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Peer Review File

A Thin Film Lithium Niobate Near-Infrared Platform for Multiplexing Quantum Nodes

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The paper presents a comprehensive and timely study on the development of a thin film lithium niobate (TFLN) platform for near-infrared applications, specifically aimed at multiplexed quantum nodes. This work addresses significant challenges in the field of quantum networking by focusing on electro-optic frequency shifting, photonic integration, and system considerations necessary for scalable quantum networks. The experimental results and theoretical models convincingly demonstrate the potential of this platform in enhancing quantum communication protocols.

I recommend this paper for publication. However, the authors should address the following comments to improve clarity and provide additional insights that could benefit the readership.

• Frequency Shifting Precision: What are the limits of precision for the frequency shifting techniques discussed in the paper? How do these limits affect the synchronization and fidelity of quantum communication protocols? The authors could explore potential precision improvements, such as advanced control algorithms or enhanced modulator designs, and discuss their impact on quantum communication applications.
Specific Questions and Suggestions:

• Frequency Shifting Efficiency: Can the authors provide more insights into the challenges and possible solutions for achieving high efficiency in frequency shifts beyond the 15 GHz range, especially considering the analog bandwidth limitations? Reference to Figure 4d would be helpful.

• Quantum Memory Compatibility: Can the authors provide more details on the compatibility of the TFLN platform with different types of quantum memories? How does the platform handle variations in emission wavelengths and decoherence times across different quantum memory systems? Including a discussion or case studies on interfacing with technologies like diamond NV centers or rare-earth doped crystals would clarify its versatility.

• Operating point drift in LNOI Devices: How does operating point drift and hysteresis in LNOI affect the operational stability and precision of the system, and its implication on quantum memory interfacing? Discussing experimental observations and their significance.

• Mitigation of operating point drift: What strategies can be employed to minimize the impact of operating point drift and hysteresis in LNOI devices?

• Given that lithium niobate (LN) modulators are susceptible to various factors such as material defects, charge accumulation, photorefractive effects, and pyroelectric responses, how do these contribute to the overall noise in your TFLN system? Specifically, could you discuss how these sources of noise impact the fidelity of quantum operations in your platform? What noise mitigation strategies have you implemented, such as enhanced material processing, improved device design, or advanced signal processing techniques, to address these challenges and ensure reliable and high-fidelity performance of the system?

• Potential for Hybrid Integration: What are the prospects for hybrid integration of the TFLN platform with other photonic or electronic components? How can such integration enhance the functionality and performance of quantum communication systems? Discussing schemes like combining TFLN with silicon photonics or integrating with superconducting circuits could open avenues for multifunctional quantum devices.

• Thermal Management in Cryogenic Environments: Given the power dissipation issues discussed, what are the possible approaches to improve thermal management in cryogenic environments, especially for large-scale quantum networks?

Reviewer #2

(Remarks to the Author)
The authors present a study of a thin film lithium niobate (TFLN) photonic platform for multiplexing quantum nodes. The authors first propose a TFLN based photonic integrated circuit (PIC) that enables a quantum node. Next, the authors discuss the performance (both simulated and measured) of the individual components of the PIC - tapered optical fiber coupler, switches, phase modulators, laser control unit. Finally, the authors discuss the multiplexing advantage achieved by the TFLN platform presented in this paper. The results presented in this paper are promising for the field of quantum information processing and suitable for publication in Nature Communications and the paper is well organized with a systematic flow of ideas. The experiments were very clearly discussed in the main text and supplementary information.

I have a broad question with several sub questions for the authors:

The photons generated by each of the quantum nodes need to be sent over fiber to an intermediate location for entanglement purposes. The photons at the emission wavelengths of silicon vacancies experience higher losses in fiber and researchers have used frequency up- and down-conversion before sending them over fiber (Eric Bersin et al. PRX Quantum 5, 010303, 2024).
1. Would the improvements in entanglement rates achieved by this promising TFLN platform outweigh the losses in the fiber (say 50 km)? It would be useful for the reader to have a comment about the advantage achieved by this platform with regards to fiber propagation losses as well.
2. Have the authors considered the possibility of frequency up-/down-conversion to/from telecom wavelengths using components on TFLN PIC to further boost the success rates of the entanglement protocols? Or the possibility of frequency conversion using periodically poled lithium niobate (PPLN) in the calculations presented in the discussion.

There are a few minor typos and I am attaching the manuscript file highlighting them.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The authors responded to all my my comments, and I am very satisfied with the manuscript. I highly recommend it for publication.

Reviewer #2

(Remarks to the Author)
The authors present a photonic platform using thin film lithium niobate (TFLN) that meets the performance and scalability benchmarks for implementing large-scale quantum networks. The authors addressed questions from the reviewers clearly and made necessary additions to the main text and supplementary information of the manuscript, thus, increasing the overall quality and readability of this work on a promising photonic platform. I recommend this manuscript be published without any further reviews and the manuscript is highly suitable for publication in Nature Communications.

Reply of the authors to the reviewers' comments

The comments by the reviewers are written in blue. The reply by the authors is written in red. The references in this document are listed at the end and do not correspond to the reference numbers in the original manuscript.

Reviewers' comments

Authors' response

Manuscript modified text

Manuscript retained text in black

Reviewers #1 comments:

The paper presents a comprehensive and timely study on the development of a thin film lithium niobate (TFLN) platform for near-infrared applications, specifically aimed at multiplexed quantum nodes. This work addresses significant challenges in the field of quantum networking by focusing on electro-optic frequency shifting, photonic integration, and system considerations necessary for scalable quantum networks. The experimental results and theoretical models convincingly demonstrate the potential of this platform in enhancing quantum communication protocols. I recommend this paper for publication. However, the authors should address the following comments to improve clarity and provide additional insights that could benefit the readership.

We thank the reviewer for their detailed summary and their positive comments regarding our work.

• Frequency Shifting Precision: What are the limits of precision for the frequency shifting techniques discussed in the paper? How do these limits affect the synchronization and fidelity of quantum communication protocols? The authors could explore potential precision improvements, such as advanced control algorithms or enhanced modulator designs, and discuss their impact on quantum communication applications.

For electro-optic shifting, frequency precision and noise of the frequency shifting technique discussed in this work is largely set by the temporal precision of the electrical waveform that is applied to the modulator. This waveform is generated digitally by a digital to analog converter (DAC), and therefore is set by the temporal jitter of the DAC and its associated phase noise ultimately limits the precision. In our work, the jitter is quite low, equivalent to a linewidth of 17 Hz, and thus is unlikely to significantly impact the operation of solid-state qubits whose linewidths are typically on the order of MHz. The jitter can be further improved through the integration of more sophisticated timing electronics if necessary. To clarify this we have added an additional section to the SI (section 1.2.3) and added the following line to the main text:

Beyond this, the frequency precision of serrodyning is ultimately set by the temporal jitter and the phase noise of the electrical wave, applied to the modulator, which can be very high for state of the art electronics. For example, we estimate that the digital to analog converter (DAC) used in our work (Keysight M8196A) results in jitter equivalent to a 17 Hz linewidth, which is significantly smaller than the MHz linewidths of the solid-state qubits considered in this work (see supplementary section for details).

Specific Questions and Suggestions:

• Frequency Shifting Efficiency: Can the authors provide more insights into the challenges and possible solutions for achieving high efficiency in frequency shifts beyond the 15 GHz range, especially considering the analog bandwidth limitations? Reference to Figure 4d would be helpful.

We thank the reviewer for this comment. The serrodyne demonstration was limited to 15 GHz primarily due to the limited analog bandwidth of the equipment. We emphasize that test equipment with analog bandwidths up to 80 GHz is commercially available (Keysight M8199B), with even higher bandwidth analog ICs having been demonstrated in the literature (Chen et al. JLT 35, 3, (2017), Wakita et al. IEEE MWTL 33, 6, (2023)). Thus we do not view the 15 GHz of shifting demonstrated in this work as a fundamental limit, and can be further increasing using readily available high bandwidth electronics. To address this we have added a citation to Wakita et al. in addition to the previous citation to Chen et al in the main text.

Going forward, we note that using state-of-the-art commercially-available high-bandwidth electronics, shifts beyond the 15 GHz demonstrated in this work can be achieved using the same modulator (Fig. 4d, see supplementary information for details) [1, 2]

• Quantum Memory Compatibility: Can the authors provide more details on the compatibility of the TFLN platform with different types of quantum memories? How does the platform handle variations in emission wavelengths and decoherence times across different quantum memory systems? Including a discussion or case studies on interfacing with technologies like diamond NV centers or rare-earth doped crystals would clarify its versatility.

We thank the reviewer for this comment. We note that a large variety of leading quantum memories such as quantum dots (InGaAs - 940nm - Sund et al. Science Advances. 9, 19 (2023)), solid state color centers (NV - 637nm - Ruf et al. J. App. Phys. 130, 7 (2021), SiV - 737nm - Ruf et al. J. App. Phys. 130, 7 (2021), $^{171}Yb^{3+}$ - 984.5 nm - Kindem et al. Nature, 580, 201-204 (2020)), and even trapped ions ($^{40}Ca^{+}$ - 850 nm - Krutyanskiy et al. PRL 130, 050803 (2023)) have emission wavelengths in the operating regime of TFLN (> 400nm).

In terms of compatibility, the main concern beyond wavelength is photon temporal duration, as a shorter entangled photon requires a correspondingly higher bandwidth of switching to maximally multiplex multiple memories emitting photons. We note that the shortest lifetime quantum memories are typically solid-state quantum memories with lifetimes on the order of ns (Ruf et al. J. App. Phys. 130, 7 (2021), Uppu et al. Sci. Adv. 6, 50 (2020)). This is still orders of magnitude slower than the 100ps pulse shapes demonstrated in this work, thus is a non issue.

The coherence time of the quantum memory does not affect the requirements of the PIC devices, though we note it does mean that a larger number of memories are required to be interleaved per channel thus requiring a comparatively larger PIC.

To address this we have added section 2.2 to the supplementary and added the following text to the main text.

For discussion purposes we focus on solid-state defects in diamond, and specifically the silicon vacancy center in diamond, due to their excellent optical and spin properties and ability to be fabricated at scale [3–7]. Owing to the wide transparency window of TFLN (> 400nm) we emphasize that this PIC platform is compatible with many other quantum memories, including quantum dots, trapped atoms, and rare-earth doped crystals, which also emit at visible wavelengths (see supplementary information for a discussion of compatible quantum memories).

• Operating point drift in LNOI Devices: How does operating point drift and hysteresis in LNOI affect the operational stability and precision of the system, and its implication on quantum memory interfacing? Discussing experimental observations and their significance. • Mitigation of operating point drift: What strategies can be employed to minimize the impact of operating point drift and hysteresis in LNOI devices?

We thank the reviewer for this question. Bias drift is indeed an issue in lithium niobate modulators, a careful study of which is beyond the scope of this work but has been investigated in recent, related works from our group (Holzgrafe et al. Optics Express 32 (3) 2024, Renaud et al). The literature highlights that through device and process optimizations, which were implemented in the devices presented in this work, bias drift in TFLN can be limited to time scales of seconds or longer. At these time scales implementation of feedback electronics to alleviate the drift is relatively straightforward. We in fact, utilized an electro-optic bias feedback loop in our demonstration of shearing (Fig 5) to keep the amplitude modulator at the null point using standard benchtop electronics and a software-based control loop. We thus believe that this combination of optimized devices with minimal feedback is a scalable method for creating bias-stable devices. To address this comment we have added a section in the SI detailing the bias feedback protocol we implemented and discussing the feasibility of performing electrical bias feedback on a large scale (Section 2.3). In addition we have added the following text to the main text to better highlight the work undertaken to minimize operational bias drift in our devices:

We note that low frequency rolloff of the electro-optic response can result in observed operational bias drifts in TFLN devices [8]. In our work, the observed V_π is flat as a function of frequency down to 0.1 Hz which is important both for low frequency switching operation and achieving a stable modulator bias [8]. This excellent low-frequency response is due to engineering of the TFLN-electrode interface and process conditions and is sufficient to enable simple electrical biasing of the modulator with minimal electrical feedback (see supplementary information for additional details).

As well as the following line highlighting the use of electrical feedback to prevent operational drift in our shearing demonstration:

We bias the amplitude modulator at the null point for pulse generation using a quasi-DC electro-optic bias whereby a feedback loop is applied to the low-frequency electrical bias of the modulator loop to overcome the DC bias drift prevalent in TFLN modulators [8, 9]. As our modulators are optimized to minimize bias drift, we are able to compensate for the drift using off-the-shelf electronics and a simple software-based feedback loop. This demonstration thus highlights the ability of our devices to be biased purely electrically with minimal feedback, enabling their operation in cryogenic environments.

In terms of how significant bias drift affects the proposed PIC platform, the two elements that are sensitive to bias drift are the amplitude modulator in the laser control unit and the switching network. Drift in the LCU bias will limit the effective extinction ratio of the generated optical pulses. For the switch newtork, if the switch network is solely used for multiplexing of quantum memories onto a common channel bias drift principally effects efficiency as opposed to fidelity, and thus the devices are less sensitive to it. We added a section discussing this in the SI, section 2.3.1

• Given that lithium niobate (LN) modulators are susceptible to various factors such as material defects, charge accumulation, photorefractive effects, and pyroelectric responses, how do these contribute to the overall noise in your TFLN system? Specifically, could you discuss how these sources of noise impact the fidelity of quantum operations in your platform? What noise mitigation strategies have you implemented, such as enhanced material processing, improved device design, or advanced signal processing techniques, to address these challenges and ensure reliable and high-fidelity performance of the system?

We thank the reviewer for this comment. All of these effects ultimately cause bias drift in the LN modulator and thus the previously mentioned bias feedback can effectively compensate for them. In addition, we will note that photorefractive effects, which have long been known to be an issue in lithium niobate particularly at short wavelengths, have been shown to only occur in TFLN at optical powers on the order of mW (Celik et al, IEEE Photonics Conference 2023). As solid-state quantum networks typically require a maximum power of uW for input control power (and typically much less) (Nguyen, PRB, 100, 165428 (2019)), this is orders of magnitude lower than the photorefractive bound and thus photorefractive effects are unlikely to play a major role in the operation of these quantum PICs.

To address this we added this to the discussion in section 2.3:

One concern with short-wavelength LN modulators is photorefractive effects that can occur at mW power levels [10]. However, the optical power required to control and read out solid-state quantum emitters is orders of magnitude smaller, in the uW range and single photon range, respectively, and therefore we do not anticipate issues with the photorefractive effect.

• Potential for Hybrid Integration: What are the prospects for hybrid integration of the TFLN platform with other photonic or electronic components? How can such integration enhance the functionality and performance of quantum communication systems? Discussing schemes like combining TFLN with silicon photonics or integrating with superconducting circuits could open avenues for multifunctional quantum devices.

We thank the reviewer for this comment. We agree that integration of this platform with other photonic platforms, such as III-V active materials or low-loss silicon nitride platforms, or integration with superconducting circuits could enable novel functionalities that are being actively explored by other works within our group and beyond. To highlight these possibilities we have added the following sentence to the conclusion of the main text.

Furthermore, future work can investigate the integration of other materials into the platform such as III-V for on-chip classical and non-classical light sources and photodetectors [11–13], silicon-nitride for ultra low-loss waveguides [14], or superconducting circuits to further minimize power dissipation of the PIC and enable hybrid microwave-optical systems [15–17]. Together these can enable novel functionalities for new quantum architectures.

• Thermal Management in Cryogenic Environments: Given the power dissipation issues discussed, what are the possible approaches to improve thermal management in cryogenic environments, especially for large-scale quantum networks?

We thank the reviewer for this question. We first note that integration of the PIC within a cryostat is not necessarily required to realize large-scale quantum network nodes as we discuss in SI Section 2.3, in which case the thermal management becomes a non-issue. In the case that diamond qubits are integrated on TFLN, indeed thermal dissipation needs to be taken into account. Then, additional device additional device improvements can potentially further improve the power dissipation such as integration of superconducting material to limit electrical losses. To address this we have added the following statements in the main text:

Beyond that, future work can investigate the integration of other materials into the platform such as III-V for on-chip classical and non-classical light sources and photodetectors [11–13], silicon-nitride for ultra low-loss waveguides [14], or superconducting circuits to further minimize power dissipation of the PIC and enable hybrid microwave-optical systems [15–17]. Together these can enable novel functionalities for new quantum architectures.

And the following response to the SI Section 2.4 on power dissipation.

If further improvements to power dissipation are required, the integration of superconducting electrodes in the modulator could potentially improve this further.

Reviewers #2 comments:

The authors present a study of a thin film lithium niobate (TFLN) photonic platform for multiplexing quantum nodes. The authors first propose a TFLN based photonic integrated circuit (PIC) that enables a quantum node. Next, the authors discuss the performance (both simulated and measured) of the individual components of the PIC - tapered optical fiber coupler, switches, phase modulators, laser control unit. Finally, the authors discuss the multiplexing advantage achieved by the TFLN platform presented in this paper. The results presented in this paper are promising for the field of quantum information processing and suitable for publication in Nature Communications and the paper is well organized with a systematic flow of ideas. The experiments were very clearly discussed in the main text and supplementary information.

We thank the reviewer for their detailed summary of our work and their positive comments regarding our work.

I have a broad question with several sub questions for the authors:

The photons generated by each of the quantum nodes need to be sent over fiber to an intermediate location for entanglement purposes. The photons at the emission wavelengths of silicon vacancies experience higher losses in fiber and researchers have used frequency up- and down-conversion before sending them over fiber (Eric Bersin et al. PRX Quantum 5, 010303, 2024). 1. Would the improvements in entanglement rates achieved by this promising TFLN platform outweigh the losses in the fiber (say 50 km)? It would be useful for the reader to have a comment about the advantage achieved by this platform with regards to fiber propagation losses as well.

We thank the reviewer for this comment. We note that the relative advantage of using multiplexing as compared to using a single memory would increase for longer lengths. This is since it would take a longer time for the photons to travel from the memory nodes at the edges of the link to the central measurement node, thus leaving more dead time on the channel. However, we note that this advantage does not in general outweigh the excess losses due to the longer fiber length. This is since the loss of the transmission medium scales exponentially with length, whereas the dead time of the channel only scales linearly. Thus it is still important to minimize the loss per km of the channel, meaning that quantum frequency conversion of the entangled photons from visible to telecom wavelengths is still required (see response to question 2). In response to this we have added a new figure 9 in the SI and have made the following modification to the main text:

At larger channel lengths, we estimate that by using TFLN based temporal multiplexing we can maintain entanglement rates in excess of a kHz for lengths beyond 60km. Although this is lower in absolute rate compared to the 20km channel due to the exponential increase of loss with fiber length, it is over three order of magnitudes larger than that achieved with a single quantum memory (see SI).

2. Have the authors considered the possibility of frequency up-/down-conversion to/from telecom wavelengths using components on TFLN PIC to further boost the success rates of the entanglement protocols? Or the possibility of frequency conversion using periodically poled lithium niobate (PPLN) in the calculations presented in the discussion.

We thank the reviewer for this comment. In the entanglement calculations presented in Figure 6, we in fact did assume the use of nonlinear optical based frequency conversion of the memory-entangled photons from the visible spectrum to the telecommunication band to facilitate low-loss transmission through optical fiber, though we assumed this would be done through using a discrete PPLN component available commercially and assumed a conversion loss of 50% (including both conversion and filtering) as demonstrated by recent works (van Leent et al. PRL 124, 010510 (2020)). We agree that although this was discussed in the supplementary information, it was not made clear in the main text and thus we have added the following sentence: In our calculations we considered propagation losses of 0.3dB/km typical of optical fibers at 1350nm. We also included a 3dB loss associated with frequency down-conversion of 737nm photon to 1350 nm that is typical in state of the art PPLN components [18–20].

We agree that while directly integrating PPLN in the TFLN circuit is a promising future direction, it is beyond the scope of this work. Namely, although TFLN based PPLN could enable lower loss conversion efficiencies due to the direct integration of conversion on the same PIC, since switching in our architecture is done at visible wavelengths, only a single wavelength-conversion stage is needed per fiber link ensuring a significantly reduced number of PPLN devices are needed as compared to quantum memory devices for large scale multiplexed quantum network nodes. Thus bulk PPLN components are likely sufficiently scalable from a manufacturing point of view to enable future quantum nodes. To address this we have added the following text to the main text:

In addition, the future integration of thin film periodically-poled lithium niobate structures within the platform can decrease system complexity and enable higher efficiency visible to telecom conversion to achieve performance beyond that projected in Fig 6 [21, 22].

We also added the following text to the supplementary information section 2.1:

Note that we assume the use of nonlinear-optic based quantum frequency conversion (QFC) outside of the TFLN PIC to convert entangled photons from visible to telecom wavelength to enable transmission across long-distances of fiber. Although in the future the integration of periodically poled lithium niobate (PPLN) could potentially enable nonlinear optical frequency conversion directly on the PIC, for the purposes of this work we assume it is performed separately from the PIC using commercially available conventional PPLN waveguides realized in bulk crystals. The reason for this is that bulk QFC systems have already demonstrated impressive performances sufficient to realize large-scale quantum networks [18, 19]. Furthermore, in the architecture proposed in this work, multiplexing is performed at visible wavelengths and therefore only a single QFC stage is required per fiber channel (as opposed to the 1000s of memories and switch elements required per fiber channel). Although the integration of thin film PPLN could enhance the performance and versatility of our platform, it may not be required to realize large-scale quantum networks proposed in this work.

There are a few minor typos and I am attaching the manuscript file highlighting them.

We thank the reviewer for highlighting these. They have been corrected.

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