NQSTI
National Quantum Science and Technology Institute

A Quantum-Key-Distribution State Encoder in Thin Film Lithium Niobate for Free-Space Channels at 1550 nm

Lorenzo De Marinis[1], **Peter Seigo Kincaid**[1], **Peppino Primiani**[2], **Carlo Liorni**[3], **Pierfrancesco Ulpiani**[3], **and Giampiero Contestabile**[1]

1. Scuola Superiore Sant'Anna, TeCIP Institute, 56124, Pisa, Italy – lorenzo.demarinis@santannapisa.it
2. Leonardo Innovation Hub, Via delle Officine Galileo 1, Campi Bisenzio 50011, Italy
3. Leonardo Innovation Hub, Via Tiburtina km 12400, Rome 00131, Italy

Abstract: A Quantum Key Distribution state encoder is presented for free space links based on the TFLN platform, allowing higher secret key rate and lower quantum bit error rate compared to the state of the art.

The realization of a global quantum communication network requires the deployment of compact, high-performance state encoders capable of operating across both fiber and free-space channels. Although silicon photonics has provided a robust platform for miniaturisation and large-scale production of quantum chips, the performance of high-speed silicon chips is limited by the high insertion losses of carrier-depletion modulators. The recent developments in the thin-film lithium niobate (TFLN) platform opened the possibility to manufacture miniaturized high-quality modulators made of this material with a high yield [1]. In this work, we present a high-efficiency Quantum Key Distribution (QKD) state encoder designed for a TFLN platform, implementing a 3-state 1-decoy protocol [2] at 1550 nm. Our TFLN-based architecture, depicted in Fig. 1, leverages the low losses and superior electro-optic properties of lithium niobate to enhance the quantum bit error rate (QBER) and secret key rate (SKR). The encoder integrates a decoy-state generation stage followed by a polarization-encoding stage, utilizing high-speed Mach-Zehnder Interferometers, which terminate in a two-dimensional grating polarization splitter, used to convert the path information of the photons into polarization-encoded information at the chip output. The chip dimensions are $10\ mm \times 5\ mm$, with $5\ mm$ long high-speed modulators.

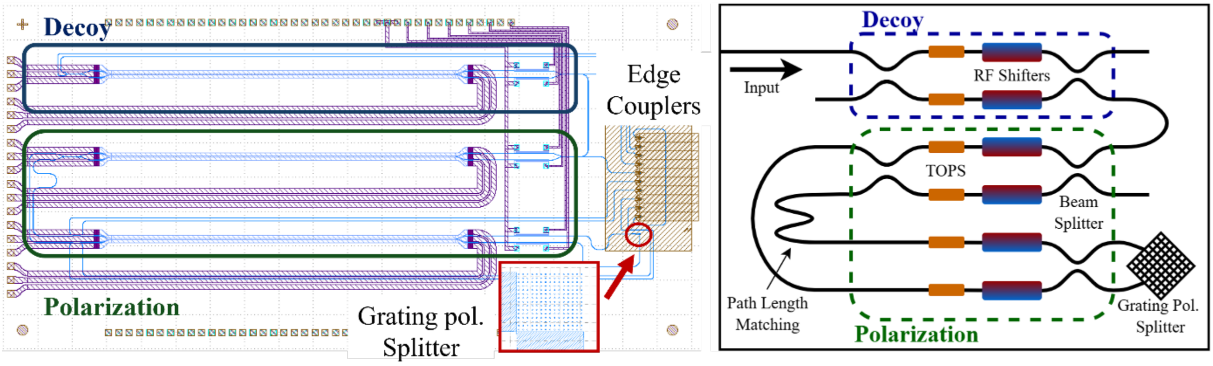

Fig. 1 GDS layout of the TFLN photonic integrated circuit (left). Schematic of the circuit (right). TOPS: Thermo-optic phase shifter.

To quantify the impact of the TFLN platform, we perform a comparative link-budget analysis against the silicon-photonics benchmark [3]. The key rate R can be modelled in the asymptotic limit as $R \approx 0.5 f_s \mu \eta [1 - H_2(e)]$, where f_s is the repetition rate, μ is the mean photon number per pulse, η is the system transmittance, and $H_2(e)$ is the binary entropy of the QBER. The total optical loss of the TFLN is estimated at 3.5 dB, compared to the 12 dB of the Si implementation [3]. This 8.5 dB reduction corresponds to a linear gain in η by $G_\eta = 10^{8.5/10} \approx 7.08$. Hence, the TFLN encoder theoretically delivers a 7-fold increase in the photon count at the receiver. In the presence of identical channel conditions, the SKR increases from 30 kbps to 212 kbps with a 50 MHz clock as in the reference scenario [3]. Instead, by employing a 1 GHz clock, the secure key generation can reach 4.2 Mbps. The linear electro-optic response of TFLN ensures that the pulse intensity remains constant regardless of the phase shift applied (no residual amplitude modulation), which is a common source of state leakage and increased QBER in silicon photonics. Consequently, we anticipate a more stable "null" state and a reduction in the intrinsic QBER below the 0.5% threshold. As a reference, the highest reported SKR for a QKD ground-to-ground free space link is $\approx$ 160 kbps, with a QBER of 2.3% [4].

References

[1] Hu, Yaowen, et al. "Integrated electro-optics on thin-film lithium niobate." *Nature Reviews Physics* 7.5 (2025): 237-254.

[2] Rusca, D., Boaron, A., Grünenfelder, F., Martin, A. & Zbinden, H. Finite-key analysis for the 1-decoy state qkd protocol. Appl. Phys. Lett. 112, 171104 (2018)

[3] Avesani, M., et al. "Full daylight quantum-key-distribution at 1550 nm enabled by integrated silicon photonics." npj Quantum Information 7.1 (2021): 93.

[4] Zhang, Li, et al. "High-speed phase-encoded quantum key distribution over a 1.4-km free-space channel." *Optica Quantum* 4.2 (2026)