A Review of Thin-Film Lithium Niobate Platform for Terahertz Photonic Integrated Circuits

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Introduction: A terahertz (THz) regime, typically defined as frequencies from 100 GHz to 30 THz, is of great interest across diverse applications. Electronic approaches like monolithic microwave integrated circuits (MMICs) offer the advantage of integrating THz electronics with existing systems. However, this approach faces the challenges of high power consumption and limited bandwidth. Meanwhile, THz photonics can achieve greater bandwidth with lower noise, though it is more complex and expensive to implement compared to electronic solutions [1], [2]. Recently, advances in thin-film lithium niobate (TFLN) have emerged as one of the most promising techniques in realizing THz photonic integrated circuits (PICs) [3]. This paper explores the distinctive characteristics of the TFLN platform, highlighting recent breakthroughs in THz TFLN-based PICs, along with their challenges and opportunities for future research.

TFLN Platform: Lithium Niobate ($LiNbO_3$, LN) is a ferromagnetic material that inherits extraordinary electro-, nonlinear-, and acousto-optic properties, which are attractive to applications in various domains [4]. For applications in optics, a strong $\chi^{(2)}$ nonlinearity, owed to its non-centrosymmetric crystal structure, makes LN attractive for THz conversion through *optical rectification*. Although research on LN 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-based PICs became feasible through Smart Cut technology, which was originally developed for silicon-on-insulator (SOI) wafers [5]. This technique involves ion implantation and wafer bonding to transfer thin crystalline layers, as depicted in Fig. 1a. 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 hard to scale [4]. Compared to bulk LN crystal, TFLN offers a much stronger confinement (see Fig. 1b) and electro-optic effect, a wider transparency window, lower optical losses, and high-power handling capability, making TFLN an ideal platform for PICs [4].

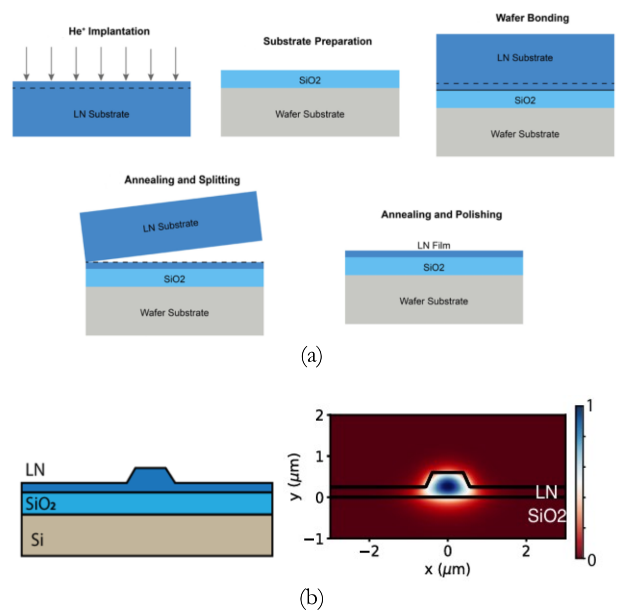

Figure 1 (a) LNOI Smart Cut fabrication processes. First, a bulk LN substrate is implanted by He^+ or H^+, causing a weakened layer. The penetration depth defines the thickness of the film. Next, the implanted LN substrate is bonded to a Si wafer with an oxide layer (SiO_2) by using adhesive or direct bonding. Then, thermal annealing splits out the bulk LN at the weakened interface, forming a TFLN platform. The resulting LN-on-insulation wafer is further annealed to reduce implantation-induced defects and finally polished for surface smoothness. (b) A strong light confinement inside a rib TLFN waveguide (adapted from [4])

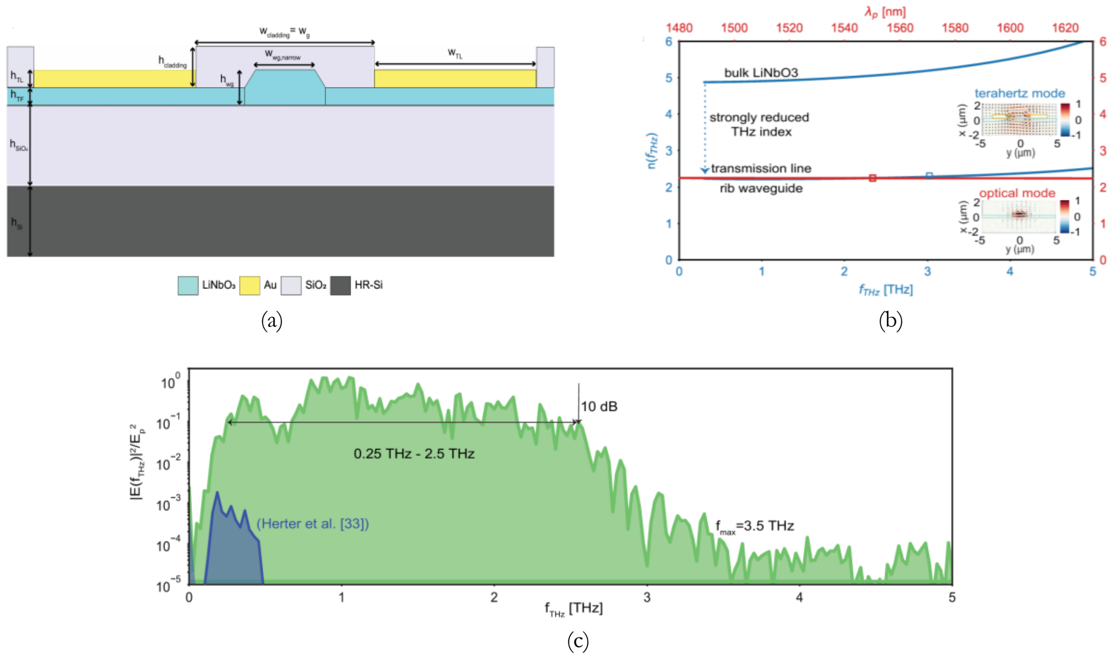

Figure 2 (a) Cross-section of the THz conversion region. (b) The effective index of the fundamental mode of THz signals inside the coplanar transmission line is well-matched with the group refractive index of the rib waveguide. Insets show that the conversion region provides good spatial overlap. (c) The normalized spectra of the generated THz pulse represent the conversion efficiency. It is evident that the proposed THz coplanar transmission outperforms the previous work of [7] (ref. [33] in the original paper; adapted from [6]).

THz Transmission Line on Integrated TFLN Platform: The most recent breakthrough in THz photonics is a coplanar transmission line on the integrated TFLN platform [6]. In this work, a rib waveguide is first ion-etched on a 600-nm X-cut TFLN platform with a 300-nm etch depth. A wet chemical process is used to clean the resist and remove any redeposited material after physical etching. The waveguide is then annealed and cladded with SiO2 using inductively coupled plasma chemical vapor deposition (ICPCVD), followed by a final annealing step. Metallic patches (Au for low-loss THz propagation) are deposited beside the rib through ICPCVD SiO_2 etching and electron beam evaporation, forming a THz conversion region, as illustrated in Fig. 2a. In this design, the group velocity of the optical pump in the TFLN rib waveguide is well matched with the phase velocity of THz pulses propagating in the coplanar transmission line, as shown in Fig. 2b. This principle significantly overcomes the challenge of matching between the optical pump and the generated THz pulses, which previously drastically limited an efficient conversion to a very short distance [7]. According to Fig. 2c, this design yields a highly efficient conversion of −10 dB between 0.25 and 2.5 THz, outperforming the previous design. It is noticeable that efficient operation occurs within only the phase-matched frequency range, emphasizing the importance of phase matching in the design of the conversion region.

Challenges and Opportunities: Despite the unprecedented performance of on-chip THz emission achieved by [6], the optimal efficiency is only obtained by utilizing a complex off-chip optical setup, depicted in Fig. 3a, which comprises a mode-locked laser (MLL) operated at 1560 nm, an external dispersion-controlled setup, and a Mach-Zehnder modulator (MZM). The major downside of the

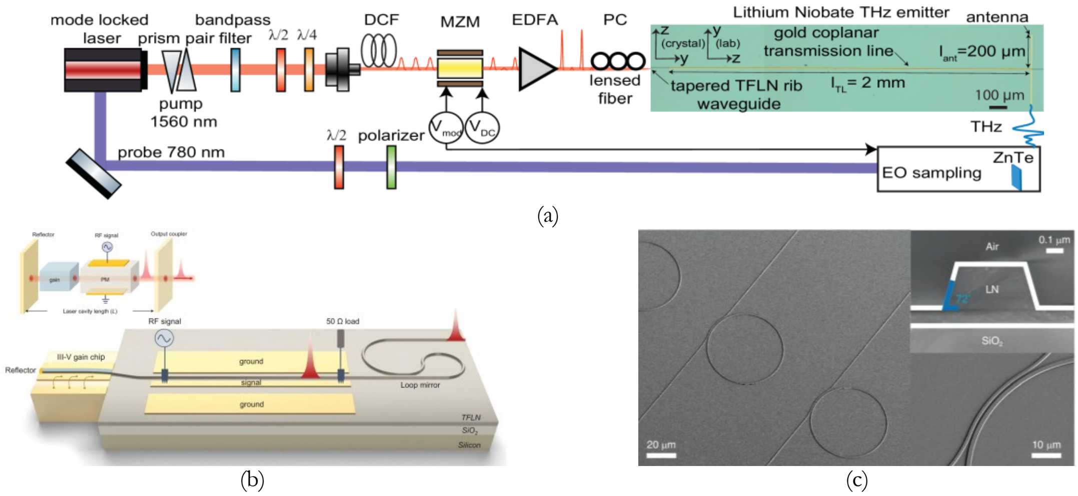

Figure 3 (a) Optical setup for THz TFLN emitter characterization. A 1560-nm MLL emits an optical pump that passes through a dispersion control section and a MZM before couples into a TFLN THz emitter through a lensed fiber. An EDFA compensates a poor coupling of only 13% between the fiber and the integrated waveguide and losses caused by the MZM (adapted from [6]). (b) The schematic diagram of an on-chip ultrafast operating around 1026 nm, consisting of a III-V gain chip and a TFLN-based electro-optic modulator. A reflector at the left end and a loop mirror at the right end mimic the cavity of a typical off-chip MML, shown in an inset (adapted from [8]). (c) TFLN-based microring resonators for dispersion control in Kerr soliton frequency combs (adapted from [9]).

external feeding scheme is poor coupling efficiency between the lensed fiber tip and the tapered on-chip rib waveguide transition. The reported maximum coupling is only 13%, which leads to the need for an erbium-doped fiber amplifier (EDFA) for compensation. Accordingly, fully integrated on-chip components are essential for realizing practical THz PICs. Lately, an on-chip ultrafast MLL operating around 1026 nm was demonstrated on the TFLN platform for the first time [8]. The researchers combined an electrically pumped single-angled facet (SAF) GaAs gain chip with a 700-nm-thick X-cut magnesium oxide (MgO)-doped TFLN integrated electro-optic modulator and a broadband loop mirror, as illustrated in Fig. 3b. This design principle could be applied to replace the off-chip 1560-nm MLL and MZM used in the THz waveform synthesizer. For dispersion control, various TFLN-based micro- and nanostructures, such as microresonators [9] (see Fig. 3c) and periodically-poled waveguide [10], could be adopted to optimize the design of fully integrated THz systems. Notably, the major challenge in realizing *fully integrated* THz PICs is how to implement all those devices on a single platform.

Conclusion and discussion: This review covers various essential aspects of the TFLN platform for THz PICs. An emphasis is placed on the THz transmission line to highlight their role in achieving efficient THz conversion. Although the state-of-the-art THz transmission line on the TFLN platform presented here covers an octave of the THz band while overcoming the bulkiness and limitations of a bulk crystal, it is evident that a fully integrated THz PIC on the TFLN platform that contains on-chip optical components is needed to make the THz system practical for wide-spread practical uses. This requirement, along with the inherent physical challenges of nonlinear photonics, calls for advancements not only in the RF photonic domain but also in material preparation, device fabrication, and system integration. Notably, the properties of TFLN open doors to interdisciplinary research in existing microelectromechanical systems as well.

References:

[1] A. Leitenstorfer *et al.*, "The 2023 terahertz science and technology roadmap," *Journal of Physics D: Applied Physics*, vol. 56, no. 22, p. 223001, Apr. 2023. doi:10.1088/1361-6463/acbe4c.

[2] I. F. Akyildiz, C. Han, Z. Hu, S. Nie and J. M. Jornet, "Terahertz band communication: an old problem revisited and research directions for the next decade," *IEEE Transactions on Communications*, vol. 70, no. 6, pp. 4250-4285, June 2022, doi: 10.1109/TCOMM.2022.3171800.

[3] S. Rajabali and I.-C. Benea-Chelmus, "Present and future of terahertz integrated photonic devices," *APL Photonics*, vol. 8, no. 8, Aug. 2023. doi:10.1063/5.0146912.

[4] D. Zhu *et al.*, "Integrated photonics on thin-film lithium niobate," *Advances in Optics and Photonics,* vol. 13, no. 2, pp. 242-352, May 2021. doi:10.1364/AOP.411024.

[5] X. Q. Feng and Y. Huang, "Mechanics of Smart-Cut® technology," *International Journal of Solids and Structures*, vol. 41, no. 16-17, pp. 4299-4320, Aug. 2004. doi:10.1016/j.ijsolstr.2004.02.054.

[6] Y. Lampert *et al.*, "Photonics-integrated terahertz transmission lines," arXiv:2406.15651 (physics), Jun. 2024. doi: 10.48550/arXiv.2406.15651.

[7] A. Herter *et al.*, "Terahertz waveform synthesis in integrated thin-film lithium niobate platform," *Nature Communications*, vol. 14, no. 1, Jan. 2023. doi:10.1038/s41467-022-35517-6.

[8] Q. Guo *et al.,* "Ultrafast mode-locked laser in nanophotonic lithium niobate," *Science,* vol. 382, no. 6671, pp. 708-713, Nov. 2023. doi:10.1126/science.adj5438.

[9] Y. Song, Y. Hu, X. Zhu, K. Yang, and M. Lončar, "Octave-spanning Kerr soliton frequency combs in dispersion- and dissipation-engineered lithium niobate microresonators," *Light: Science & Applications,* vol. 13. no. 25, Sep. 2024. doi: 10.1038/s41377-024-01546-7.

[10] C. J. Xin *et al.,* "Spectrally separable photon-pair generation in dispersion engineered thin-film lithium niobate," Optics Letters, vol. 47, no. 11, pp. 2830-2833, Jun. 2022. doi:10.1364/OL.456873.