Improving efficiency of LNOI terahertz waveguide via geometry optimisation

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Introduction

Densely populated cities are highly vulnerable to infectious disease outbreaks. The COVID-19 pandemic highlighted the need for advanced, non-invasive diagnostic tools. Terahertz (**THz**) sensing offers promise for rapid virus screening, as THz waves penetrate many opaque materials and have low photon energies, making them suitable for biological detection [1, 2].

A key challenge is strong molecular absorption, which attenuates THz signals in air [4]. Thin-film lithium niobate on insulator (LNOI) waveguides provide a promising detection platform, with large electro-optic (EO) coefficients and strong phase-matching potential [5]. Detector geometry—film thickness, modulator length, and spacing—directly influences phase matching and optical confinement, both critical for weak THz signals.

This project investigates optimal electrode-less LNOI waveguide geometries to balance confinement and phase matching, enabling efficient, sensitive THz sensing for healthcare applications.

Related Work

Prior work on lithium niobate (LN) waveguides has established the feasibility of electrode-less electro-optic (EO) sensing. Gutiérrez-Martínez et al. [3] modeled and experimentally characterized LN waveguides as dielectric field sensors, showing EO response without electrodes. More recently, Wilke et al. [5] demonstrated a thin-film LN EO THz detector, validating LNOI-based detection with near-infrared probes. While much of the literature focuses on modulators, their geometric analysis remains relevant: studies on high-speed LNOI modulators provided methods to calculate refractive index change (Δn) and showed how film thickness, ridge width, and electrode spacing affect confinement and the voltage-length product ($V\pi L$). Work on LN slot waveguides further demonstrated how slot width and thickness control effective index and cutoff, highlighting geometry as the dominant factor in balancing confinement with phase matching. Unlike Mach-Zehnder interferometers, this project leverages the intrinsic birefringence of LNOI for phase matching and employs electrode-less waveguides, which minimally disturb the field and enhance sensitivity [3]. The research investigates geometric optimization of electrode-less LNOI waveguides for strong confinement and efficient THz detection.

Methods

0.1 Detection Scheme

The electro-optic modulation (EOM) mechanism relies on the Pockels effect, where an applied electric field E_z induces a refractive index change in lithium niobate (LN). The relation is

$$\Delta n = -\tfrac{1}{2} n_e^3 \gamma_{33} E_z, \tag{1}$$

where n_e is the extraordinary refractive index and γ_{33} the EO coefficient. The simulated setup uses an optical probe ($\lambda = 800$ nm) polarized at $45°$ to the LN optical axis on a SiO_2 substrate. The terahertz field modulates the probe polarization, enabling detection of the THz signal.

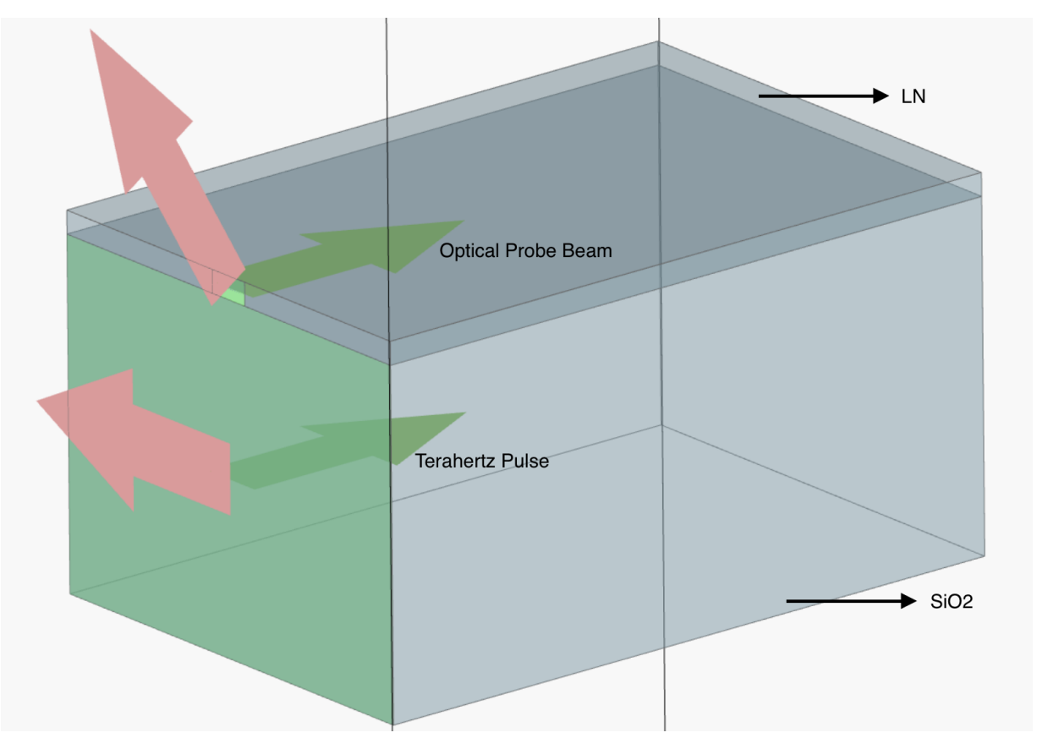

Figure 1: *Thin film LN waveguide setup*

0.2 Optical Confinement

Strong confinement in LN films enhances EO interaction and reduces substrate loss. Modes were simulated at 800 nm using FEM and FDTD on the Tidy3D platform. The effective index n_{eff} was extracted from eigenmodes, and confinement quantified by

$$\Gamma = \frac{\iint_{\text{LN}} |E(x,z)|^2 dx\, dz}{\iint_{\infty} |E(x,z)|^2 dx\, dz}.$$

Geometric variations were compared to optimize guiding efficiency.

0.3 Phase Matching

Chernekov phase matching was adopted to align optical and THz velocities without periodic poling. By tailoring film geometry, the optical mode at $\lambda = 800$ nm was matched to the THz phase index. The Cherenkov angle β follows

$$\cos\beta(\Omega) = \frac{n_{\text{eff}}(\lambda = 800\ \text{nm})}{n_{\text{THz}}(\Omega)}.$$

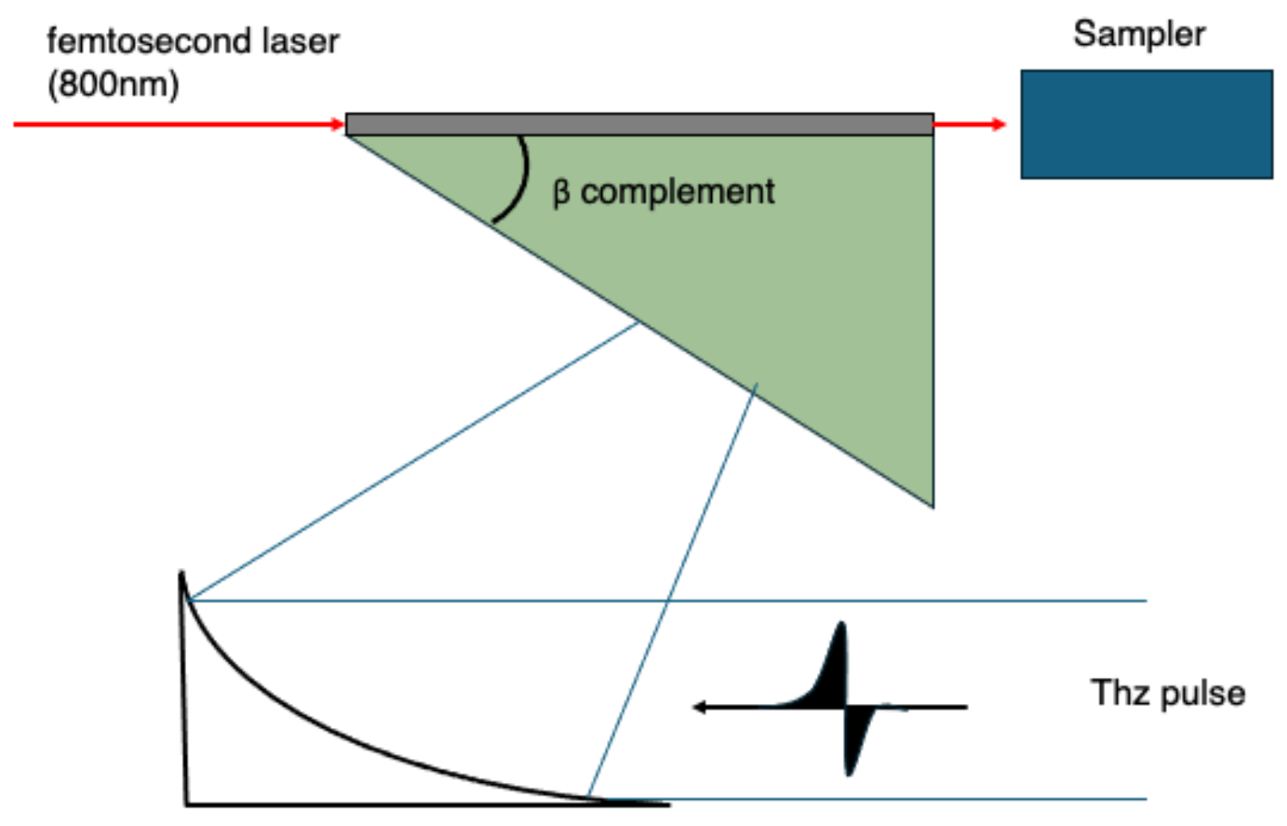

Figure 2: *Cherenkov phase matching scheme*

Mode properties were obtained by FDTD with parameter sweeps of film thickness, width, and etch depth.

Results

0.4 Optical Confinement

Eigenmode simulations with Tidy3D were performed for slot, slab ridge, and ridge LN waveguides. The slot waveguide ($h = 500$ nm, $W = 400$ nm, $W_s = 100$ nm) exhibited the strongest TE confinement in the LN layer, minimizing leakage to the SiO_2 substrate and reducing mode area. Ridge and slab ridge geometries showed weaker confinement, especially for TM modes, confirming that slot designs maximize overlap with THz fields.

Parametric sweeps revealed that increasing film thickness h raises the effective index n_{eff} and confinement, while larger slot width W_s lowers n_{eff} by spreading the field. This trade-off highlights the need to balance confinement with phase matching.

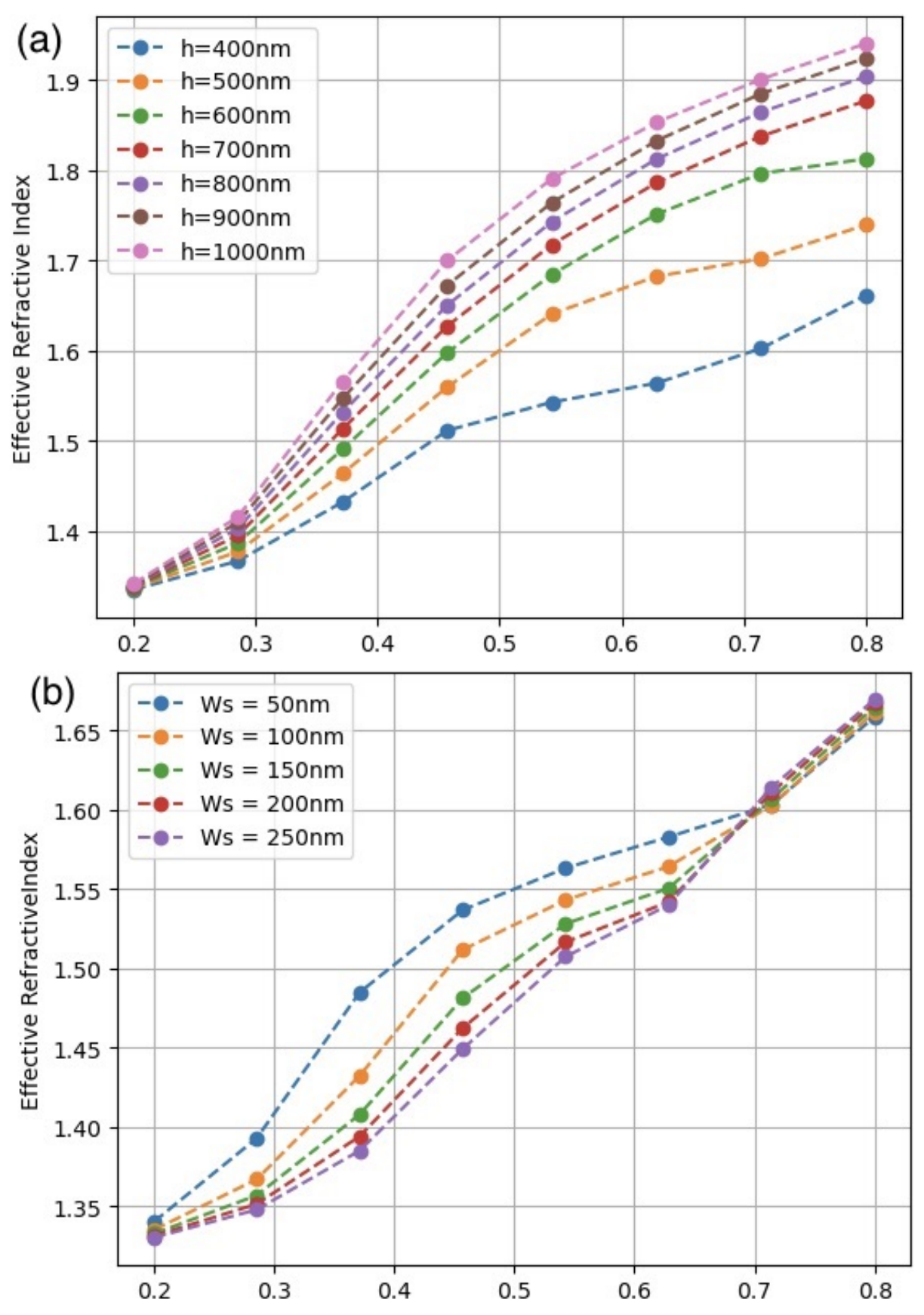

Figure 4: *Variation of effective index with (a) ridge height h and (b) slot gap W_s*

0.5 Cherenkov Phase Matching

Figure 5 shows the dependence of the Cherenkov angle β on waveguide height h and slot width W_s. The angle was obtained from simulated n_{eff} values, with trends indicating that increasing h lowers β, while larger W_s raises it. These variations are consistent with optical confinement: taller films enhance confinement and reduce emission angle, whereas wider slots loosen confinement and increase β.

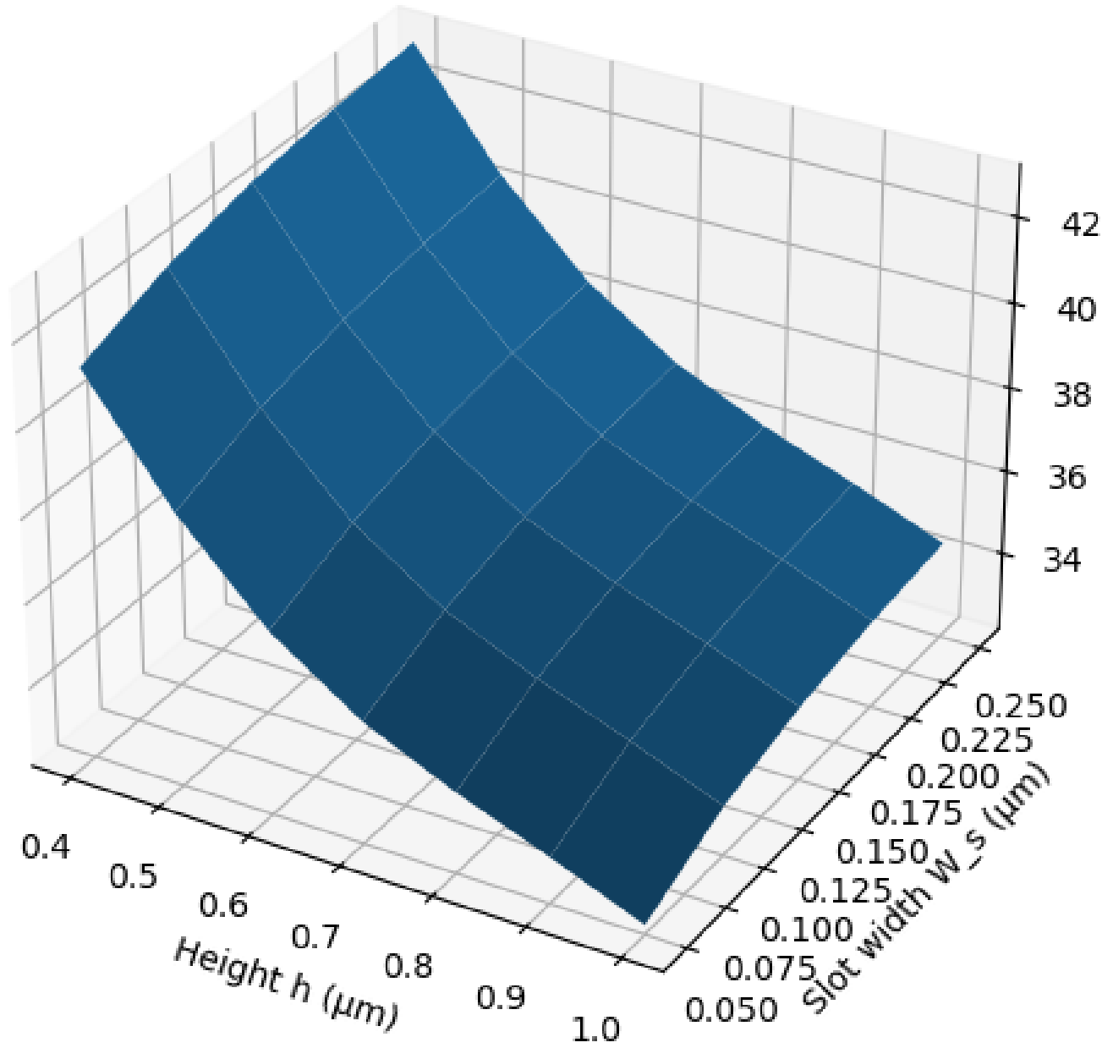

Figure 5: *Cherenkov angles for slot waveguide*

The coherence length,

$$L_c = \frac{\pi}{|\Delta k|}, \quad \Delta k = k_{\text{opt}} - k_{\text{THz}} \cos\beta, \tag{2}$$

peaks at the phase-matching angle β_{pm}, where long interaction lengths are achieved. Slot geometries provide finer tunability of β than ridge designs, enabling simultaneous optimization of confinement and phase matching. Importantly, slot waveguides yield broader $L_c(\beta)$ plateaus, which translates to improved tolerance against fabrication imperfections and alignment errors, making them advantageous for robust THz sensing applications.

Conclusion

This study investigated geometry optimization of thin-film LNOI terahertz waveguides for improving detection efficiency in healthcare sensing. Simulations confirmed geometry as decisive in balancing optical confinement and phase matching, both essential for strong electro-optic interactions. Slot waveguides outperformed ridge and slab ridge designs by concentrating the optical field in the LN layer, reducing substrate leakage, and enhancing sensitivity. Phase-matching analysis using Cherenkov geometry showed waveguide height and slot width strongly influence effective index, tuning the Cherenkov angle and coherence length. Slot geometries provided higher confinement and broader operational windows, improving fabrication tolerance. These results indicate carefully engineered slot waveguides are a promising route for robust electrode-less LNOI detectors. Future work should pursue experimental validation, optical integration, and testing with biological samples to advance LNOI-based THz diagnostics.

References

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