Post-selection free time-bin entanglement on a thin-film lithium niobate photonic chip

A. Bernardi[1,2], M. Bacchi[3], M. Clementi[3], S. Congia[3], F. Garrisi[2], A. Martellosio[2], M. Passoni[2], A. Wrobel[2], F. A. Sabattoli[2], M. Galli[3], and D. Bajoni[1]

1. Dipartimento di Ingegneria Industriale e dell'Informazione, Università di Pavia, Via Ferrata 5, 27100 Pavia, Italy

2. Advanced Fiber Resources Milan s.r.l., Via Fellini 4, 20097 San Donato Milanese, Italy

3. Dipartimento di Fisica, Università di Pavia, Via Bassi 6, 27100 Pavia, Italy

Abstract: We experimentally demonstrate a thin-film lithium niobate photonic chip to measure time-bin entanglement without the temporal post-selection loophole. We show a violation of the Bell inequality by more than 20 standard deviations.

Entangled photons shared between parties are pivotal in quantum communication protocols, such as quantum teleportation and quantum key distribution (QKD). Time-bin entanglement offers significant advantages in long-distance communication due to its robustness and simplicity in optical fiber and free space. However, it is hindered by the post-selection loophole (PSL), allowing local hidden variable models to reproduce quantum predictions [1]. Temporal post-selection also opens the door to attack schemes and demands high temporal resolution, limiting its practical utility. The PSL was first removed using hyperentangled states in polarization and time-bin [2]. Vedovato et al. later demonstrated genuine time-bin entanglement via active switching [3], and recently, PSL-free certification was achieved with the "hug" scheme [4], which requires a phase-stabilized optical link.

We present an integrated photonic circuit in thin-film lithium niobate (TFLN) technology for PSL-free Bell tests with time-bin entangled states. The device uses a high-speed Mach-Zehnder modulator (MZM) as an active switch, routing early (late) entangled photon pairs in the long (short) path of an unbalanced Franson interferometer. TFLN's electro-optic modulation capabilities allow to close the PSL and mitigate the need for high-speed detectors and time taggers.

The device was tested with and without modulation applied to the optical switch. Without modulation, the optical switch behaves as a 50:50 beam-splitter, and three peaks are seen in the correlation histogram (Fig. 1b). The maximum observable visibility of two-photon quantum interference in this condition is limited to 25% [5]. In our experiment, we recorded a visibility of (22.30±0.62)% (Fig. 1c). When the optical switch is modulated with a sinusoidal signal at a peak-to-peak voltage of $V\pi$=4.35V at a frequency of 5 GHz, photons experience the same time delay, and histograms display one single peak (Fig. 1b). Here, we observe a visibility of (86.11±0.68)% (Fig. 1c), corresponding to a violation of Bell's inequality by more than 20 standard deviations.

This is the first integrated optical circuit for genuine time-bin entanglement with active switching. Spurious sidebands are suppressed (Fig. 1b), simplifying measurements by reducing temporal resolution requirements. These results mark progress toward practical, market-oriented quantum telecommunication systems.

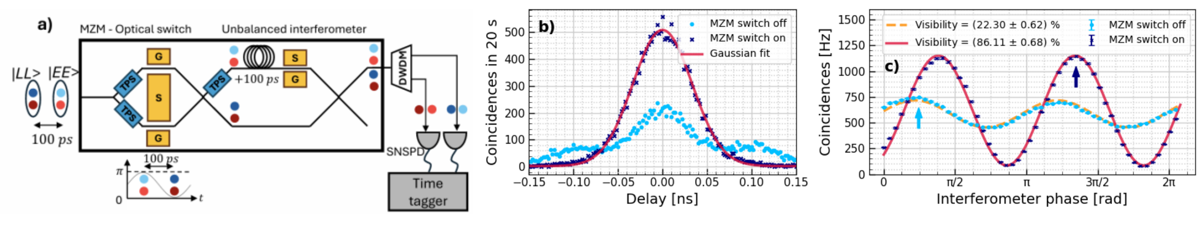

Fig. 1 a) Schematic of the integrated photonic circuit. TPS: Thermal Phase Shifter, S: Signal, G:Ground, SNSPD: Superconducting nanowire single-photon detector. Red and blue dots correspond to signal and idler photons generated by the early or late pump pulse. b) Correlation histograms corresponding to points of maxima of the two-photon interference curves (light and dark blue arrows in panel c). The histogram width is limited by the detectors jitter (70 ps). c) Bell's curve without (light blue) and with (dark blue) modulation applied to the optical switch. Coincidences are obtained by integrating all detection events recorded in the temporal histograms without any post-selection.

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