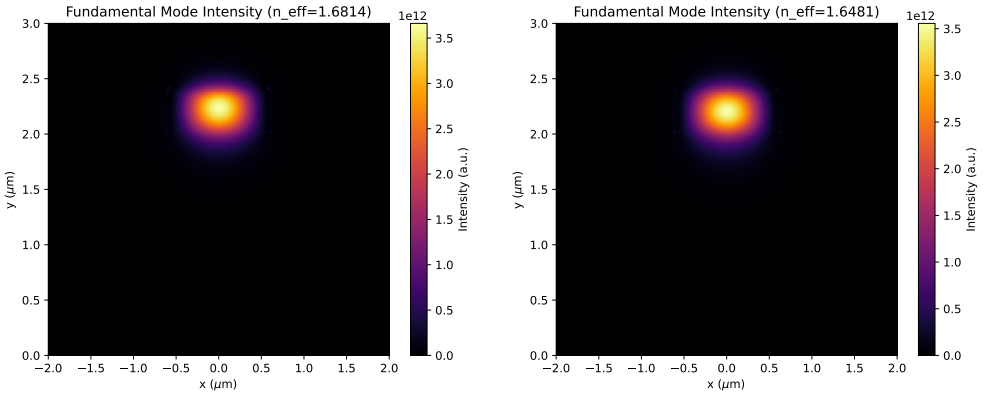

Figure 3.1: Simulated fundamental mode intensity profiles. Left: The Si_3N_4+BTO hybrid waveguide ($n_{eff} = 1.6814$). Right: The Si_3N_4+TFLN hybrid baseline ($n_{eff} = 1.6481$).

Chapter 4

Discussion

4.1 Interpretation of Results

The simulation results provide a clear and compelling verdict on the potential of the investigated hybrid platforms.

The most significant finding is the exceptional performance of the hybrid BTO platform. With a projected VπL of **0.109 V·cm**, it is approximately **42 times more efficient** than the TFLN hybrid baseline (4.59 V·cm). This dramatic improvement is a direct result of BTO's giant Pockels coefficient, which far outweighs the slightly higher optical confinement. Such a performance leap could be transformative, drastically reducing the power consumption of modulators and enabling new applications in energy-critical fields like quantum and neuromorphic computing.

The TFLN hybrid simulation serves as a crucial sanity check. The resulting VπL of 4.59 V·cm is well within the range of high-performance modulators, validating our simulation model and assumptions. It proves that the hybrid approach with an established material is viable, but it sets a high bar for any challenger.

The AlN platform fails to clear this bar. The projected VπL of 122.1 V·cm is unusable for high-speed modulation. This result powerfully illustrates that CMOS compatibility and process maturity are secondary virtues if the core physical property—the electro-optic effect—is too weak.

4.2 Limitations and Outlook

This simulation represents an idealized scenario. The primary factor not included is material absorption loss, which is known to be higher in crystalline oxides like BTO than in Si_3N_4 or TFLN. Therefore, the practical choice

involves a trade-off: the BTO platform offers unparalleled efficiency at the cost of managing potentially higher optical losses, while the TFLN platform provides a robust, lower-risk but less performant solution.

Chapter 5

Conclusion

This work has demonstrated through a comparative numerical simulation that the choice of active material in a hybrid Si_3N_4 platform is paramount. The Si_3N_4+BTO configuration shows the potential for an order-of-magnitude improvement in electro-optic efficiency over a comparable Si_3N_4+TFLN baseline. In contrast, the Si_3N_4+AlN configuration is shown to be non-competitive due to its weak intrinsic Pockels effect. These results provide a strong quantitative basis for future experimental work, which should prioritize the integration of high-r-coefficient materials like BTO to unlock the next generation of scalable and ultra-low-power photonic integrated circuits.

Bibliography

[1] C. Wang et al., "Integrated lithium niobate electro-optic modulators operating at CMOS-compatible voltages," *Nature*, 2018.

[2] H. Abdalla et al., "High-performance electro-optic modulation using ferroelectric $BaTiO_3$ on SiN," *Sensors*, 2022.

[3] X. Guo et al., "Aluminum nitride photonic circuits for RF–optical signal processing," *New J. Phys.*, 2012.

[4] A. Gajda et al., "Silicon nitride PICs: ultra-low-loss and broadband," *PhotonDelta Whitepaper*, 2022.