

7 – Quantum Photonics with Thin-Film Lithium Niobate

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Status

Optical photons have many attractive properties for realization of quantum technologies [1]: they exist under ambient conditions, are generally impervious to environmental noise, and, to an extent, can be generated, manipulated and detected easily. Since they can also travel long distances without significant loss, individual photons are well-suited for quantum key distribution, which aims to secure messages between distant parties using quantum uncertainty. Yet, these properties of photons also introduce challenges to realize quantum technologies that require deterministic interactions between individual photons, e.g. for photonic quantum information processing.

Integrated photonics will play a crucial role in realizing long- (e.g. worldwide), medium- (e.g. metropolitan- or room-sized), and short-range (e.g. inter- or intra-chip) quantum networks. However, the performance of a photonics platform for quantum technology applications needs to be much better than, and in some ways different from, what is required for classical applications. For example, a quantum photonics platform needs to: (i) be ultra-low loss in order to preserve fragile quantum states; (ii) enable precise control of the temporal and spectral profiles of photons; (iii) allow fast and low-loss optical switches to route quantum information; (iv) be able to operate in visible and telecom wavelengths, where many single-photon sources and quantum memories operate, and low-loss optical fibers exist, respectively; (v) feature strong nonlinearities for efficient frequency up- and down-conversion, quantum transduction, and entangled photon pair generation; (vi) allow integration of photodetectors and operating electronics. Silicon and silicon-nitride, the leading integrated photonic platforms, do not meet these requirements due to the lack of a second-order nonlinearity, which restricts their functionality [1]. Although this could be addressed with crystal modification or heterogeneous integration, it remains to be seen what trade-offs, e.g. in terms of efficiency and scalability, this would encompass.

Thin film Lithium niobate (TFLN) has emerged as a promising quantum photonic platform. LN is transparent to optical photons (band gap of ~ 4 eV), possesses a strong electro-optic (EO) effect, allowing the phase of light to be rapidly varied using microwaves, and has a high second-order optical nonlinearity that can be engineered through ferroelectric domain modulation (i.e. periodic poling) [2]. Importantly, 4" and 6" TFLN wafers have recently become commercially available, which have stimulated interest in this exciting material platform.

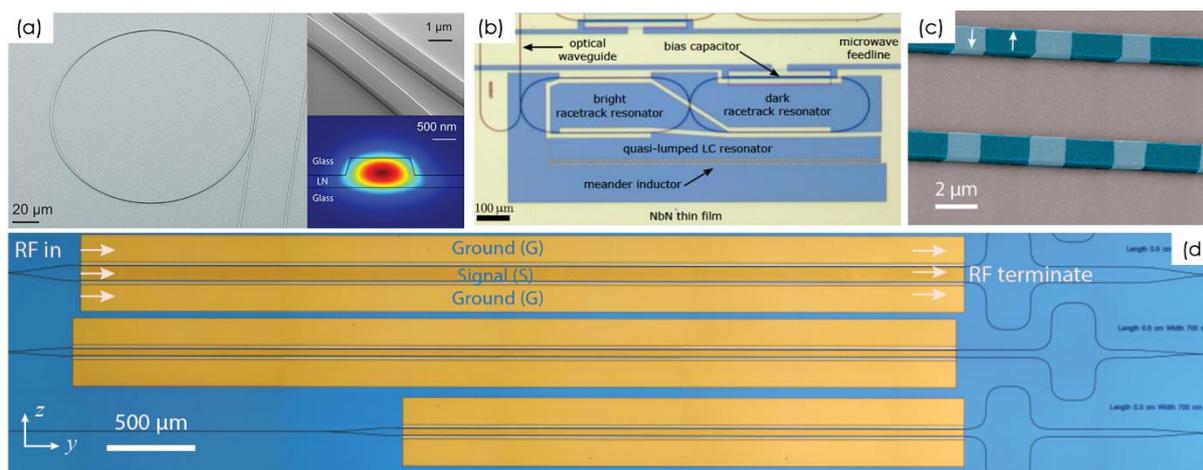


Fig 1. Integrated TFLN Photonics. (a) ultra-low loss (3 dB/m) optical waveguides and high-Q resonators ($Q \sim 10,000,000$). (b) Microwave-to-optical transducer. (c) Periodically poled TFLN frequency converter. (d) Efficient and wideband EO modulator. Reprinted with permission from [3], [9], [5], and [4], respectively.

Current and Future Challenges

Breakthroughs in TFLN nanofabrication [3] have enabled the creation of opto-electronic components with performance that surpasses those based on bulk LN, laying the groundwork for developing state-of-the-art photonic quantum processors. These components (Fig. 1) range from high-bandwidth EO modulators [4], which can enable rapid encoding of qubit states onto light or low-latency routers, to poled waveguides and resonators that convert the wavelength of a photon [5, 6] as well as generate non-classical states of light. These devices are particularly appealing for frequency-domain photonic processing applications that leverage wide bandwidth of optical photons but requires high speed modulators as well as frequency shifters/ beam splitters. The latter could be realized using an EO photonic molecule [7, 8], formed by coupling two electrically-driven resonators

Among several challenges, one common to all on-chip photonic platforms is propagation loss. TFLN has demonstrated ultra-low optical loss of less than 3 dB/m and on/off a chip coupling loss of 1.7 dB/facet using TFLN waveguide tapering [10]. The insertion loss of active EO devices must be considered, often taking into account trade-offs between efficiency and loss when designing the metal electrodes for example.

The bandwidths of TFLN EO modulators already exceed 100 GHz and is thus sufficient for many quantum applications. However, further reduction in drive voltages is important, especially when considering realization of multiplexed and dynamic switch networks and gates. These must also be interfaced with large-scale microwave circuitry for precision control and synchronization.

TFLN allows EO control of optical photons without any additional uncorrelated optical (noise) photons being induced by the (low-energy) microwave field. However, optical frequency conversion is accompanied by additional noise photons, e.g. due to Raman processes, which must be suppressed for single photon-level operation. Such conversion is important for interfacing telecommunication-wavelength photons with visible-wavelength devices, e.g. Si photodiodes and quantum memories. For that matter, TFLN circuits which operate at wavelengths out of the infrared must be further developed beyond that shown in proof-of-principle demonstrations. This would also benefit quantum state

generation by way of nonlinear processes such as spontaneous parametric down conversion, which can convert a visible photon into two telecommunication wavelength photons, and squeezing.

Heterogeneous integration of devices with TFLN, an exciting prospect to realize high-bandwidth photonic interconnects between hybrid systems, is still in its infancy. Hybrid systems include acousto-optics, single photon detectors, or atomic interfaces on TFLN. The latter could be quantum dots, color centers, or rare-earth ions, of which could act as single photon sources or mediate photonic gates. Single photon detectors on TFLN must be improved beyond that shown in initial demonstrations, e.g. with respect to efficiency (46%) and timing resolution (32 ps) [11], while also sourcing feed-forward signals for control of later operations.

Finally, full integration of all functionalities must be realized (Fig. 2). This is especially challenging for quantum circuits that require high-contrast interference, meaning no distinguishing information about a photon may be introduced by the devices. Chips must be robust to environmental disturbances, e.g. heat generated at electrodes, and operate over long periods of time in order to allow statistically relevant measurements. The latter could be problematic due to photorefraction in LN [2], which is a change of refractive index with high laser intensities, e.g. during optical frequency conversion.

Advances in Science and Technology to Meet Challenges

Along with device demonstrations and improvements, photonic loss must be reduced to the levels of the material limit, which is 0.1 dB/m for LN. This could allow optical nonlinearities at the single photon level inside ultra-high-Q TFLN resonators. Large waveguides will help in this regard by ensuring the optical mode does not interact with the rough sidewalls that are introduced by etching, but this will reduce the interaction strength with LN, and hence reduce device performance. Sidewall loss can be mitigated with further optimization at the etch step, e.g. using purer chamber gases or improved removal of re-deposited material during dry etching. The role of surrounding materials must be carefully examined, including absorption or surface chemistry from deposited oxides. Further, imperfections from the TFLN production process, such as surface roughness or impurities can be addressed by polishing and annealing. Material improvement itself must be investigated, including stoichiometric or doped TFLN, including magnesium doping which will reduce the impact of photorefraction. These improvements must be consistent across the wafer and be repeatable.

Other fundamentals, such as improving the electro-optic bandwidth of modulators must be undertaken. For resonator-based modulators, this bandwidth is restricted to tens of GHz by the width of the optical resonance and resistance-capacitance limit of the electrode. Traveling-wave modulators allow bandwidths into the hundreds of GHz using optimized velocity and impedance matching between microwave and light. The role of piezoelectric loss should also be accounted for. Among other improvements, poling precision, uniformity, repeatability, and scaling must also be addressed. Shortfalls of TFLN must be overcome with suitable heterogeneous integration, e.g. integration of diamond color centers or by leveraging microwave-frequency quantum acoustics.

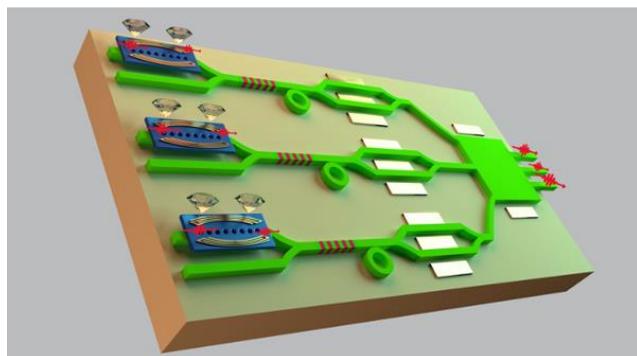


Fig. 2. Multiplexed quantum repeater node in LN that combines diamond quantum memories with low-loss nonlinear photonics.

Concluding Remarks

We are currently only beginning to see the potential that TFLN can provide to develop quantum photonics. Further steps must be taken to realize advanced and fully integrated quantum functionalities at scale. This will critically advance emerging quantum technologies, in particular quantum networks, and will result in improvements to devices used for classical photonics and telecommunications. Going forward, we expect light to play a significant role in quantum technology due to its ability to carry large amounts of frequency-multiplexed qubit information in a single spatial mode, which will allow the redundancy needed to overcome system loss and errors with a lower scaling overhead. Thus, focus should be placed on creating and improving light-matter qubit interfaces, a task well-suited to TFLN.

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