$LiNbO_3$ crystals: from bulk to film

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Lithium niobate[1,2] is a ferroelectric crystal that features superior electro-optical, nonlinear optical, and acoustic optical performance, and it is thus prominent in various optoelectronic applications. Recent breakthroughs in the fabrication of thin film lithium niobate (TFLN) combine the unique features of the bulk crystal onto an integrated platform with submicron light confinement, driving new records in reducing the energy consumption for high-speed electro-optical modulation,[3–5] the footprint for acoustic wave filtering,[6] and the power requirement for efficient optical frequency conversion.[7–9] TFLN is mainly fabricated using the smart cut technique,[10,11] which was developed for silicon-on-insulator materials[12] and is known for its capability for manufacturing high-quality, large-sized crystalline wafer. Revolutionary performances are expected by moving from bulk to TFLN, e.g., in the form of lithium-niobate-on-insulator (LNOI) optical communication and wireless communication devices, and this trend may also lead to fundamental breakthroughs in optical computation, microwave photonics, and quantum optics, as discussed below.

Lithium-niobate-based electro-optical modulators (EOMs) have been the choice of long-distance optical communication for decades. However, their relatively large size and high cost make them only applicable for the backbone connections. LNOI EOM, however, is capable of the same high modulation speed and CMOS-compatible low drive voltage in a much smaller package. Power consumption as low as 0.37 fj/bit has been demonstrated.[3] These performances make the LNOI EOM not only a direct alternate to the bulk lithium niobate EOM, but also a promising candidate for optical links in/between data centers and local area networks at the data rates of 200-800 Gbps and above, therefore driving the next generation optical communication technology. It is worth noting that laser sources and amplifiers have been demonstrated using rare-earth-ion-doped LNOI chips,[13] which may enable a fully integrated optical communication module. Hybridization with laser-active materials or silicon is another attractive approach towards full integration that adds a light source or driving electronics capabilities.[14] Such hybrid integration can also enable simultaneous signal processing and memory operations, leading toward artificial intelligence applications.[15]

Optical computation may change the power-hungry nature of modern electronic computation technology, in both classical[16] and quantum approaches,[17] by demonstration of computation speed acceleration and quantum supremacy. In either approach, larger scale photonic circuitry is required, with phase sensitive optical paths as the interaction mechanism. The low loss nature of lithium niobate qualifies LNOI for such large-scale photonic integration, achieving a level of 2.7 dB per meter in different demonstrations.[18,19] A further crucial challenge for optical computation is circuit reconfigurability, and LNOI is the only mature material to combine fast and accurate phase control using electro-optical modulation, acoustic-optical modulation, or thermal-optical modulation.

Microwave photonics has been a long-chased dream to bring optical accuracy and bandwidth into microwave technology. Photonic integration is key to push complex microwave photonics systems, including high-bandwidth electro-optic modulators, low-noise frequency synthesizers, and chip signal processors, into practice.[20] The LNOI platform contains the most powerful toolbox, including the EOM and dispersive Kerr soliton (DKS) frequency combs.[21] Self-referencing is necessary to further stabilize DKS comb. With high nonlinear coefficients in both $\chi^{(2)}$ and $\chi^{(3)}$, octave-spanning supercontinuum generation[22] and efficient frequency doubling[9] have been reported separately using LNOI, and self-referencing can be expected combining these processes on the same chip. The only missing parts are the photodetector and control electronics in the on-chip signal processing, and their integration relies on the hybrid integration technology.

Domain engineered bulk lithium niobate crystal, also known as optical superlattice,[23] has been a great success for nonclassical light generation and photon state manipulation, for quantum optics research. However, photonic integration is the key to the practical application of quantum information technology. Compared to other photonics integration platforms, LNOI features high nonlinearity in $\chi^{(2)}$ and fast EOM for photon state modulation. Ultrabright photon pair generation has been reported in both straight waveguide and micro-resonator using LNOI to achieve revolutionary photon generation rates of 2.79×10^{11} Hz/mW[24] and 2.7 MHz/μW,[25] respectively. Together with the low-loss waveguide and other passive devices, larger scale on-chip photon state manipulation can be expected.

On one hand, the above important advances may be seen as incremental steps toward practical application of quantum information technology that are expected directly from the high nonlinearity of LNOI. On the other hand, the practical application of quantum information relies on sources of the deterministic multiqubit state, which is the multiphoton state in photonics quantum systems. While such a problem is yet to be resolved, a theoretical study shows that LNOI may be the only candidate for such deterministic multiphoton state generation considering the material limitations.[26] Deterministic nonlinear interaction is possible at single photon level, and the required quality factor is on the order of 10^7 to 10^8 for domain engineered micro-ring resonators, within the reach of existing fabrication limits.[26]

In summary, from bulk devices to chips, LNOI technology has shown its capability to push the performance of optoelectronic devices to new heights, for electro-optical modulation and acoustic wave filtering functions in next-generation optical and wireless communications. In conjunction with hybrid integration, LNOI can also be an enabling technology for optical computation, microwave photonics, and quantum information, with large-scale photonic integration, high optical reconfigurability, and strong nonlinear interaction at the single photon level. To make these happen, large-size low-defect TFLN wafer and high-performance device fabrication techniques are key areas of future research.

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References

1. J. Sun et al., "Brief review of lithium niobate crystal and its applications," *J. Synth. Cryst.* **49**(6), 947–964 (2020).
2. B. Gao et al., "Long-lived lithium niobate: history and progress," *J. Synth. Cryst.* **50**(7), 1183–1199 (2021).
3. C. Wang et al., "Integrated lithium niobate electro-optic modulators operating at CMOS-compatible voltages," *Nature* **562**(7725), 101–104 (2018).
4. M. He et al., "High-performance hybrid silicon and lithium niobate Mach–Zehnder modulators for 100 Gbit s-1 and beyond," *Nat. Photonics* **13**(5), 359–364 (2019).
5. M. Li et al., "Lithium niobate photonic-crystal electro-optic modulator," *Nat. Commun.* **11**, 4123 (2020).
6. L. Shao et al., "Microwave-to-optical conversion using lithium niobate thin-film acoustic resonators," *Optica* **6**(12), 1498–1505 (2019).
7. C. Wang et al., "Ultrahigh-efficiency wavelength conversion in nanophotonic periodically poled lithium niobate waveguides," *Optica* **5**(11), 1438–1441 (2018).
8. J.-Y. Chen et al., "Ultra-efficient frequency conversion in quasi-phase-matched lithium niobate microrings," *Optica* **6**(9), 1244 (2019).
9. Y. Niu et al., "Optimizing the efficiency of a periodically poled LNOI waveguide using in situ monitoring of the ferroelectric domains," *Appl. Phys. Lett.* **116**(10), 101104 (2020).
10. G. Poberaj et al., "Lithium niobate on insulator (LNOI) for micro-photonic devices," *Laser Photonics Rev.* **6**(4), 488–503 (2012).
11. Y. Jia, L. Wang, and F. Chen, "Ion-cut lithium niobate on insulator technology: recent advances and perspectives," *Appl. Phys. Rev.* **8**(1), 011307 (2021).
12. A. E. Lim et al., "Review of silicon photonics foundry efforts," *IEEE J. Sel. Top. Quantum Electron.* **20**(4), 405–416 (2014).
13. S. Dutta et al., "Integrated photonic platform for rare-earth ions in thin film lithium niobate," *Nano Lett.* **20**(1), 741–747 (2020).
14. D. Zhu et al., "Integrated photonics on thin-film lithium niobate," *Adv. Opt. Photon.* **13**(2), 242–352 (2021).
15. L. Tong et al., "2D materials–based homogeneous transistor-memory architecture for neuromorphic hardware," *Science* **373**(6561), 1353–1358 (2021).
16. Y. Shen et al., "Deep learning with coherent nanophotonic circuits," *Nature Photonics* **11**(7), 441–446 (2017).
17. H.-S. Zhong et al., "Quantum computational advantage using photons," *Science* **370**(6523), 1460–1463 (2020).
18. M. Zhang et al., "Monolithic ultra-high-Q lithium niobate microring resonator," *Optica* **4**(12), 1536–1537 (2017).
19. J. Zhou et al., "Electro-optically switchable optical true delay lines of meter-scale lengths fabricated on lithium niobate on insulator using photolithography assisted chemo-mechanical etching," *Chin. Phys. Lett.* **37**(8), 084201 (2020).
20. D. Marpaung, J. Yao, and J. Capmany, "Integrated microwave photonics," *Nat. Photonics* **13**(2), 80–90 (2019).
21. Y. He et al., "Self-starting bi-chromatic $LiNbO_3$ soliton microcomb," *Optica* **6**(9), 1138 (2019).
22. M. Jankowski et al., "Ultrabroadband nonlinear optics in nanophotonic periodically poled lithium niobate waveguides," *Optica* **7**(1), 40–46 (2020).
23. S. Zhu, Y. Zhu, and N. Ming, "Quasi-phase-matched third-harmonic generation in a quasi-periodic optical superlattice," *Science* **278**(5339), 843–846 (1997).
24. G.-T. Xue et al., "Ultrabright multiplexed energy-time-entangled photon generation from lithium niobate on insulator chip," *Phys. Rev. Appl.* **15**(6), 064059 (2021).
25. Z. Ma et al., "Ultrabright quantum photon sources on chip," *Phys. Rev. Lett.* **125**(26), 263602 (2020).
26. H.-Y. Liu et al., "A scheme for deterministic N-photon state generation using lithium niobate on insulator device," https://doi.org/10.48550/arXiv.2205.14956 (2022).