Integrated Thin-film Lithium Niobate Platforms for Terahertz Photonics: A Proposal

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ECE 396V: Advanced Semiconductor Nanotechnology

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December 15, 2024

PROJECT SUMMARY

Overview:

Terahertz (THz) technologies have transformative potential to revolutionize numerous domains, ranging from fundamental science to daily-life applications. However, various limitations, including cost, size, and fabrication processes, have hindered widespread utilization of THz. Overcoming these barriers would unlock the full potential of the THz spectrum, driving groundbreaking advancements and innovations across various sectors. To realize this vision, our approach focuses on addressing three critical challenges: application-oriented requirements, the unique propagation characteristics of THz waves, and the operational demands of photonic devices. With the advent of integrated thin-film lithium niobate (TFLN) platforms, we can leverage exceptional optical properties and extraordinary nonlinear effects of this emerging platform to overcome the limitations that have traditionally confined THz photonics to laboratory settings. By advancing lithium niobate-on-insulator (LNOI) fabrication and integration techniques, we aim to develop a miniaturized platform for chip-scale THz systems, enabling compact, efficient, and accessible TFLN-based THz solutions.

Intellectual Merit:

This project aims to address the critical challenges and highlight promising opportunities in developing fully integrated THz components on the TFLN platform. To achieve highly efficient, cost-effective solutions, this work will delve into the holistic processes involved in the design and integration of the THz TFLN photonics. Specifically, it will investigate advanced fabrication techniques, focusing on LNOI-based approaches, and propose innovative system design and integration strategies that bridge the existing photonic and electronic regimes. The research will lay the groundwork for the realization of compact, chip-scale THz systems—an advancement that has been sought after for decades.

Broader Impact:

Successful integration of THz photonics could lead to extensive applications of THz technologies that would possibly result in transformative benefits across numerous disciplines. These applications range from highly fundamental scientific research, such as spectroscopy, astronomy, and quantum studies, to practical uses in various fields like biomedical imaging, high-speed wireless communication, and security screening. Realizing chip-scale THz systems would not only drive mainstream commercialization by opening new markets but also make advanced technologies accessible beyond specialized laboratories. This democratization of innovation could accelerate technological progress and significantly enhance the quality of life.

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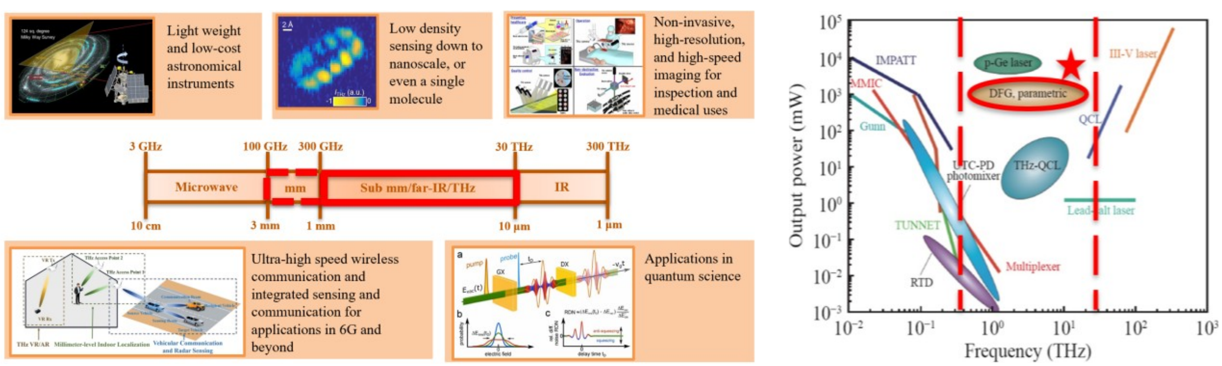
1. PROJECT DESCRIPTION

Terahertz (THz) radiation, an electromagnetic spectrum ranging from 100 GHz to 30 THz, offers a unique set of capabilities for applications in diverse areas, including next-generation communications, nondestructive high-resolution sensing and imaging, and advanced scientific studies [1]-[6], as depicted in Fig. 1a. Recognizing its broad applicability, Research and Markets projects that the global terahertz technology market will grow from $860 million in 2023 to $2.12 billion by 2029. The detection segment, encompassing imaging and sensing applications for security, medicine, and astronomy, currently dominates the market. Meanwhile, THz communication is expected to be the fastest-growing segment during the forecast period [7]. To realize the full commercial potential of THz technology, it is essential to address challenges in both performance optimization and functional integration. According to Fig. 1b, the generation of THz signals through nonlinear optical schemes, such as difference frequency generation (DFG) and optical parametric rectification, appears to be the most effective method within the THz band at room temperature [8]. However, highly efficient THz photonic systems are rather complicated, expensive, and large. These properties have limited their adoption in practical utilization outside top laboratories. Miniaturization and integration of photonic-based THz systems would be pivotal in enabling compact, efficient, and scalable solutions for real-world applications.



(a) **(b)**

Fig. 1 | **Advancement in THz technologies. a,** Miniaturization and integration provide possibilities for high-speed data transmission using small-footprint transceivers, benefiting telecommunications, autonomous vehicles, compact wearables, low-density sensing, integrated quantum devices, affordable and lightweight astronomical instruments, and single-shot, non-invasive imaging in the millimeter wave and terahertz spectrum. Included graphics from Ref. [1]-[6] **b,** THz sources as a function of frequency. For the THz spectrum ranging between 100 GHz to 30 THz, THz generation through DFG and optical parametric rectification appears to be the most effective approach at room temperature. MMIC, microwave monolithic integrated circuit; IMPATT, impact ionization avalanche transit-time diode; RTD, resonant tunnel diode; UTC-PD, uni-traveling-carrier photodiode; DFG difference frequency generation; QCL, quantum cascade laser. Adapted from Ref. [8].

A. Holistic Design Towards Miniaturizing Terahertz-Optical Chips

The miniaturization of terahertz-optical chips is a rapidly evolving field that requires a holistic approach to design and integration to balance the requirements posed by various aspects [9], [10]. From a system-level design perspective, terahertz photonic systems can be conceptualized as the interplay of three interconnected domains, as illustrated in Fig. 2: *integrated photonics*, *THz propagation manipulation*, and *application-oriented architecture*. Firstly, integrated photonics involve optimizing the design of photonic integrated circuits (PICs). This domain focuses on optical signal processing by incorporating essential on-chip components, such as optical waveguides for low-loss signal propagation within the device, modulators for optical signal modulation, compact and efficient optical sources and detectors, interconnection with other chips in the same integrated system, and, most importantly, an optical-THz converter. Next, THz propagation manipulation addresses the control over the radiation characteristics of the THz waves. The quasi-optical properties, as well as unconventional radiation behaviors of THz radiation, allow for new opportunities in enhancing communication systems, improving imaging techniques, and developing advanced sensor technologies through *wavefront engineering* [11]-[14]. Finally, application-specific requirements dictate the functionality, architecture, and form factors of the systems. These requirements ensure that the chips are tailored to meet the specific demands of their intended use, whether in communication, sensing, or imaging applications, while maintaining an optimal balance between performance, size, and integration. Crucially, the seamless connection of these three domains is fundamental to realizing the full capability of terahertz photonic systems. Advances in fabrication, integration, and packaging techniques would play a pivotal role in achieving this synergy.

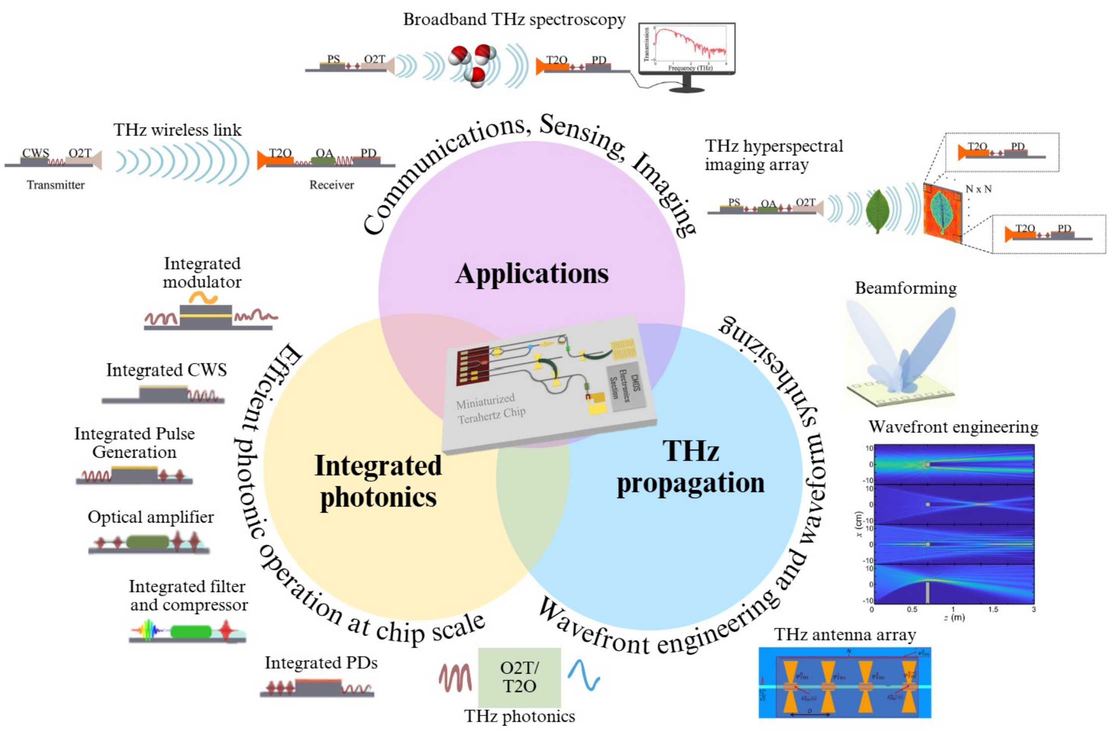


***Fig. 2* | Holistic perspectives on THz system miniaturization.** Schematic representation of the conceptualization of terahertz photonic systems highlighting three interconnected domains: integrated photonics for efficient on-chip optical signal processing, THz propagation manipulation for controlling radiation characteristics, and application-specific design to meet functional requirements, such as a THz wireless link, a broadband spectroscopy, and a hyperspectral imaging array. CWS, continuous wave source; PD, photodiode; O2T, optical-to-terahertz converter; T2O, terahertz-to-optical converter; OA, optical amplifier. Included graphics from Ref. [9]-[11] and [14].

B. Thin-film Lithium Niobate Platform

Among the various integrated photonic platforms, thin-film lithium niobate (TFLN) has emerged as a leading candidate due to its exceptional optical properties, including a broad transparency window, high light confinement, and outstanding electro-optic (EO) effects. Consequently, significant advancements in photonic integrated devices based on engineered TFLN integrated

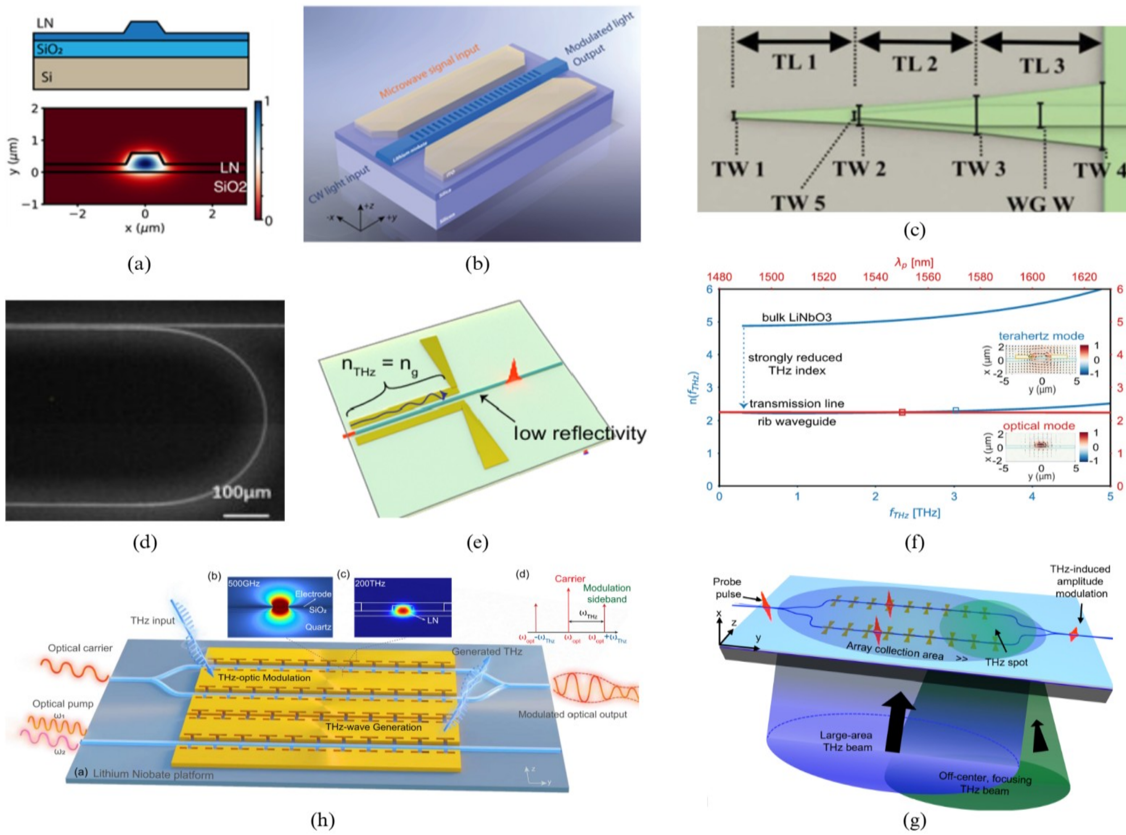


Fig. 3 **| Recent advances in TFLN-based integrated photonics. (a)** TFLN rib waveguide with simulation result showing a strong confinement within the LN rib (adapted from Ref. [16]). **(b)** An EO modulator with a periodic dielectric waveguide structure on an LN substrate. A capacitor configuration consisting of a non-resonant periodic dielectric waveguides sandwiched between two indium tin oxide (ITO) electrodes overcomes the challenge of a good balance between an ultracompact size and a high modulation bandwidth (adapted from Ref. [17]). **(c)** Edge coupler provides an efficient transition between an integrated waveguide and an off-chip optical components, such as feeding fibers. A work by Hu *et al.* highlighted notable transmission characteristics for both TE and TM modes in the integrated TFLN waveguide (adapted from Ref. [18]). **(d)** A TFLN-based integrated microresonator can remarkably achieve a Q-factor of 10^6 (adapted from Ref. [19]). **(e)** THz transmission line on TFLN consists of two golden coplanar waveguides with a rib waveguide in the middle. $\chi^{(2)}$ nonlinearity of LN causes an interaction between optical and THz signals. **(f)** The effective index of the fundamental mode of THz signals inside the coplanar transmission line is well-matched with the group refractive index of the rib waveguide. Insets show that the conversion region provides good spatial overlap. Subfigures **(e)** and **(f)** are adapted from Ref. [20]. **(h)** Schematic of the dual-functional TFLN chip for THz-optic modulation, inspired by MZI, and THz wave generation using two optical pumps (adapted from Ref. [21]). **(g)** Implementation of EO-sampling on a waveguide-based TFLN platform involves utilizing the interaction between the probe pulse and an array of THz antennas, which are placed on each arm of an on-chip interferometer (adapted from Ref. [14]).

waveguides have been reported in the past few years [15]-[19]. Examples of integrated TFLN photonic devices are given in Fig. 3a-d.

Notably, TFLN's inherent strong $\chi^{(2)}$ nonlinearity makes it particularly well-suited for nonlinear operations, with a prominent application in THz optical conversion [9], [16]. A recent breakthrough in achieving octave-wide, highly efficient conversion between THz and mid-infrared (mid-IR) light on TFLN platforms by Lampert *et al.* underscores its potential to enable chip-scale THz photonic systems. The authors proposed this dramatic wideband performance by designing a

TFLN rib optical waveguide with two golden coplanar transmission lines on its sides, depicted in Fig. 3e, matching the group velocity of mid-IR propagation with the phase velocity of THz signals in the transmission lines, as shown in Fig. 3f [20]. Additionally, Zhang *et al.* presented a technique to modulate the THz signals on the TFLN chip using an EO modulator, illustrated in Fig. 3g [21]. Furthermore, Tomasino *et al.* introduced low-noise and fast THz detection on the TFLN platform using an antenna array inspired by a Mach-Zehnder interferometer (MZI), as depicted in Fig. 4h [14].

With the emergence of state-of-the-art TFLN-based THz technologies, the opportunity to integrate these advancements on the same chip becomes increasingly viable, akin to the evolution of conventional radio-frequency integrated circuits (RFICs). To fully harness the potential of TFLN-based THz photonics, further exploration of the architecture of THz photonic integrated circuits (PICs) is essential. By leveraging advanced fabrication, integration, and packaging techniques, we can adopt a holistic and comprehensive approach to drive the universal development of compact, cutting-edge TFLN-based THz technologies.

C. Fabrication of TFLN PICs

Although the utilization of lithium niobate in photonic applications began in the 1960s, its practical usage was limited by the large footprint of bulk LN crystals due to the difficulties of material integration and processing. The development of TFLN PICs became feasible through Smart Cut technology, which was originally developed for silicon-on-insulator (SOI) wafers [22]. Compared to other well-known techniques, such as chemical vapor deposition, RF sputtering, and pulsed laser deposition, the Smart Cut yields much better film uniformity and quality. Although MBE also provides excellent film quality, it is much slower and harder to scale [15], [16]. Figure 4a illustrates the process of Smart Cut. First, a bulk LN substrate is implanted by He^+ or H^+, causing a weakened layer. The depth of penetration defines the thickness of the film. Next, the implanted LN substrate is bonded to a Si wafer with an oxide layer (SiO_2) by using adhesive or direct

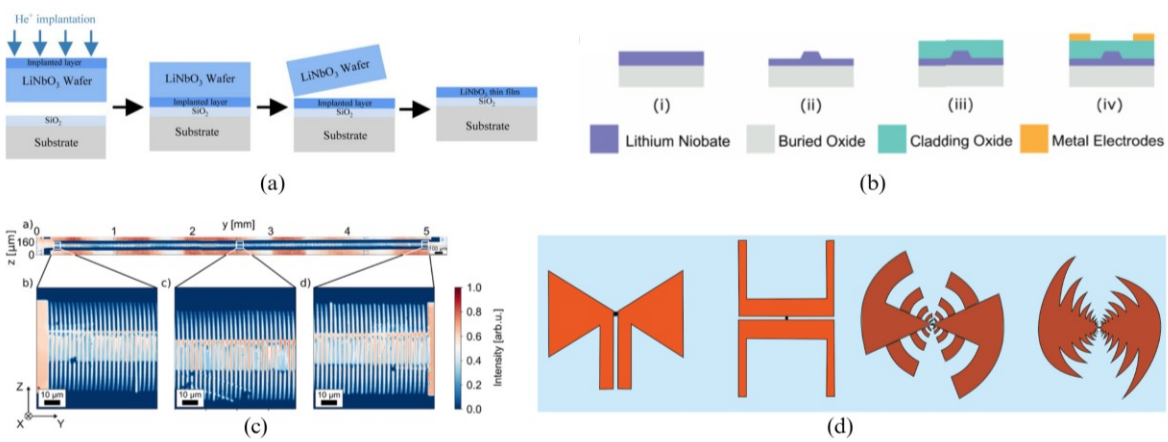


***Fig. 4* | Fabrications of TFLN photonic devices. (a)** Production of LNOI wafer using Smart Cut technique involves ion implantation, followed by bonding with a substrate, annealing, and polishing (adapted from Ref. [23]). **(b)** Fabrication process of a TFLN EO modulator starts with the formation of a rib waveguide by LN etching, followed by oxide cladding and metal deposition (adapted from Ref. [24]). **(c)** Periodically poled TFLN waveguide is a highly efficient medium for nonlinear optical wavelength conversion processes. It is widely used in broadband PICs (adapted from [25]). **(d)** Examples of wideband printed antennas. From left to right: bowtie antenna, dual U-shaped antenna, log-periodic antenna, and log-periodic sinusoidal antenna (adapted from [26]). These antenna techniques, combined with THz conversion, can be adopted to the TFLN devices through the metal deposition process.

bonding. Then, thermal annealing splits out the bulk LN at the weakened interface, forming a TFLN platform. The resulting LN-on-insulator (LNOI) wafer is further annealed to reduce implantation-induced defects and finally polished for surface smoothness [23].

The LNOI wafer can be further processed to fabricate a wide range of waveguide-based structures, enabling versatile designs for photonic integrated circuits and advanced optical devices. For instance, the fabrication process for a TFLN EO modulator presented in Ref. [24] is illustrated in Fig. 4b. Since most TFLN waveguide-based photonic devices depend on two critical steps, waveguide formation and metal deposition, they can be effectively fabricated on the same LNOI platform. Note that optical waveguide enhancement techniques, namely, periodically poled TFLN shown in Fig. 4c [25], can be included in addition to the generic waveguide formation process. Meanwhile, numerous planar antenna design techniques [26], as depicted in Fig. 4d, can be easily manipulated in the metal deposition process. Building upon these fabrication processes for TFLN waveguide-based PICs, we will delve into the design space of TFLN-waveguide-based THz PICs and demonstrate the development of THz photonic front-end chips based on the LNOI technique.

D. Integration Techniques for Fully Integrated THz Systems

The operation of THz PICs based on nonlinear processes in TFLN structure inevitably requires off-chip components, such as pulse sources and photodiodes (PDs), for both THz generation and detection, as illustrated in Fig. 5. Moreover, practical devices must be capable of interfacing with external processors or communication systems for data readout or other purposes. These stringent requirements call for advanced integration techniques to seamlessly connect LNOI-based TFLN THz devices with external components.

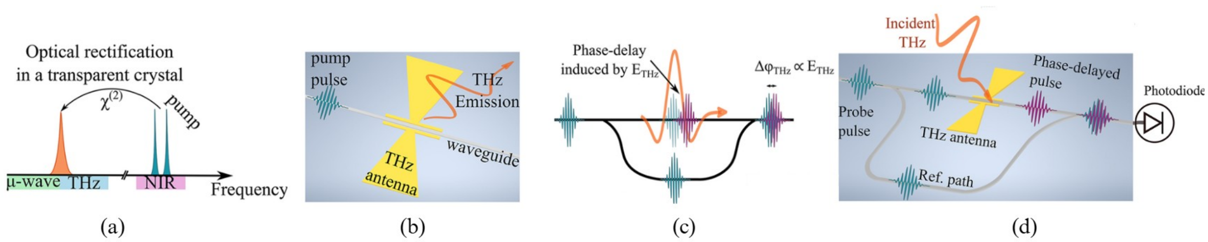


***Fig. 5* | Generation and detection of THz waves driven by $\chi^{(2)}$ nonlinearity of the TFLN platform. (a)** Schematic representation of optical rectification generating a THz signal from an optical pump. **(b)** A near-infrared (NIR) pulse, which is from a frequency comb or the beating of two optical frequencies generated off-chip, is converted to a THz wave through the optical rectification and radiate through an antenna. **(c)** Schematic representation of THz detection by EO-sampling in an MZI. **(d)** An incident THz wave introduces a phase delay to an ultrafast pulse, which can be detected by a photodiode at RF frequencies. THz TFLN devices necessitate an ultrafast pulse source and a photodiode. Adapted from Ref. [9].

1) Integration with III-V lasers for on-chip pulse generation

Despite the exceptional performance of the integrated TFLN platform, a coupling between the platform and external optical feeding (normally through a lensed fiber connected with a discrete laser) results in poor overall performance [16], [20]. To overcome this limitation, Shams-Ansari *et al.* integrated a distributed feedback (DFB) indium phosphide (InP) laser with a TFLN EO modulator through a horn coupler by the flip-chip bonding technique depicted in Fig. 6a. The efficient transmission of light is achieved by a perfect overlap between laser and TFLN modes (Fig. 6b). Figures 6c-6e indicate the fabrication steps of the flip-chip bonding process. This method achieves a 25-mW pulse at 1552 nm in a TFLN waveguide [27]. Although the method offers scalable integration at the chip scale that could potentially realize compact PICs, it still faces

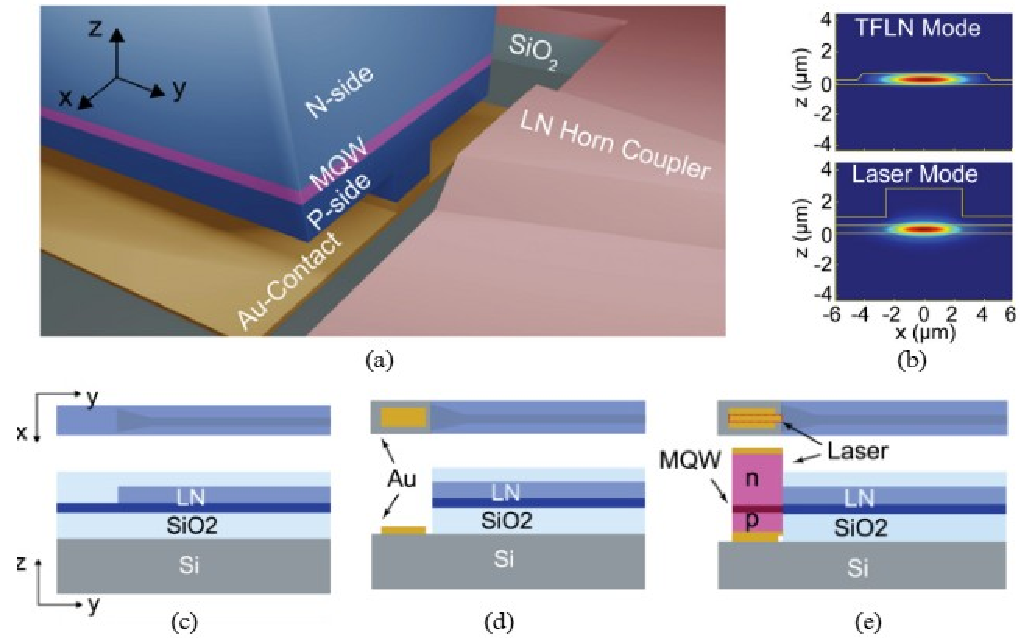


Fig. 6 | **Integration of DFB lasers onto TFLN. (a)**. The DFB laser is flipped, and the height is adjusted to ensure matched mode-heights between the two waveguides. **(b)** Optical mode profiles for both TFLN and DFB waveguides. **(c)** Top-down and cross-section illustration of the initial TFLN stack. **(d)** A trench is patterned and etched at the tip of the horn coupler. Then the bonding pad is deposited in the groove. **(e)** The DFB laser is flipped and bonded to the pad using thermo-compression Au–Au bonding. Adapted from Ref. [27].

challenges related to maximum achievable power and thermal stability. This is because adhesive bonding, typically using bisbenzocyclobutene (BCB), introduces additional thermal impedance that may affect the powers available from the laser. To address this, we will explore other bonding methods, such as direct bonding, which does not use any adhesive but relies on van der Waals forces [28], to see if this mitigates the issues. Furthermore, more efficient ultrafast pulse generation techniques could be applied to the design of the TFLN side, for instance, the introduction of a loop mirror on TFLN that mimics the partially reflected mirror of a lasing cavity [29], the adoption of microring resonators for frequency comb generation through nonlinear processes [30], or using cascaded low-loss electro-optic amplitude and phase modulators and chirped Bragg grating [31].

2) Integration with Photodiode

The detection of THz signals via $\chi^{(2)}$-driven EO sampling requires a PD to convert intensity-modulated ultrafast pulses to electrical signals for further processing. Recently, X. Guo *et al.* demonstrated heterogeneously integrated modified uni-traveling carrier (MUTC) PDs on TFLN, achieving a 3-dB bandwidth of 52 GHz for the first time [32]. The device, as depicted in Fig. 7a, comprises an epitaxial growth n down MUTC PD, which is bonded to the TFLN waveguide using SU-8 photoresist as an adhesive bonding agent. The photodetection process occurs as light propagating inside the TFLN waveguide couples to the layered PD, as shown in Fig. 7b. A similar integrated PD with a p-down configuration achieves an even wider bandwidth of 110 GHz[33]. The fabrication process of this p-down device, illustrated in Fig. 7c, involves wafer bonding, III-V material etching, and electrode fabrication. These successful demonstrations of heterogeneous integration of PDs on the TFLN platform underscore the potential for efficient, chip-scale THz

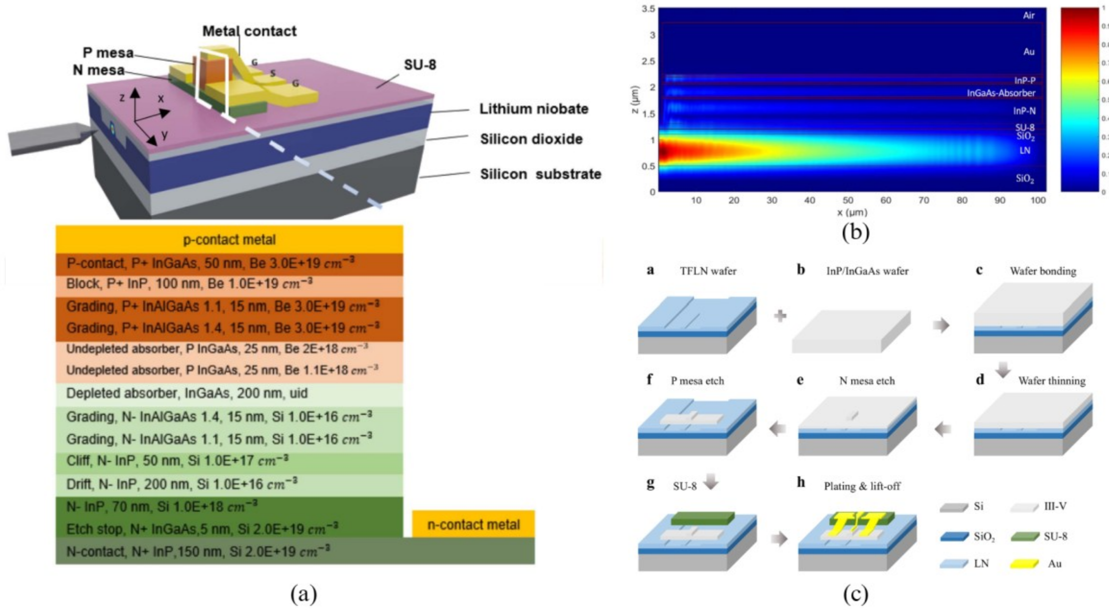


Fig. 7 | **Integration of photodiodes onto TFLN. (a)** A TFLN rib waveguide is bonded with an n down MUTC PD. The contacts of n and p mesas are connected to a 50-Ω GSG probe pad on the TFLN device via an air-bridge structure. **(b)** Light propagation simulation shows the coupling of light from the TFLN waveguide into the PD. Subfigures **(a)** and **(b)** are adapted from Ref [32]. (c) The fabrication process for a heterogeneously integrated p-down PD on the TFLN structure (adapted from Ref. [33]).

detection. We will further investigate this technique to develop highly efficient and scalable THz detection systems.

3) Hybrid Photonic-Electronic Integration and Packaging

The TFLN PICs can be simply connected to electronic circuits for signal processing or control purposes, such as driving EO modulators with RF signals, by placing photonic and electronic chips side by side in a common package and connecting them at the package level via wire bonding [34]. As we proceed with the stage of system-level integration, where TFLN-based THz PICs are combined with lasers and detectors, this wire bonding technique will be adopted to connect the THz photonic chip with an external application-specific integrated circuit (ASIC) on the same platform. To increase the integration density and advance toward the smaller footprint of THz systems, we may consider techniques like direct chip-to-wafer stacking on an ASIC [35], in which the chips are vertically attached and interconnected via either wire or flip-chip bonding, if we see it fits with the architecture of the entire system.

2. PROJECT MANAGEMENT PLAN

A. Proposed Task Plan

Task 1: Demonstration of efficient THz emission and detection on the TFLN platform. This task will involve the design of TFLN waveguide-based LNOI chips for THz generation and detection, which consists of several photonic integrated components. The main goal of the task is to realize control over THz emissions and detections within a single chip through LNOI-based fabrication processes. The task includes the design of THz PICs and THz antenna techniques.

Task 2: Exploration of TFLN-X integration techniques. We will explore the most efficient ways to integrate our TFLN platform with external devices, particularly for ultrafast pulse generation and PD-based detection. This would potentially result in new integration recipes for LNOI-based devices. We expect to reduce the disadvantages associated with external coupling previously used in PICs.

Task 3: Implementation of fully integrated THz systems. This task will focus on application-oriented architecture design and implementation.

Task 4: Demonstration of chip-scale TFLN-based THz systems in key practical applications, such as a THz wireless link, spectroscopy, and imaging.

Task 5: Dissemination and Outreach. We will disseminate research findings through publications and conference presentations.

The table below lists the tentative schedule.

Tasks		Year 1				Year 2				Year 3				Year 4			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1: Demonstration of efficient THz emission and detection on the TFLN platform.																	
1.1	Studies of optical phenomena in TFLN-based devices through simulations	■	■	■	■												
1.2	Studies of THz propagation control through simulations and prototyping	■	■	■	■												
1.3	Design and prototyping of the TFLN-based THz PICs		■	■	■	■	■	■	■								
1.4	Investigation of THz emission and detection characteristics				■	■	■	■	■								
Task 2: Exploration of TFLN-X integration techniques																	
2.1	Investigation for efficient on-chip pulse generation and coupling between laser and TFLN chips	■	■	■	■	■											
2.2	Investigation of TFLN-PD integration	■	■	■	■	■											
2.3	Integration between TFLN PICs and external laser/PD chips					■	■	■	■	■	■						
Task 3: Implementation of fully integrated THz systems																	
3.1	Investigation of THz PIC application-oriented architecture design						■	■	■	■	■	■	■	■			
3.2	Fabrication and integration of on-chip THz systems									■	■	■	■	■			
Task 4: Demonstration of chip-scale TFLN-based THz systems																	
4.1	THz system demonstration											■	■	■	■	■	■
Task 5: Dissemination and outreach																	
5.2	Disseminate research findings through publications and conference presentations				■				■				■				■

B. Facilities, Equipment, and Other Resources

This project can be classified into three types of workloads: simulation, fabrication, and characterization. For the simulation part, we require high-performance computing resources and software tools for finite element analysis. These resources will allow us to model the device performance accurately and optimize the design parameters before proceeding to fabrication. For the fabrication stage, access to a cleanroom is essential to ensure the reliability and quality of our processes. In the first task of TFLN-based THz device demonstration, we will need facilities for LNOI processing, including equipment for thin-film transferring, wafer bonding, electron-beam lithography for accurate TFLN waveguide and metal patterning, dry etching (e.g., reactive ion etching), and precision dicing. Meanwhile, for the studies of off-chip integration with the TFLN devices, we may share the same facilities as the first task. However, as the second and third tasks progress in developing more advanced integration techniques, additional specialized facilities will be required, such as tools for heterogeneous integration (e.g., flip-chip bonding systems) and advanced packaging facilities. The characterization stage can be further divided into fabrication and operational performance assessments. For fabrication characterization, we need access to a scanning electron microscope (SEM) for high-resolution imaging of the chips, ensuring the accuracy of the fabrication processes. For operational performance, we require advanced optical and electrical testing setups to evaluate the performance of our design prototypes. These include terahertz time-domain spectroscopy (THz-TDS) systems for evaluating the performance of the TFLN-based THz devices, spectrum analyzers, and high-speed oscilloscopes for signal analysis. Additional equipment, such as cryogenic measurement systems and probe stations, will be essential for assessing the devices under varying environmental conditions. Furthermore, we require antenna measurement facilities, such as an anechoic chamber, to evaluate the THz radiation characteristics. We also anticipate external collaboration that would potentially foster the development of the miniaturization of THz systems, as well as any other areas that could benefit from our project.

Reference

[1] Leitenstorfer, A., Moskalenko, A. S., Kampfrath, T., Kono, J., Castro-Camus, E., Peng, K., Qureshi, N., Turchinovich, D., Tanaka, K., Markelz, A. G., Havenith, M., Hough, C., Joyce, H. J., Padilla, W. J., Zhou, B., Kim, K., Zhang, X., Jepsen, P. U., Dhillon, S., . . . Cunningham, J. (2023). The 2023 terahertz science and technology roadmap. *Journal of Physics D Applied Physics*, 56(22), 223001. https://doi.org/10.1088/1361-6463/acbe4c

[2] Akyildiz, I. F., Han, C., Hu, Z., Nie, S., & Jornet, J. M. (2022). Terahertz Band Communication: an old problem revisited and research directions for the next decade. *IEEE Transactions on Communications*, 70(6), 4250–4285. https://doi.org/10.1109/tcomm.2022.3171800

[3] Li, X., Li, J., Li, Y., Ozcan, A., & Jarrahi, M. (2023). High-throughput terahertz imaging: progress and challenges. *Light Science & Applications*, *12*(1). https://doi.org/10.1038/s41377-023-01278-0

[4] Simonjan, J., Unluturk, B. D., & Akyildiz, I. F. (2021). In-Body bionanosensor localization for anomaly detection via inertial positioning and THZ backscattering communication. *IEEE Transactions on NanoBioscience*, 21(2), 216–225. https://doi.org/10.1109/tnb.2021.3123972

[5] Walker, C. K., Kulesa, C. A., Young, A., Verts, W., Gao, J.-R., Hu, Q., Silva, J. R., Mirzaei, B., Laauwen, W., Hesler, J. L., Groppi, C., & Emrich, A. (2022). Gal/Xgal U/LDB Spectroscopic/Stratospheric THz Observatory: GUSTO. *Proceeding of SPIE 12190,* Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy XI. 121900E. https://doi.org/10.1117/12.2629051

[6] Cocker, T. L., Peller, D., Yu, P., Repp, J., & Huber, R. (2016). Tracking the ultrafast motion of a single molecule by femtosecond orbital imaging. *Nature*, *539*(7628), 263–267. https://doi.org/10.1038/nature19816

[7] Research and Markets. (2024, September 5). *Terahertz Technology Industry Research Report 2024: A $2.12 Billion Market by 2029 - Intense Competition Fuels Innovation, Expanding Through Strategic Partnerships*. GlobeNewswire News Room; Research and Markets. https://www.globenewswire.com/news-release/2024/09/05/2941155/0/en/Terahertz-Technology-Industry-Research-Report-2024-A-2-12-Billion-Market-by-2029-Intense-Competition-Fuels-Innovation-Expanding-Through-Strategic-Partnerships.html

[8] Kou, W., Liang, S., Zhou, H., Dong, Y., Gong, S., Yang, Z., & Zeng, H. (2022). A review of terahertz sources based on planar Schottky diodes. *Chinese Journal of Electronics*, 31(3), 467–487. https://doi.org/10.1049/cje.2021.00.302

[9] Rajabali, S. & Benea-Chelmus, I.-C. (2023). Present and future of terahertz integrated photonic devices. *APL Photonics*, *8*(8). https://doi.org/10.1063/5.0146912

[10] Sengupta, K., Nagatsuma, T., & Mittleman, D. M. (2018). Terahertz integrated electronic and hybrid electronic–photonic systems. *Nature Electronics*, 1(12), 622–635. https://doi.org/10.1038/s41928-018-0173-2

[11] Singh, A., Petrov, V., Guerboukha, H., Reddy, Knightly, E. W., Mittleman, D. M., & Jornet, Josep M. (2023). Wavefront engineering: Realizing efficient terahertz band communications in 6G and beyond. *ArXiv* (Cornell University). https://doi.org/10.48550/arxiv.2305.12636

[12] Yu, N., & Capasso, F. (2010). Wavefront engineering for mid-infrared and terahertz quantum cascade lasers [Invited]. Journal of the Optical Society of America B-Optical Physics, 27(11), B18–B18. https://doi.org/10.1364/josab.27.000b18

[13] Herter, A., Amirhassan Shams-Ansari, Settembrini, F. F., Warner, H. K., Faist, J., Marko Lončar, & Ileana-Cristina Benea-Chelmus. (2023). Terahertz waveform synthesis in

integrated thin-film lithium niobate platform. *Nature Communications*, 14(1). https://doi.org/10.1038/s41467-022-35517-6
[14] Tomasino, A., Shams-Ansari, A., Lončar, M., & Benea-Chelmus, I.-C. (2024). Large-area photonic circuits for terahertz detection and beam profiling. *ArXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2410.20407
[15] Qi, Y., & Li, Y. (2020). Integrated lithium niobate photonics. *Nanophotonics*, *9*(6), 1287–1320. https://doi.org/10.1515/nanoph-2020-0013
[16] Zhu, D., Shao, L., Yu, M., Cheng, R., Desiatov, B., Xin, C. J., Hu, Y., Holzgrafe, J., Ghosh, S., Shams-Ansari, A., Puma, E., Sinclair, N., Reimer, C., Zhang, M., & Lončar, M. (2021). Integrated photonics on thin-film lithium niobate. *Advances in Optics and Photonics*, *13*(2), 242. https://doi.org/10.1364/aop.411024
[17] Qi, Y., Zhang, Z., Jia, W., Chen, S., Yang, Y., & Li, Y. (2022). Design of ultracompact high-speed-integrated lithium–niobate periodic dielectric waveguide modulator. *Advanced Photonics Research*, *3*(9). https://doi.org/10.1002/adpr.202200050
[18] Hu, C., Pan, A., Li, T., Wang, X., Liu, Y., Tao, S., Zeng, C., & Xia, J. (2021). High-efficient coupler for thin-film lithium niobate waveguide devices. *Optics Express*, *29*(4), 5397. https://doi.org/10.1364/oe.416492
[19] Wei, C., Li, J., Jia, Q., Li, D., & Liu, J. (2023). Ultrahigh-Q lithium niobate microring resonator with multimode waveguide. *Optics Letters*, *48*(9), 2465. https://doi.org/10.1364/ol.489387
[20] Lampert, Y., Shams-Ansari, A., Gaier, A., Tomasino, A., Rajabali, S., Magalhaes, L., Lončar, M., & C, B.-C. I. (2024). Photonics-integrated terahertz transmission lines. *ArXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2406.15651
[21] Zhang, Y., Yang, J., Chen, Z., Feng, H., Zhu, S., Shum, K.-M., Chan, C. H., & Wang, C. (2024). Monolithic lithium niobate photonic chip for efficient terahertz-optic modulation and terahertz generation. *ArXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2406.19620
[22] Xi Qiao Feng, & Huang, Y. (2004). Mechanics of Smart-Cut® technology. *International Journal of Solids and Structures*, *41*(16-17), 4299–4320. https://doi.org/10.1016/j.ijsolstr.2004.02.054
[23] You, B., Yuan, S., Tian, Y., Zhang, H., Zhu, X., Mortensen, N. A., & Cheng, Y. (2024). Lithium niobate on insulator – fundamental opto-electronic properties and photonic device prospects. *Nanophotonics*, *13*(17), 3037–3057. https://doi.org/10.1515/nanoph-2024-0132
[24] Yue, G., Yang, H., Zhang, Z., Hao, T., Xiao, L., & Li, Y. (2024). Dual-layer capacitance-loaded thin-film lithium niobate electro-optic modulator with high modulation efficiency. *Optics Express*, *32*(13), 23161–23161. https://doi.org/10.1364/oe.524932
[25] Reitzig, S., Rüsing, M., Zhao, J., Kirbus, B., Mookherjea, S., & Eng, L. M. (2021). "Seeing is believing"—In-depth analysis by co-imaging of periodically-poled x-cut lithium niobate thin films. *Crystals*, *11*(3), 288. https://doi.org/10.3390/cryst11030288
[26] He, Y., Chen, Y., Zhang, L., Wong, S., & Chen, Z. N. (2020). An overview of terahertz antennas. *China Communications*, *17*(7), 124–165. https://doi.org/10.23919/J.CC.2020.07.011
[27] Shams-Ansari A., Renaud, D., Cheng, R., Shao, L., He, L., Zhu, D., Yu, M., Grant, H. R., Johansson, L., Zhang, M., & Marko Lončar. (2022). Electrically pumped laser transmitter integrated on thin-film lithium niobate. *Optica*, *9*(4), 408–408. https://doi.org/10.1364/optica.448617

[28] Rabiei, P. & Günter, P. (2004). Optical and electro-optical properties of submicrometer lithium niobate slab waveguides prepared by crystal ion slicing and wafer bonding. *Applied Physics Letters*, *85*(20), 4603–4605. https://doi.org/10.1063/1.1819527
[29] Guo, Q., Gutierrez, B. K., Sekine, R., Gray, R. M., Williams, J. A., Ledezma, L., Costa, L., Roy, A., Zhou, S., Liu, M., & Alireza Marandi. (2023). Ultrafast mode-locked laser in nanophotonic lithium niobate. *Science*, *382*(6671), 708–713. https://doi.org/10.1126/science.adj5438
[30] Zhang, M., Buscaino, B., Wang, C., Shams-Ansari, A., Reimer, C., Zhu, R., Kahn, J. M., & Lončar, M. (2019). Broadband electro-optic frequency comb generation in a lithium niobate microring resonator. Nature, 568(7752), 373–377. https://doi.org/10.1038/s41586-019-1008-7
[31] Yu, M., David Barton Iii, Cheng, R., Reimer, C., Prashanta Kharel, He, L., Shao, L., Zhu, D., Hu, Y., Grant, H., Johansson, L., Yoshitomo Okawachi, Gaeta, A. L., Zhang, M., & Loncar, M. (2022). Integrated femtosecond pulse generator on thin-film lithium niobate. *Nature*, *612*(7939), 252–258. https://doi.org/10.1038/s41586-022-05345-1
[32] Guo, X., Shao, L., He, L., Luke, K., Morgan, J., Sun, K., Gao, J., Ta-Ching Tzu, Shen, Y., Chen, D., Guo, B., Yu, F., Yu, Q., Jafari, M., Marko Lončar, Zhang, M., & Beling, A. (2022). High-performance modified uni-traveling carrier photodiode integrated on a thin-film lithium niobate platform. *Photonics Research*, *10*(6), 1338–1338. https://doi.org/10.1364/prj.455969
[33] Wei, C., Yu, Y., Wang, Z., Jiang, L., Zeng, Z., Ye, J., Zou, X., Pan, W., Xie, X., & Yan, L. (2023). Ultra-wideband Waveguide-coupled Photodiodes Heterogeneously Integrated on a Thin-film Lithium Niobate Platform. *Light: Advanced Manufacturing*, *4*(3), 1–1. https://doi.org/10.37188/lam.2023.030
[34] Fischer, A., Korvink, J. G., Niclas Roxhed, Stemme, G., Wallrabe, U., & Niklaus, F. (2013). Unconventional applications of wire bonding create opportunities for microsystem integration. *Journal of Micromechanics and Microengineering*, *23*(8), 083001–083001. https://doi.org/10.1088/0960-1317/23/8/083001
[35] Fischer, A. C., Forsberg, F., Lapisa, M., Bleiker, S. J., Stemme, G., Roxhed, N., & Niklaus, F. (2015). Integrating MEMS and ICs. *Microsystems & Nanoengineering*, *1*(1), 1–16. https://doi.org/10.1038/micronano.2015.5