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

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The distribution of entangled photons between remote parties is fundamental for quantum communication protocols such as quantum teleportation and quantum key distribution (QKD). Among the various encoding schemes, time-bin entanglement is particularly promising as it ensures reliable long-distance communication for both optical fibre and free-space channels. However, the practical utility of time bin entanglement is constrained by the post-selection loophole (PSL), which allows for the possibility of local hidden variable models [1]. Temporal post-selection also opens the door to attack schemes and demands high temporal resolution. Initial efforts to close the PSL employed hyperentangled states combining polarization and time-bin degrees of freedom [2]. Later, Vedovato et al. used active switching to remove the need for post-selection [3], and an integrated "hug" scheme was used to demonstrate PSL-free certification through a phase-stabilized optical link [4].

Here we present an integrated photonic device built on thin-film lithium niobate (TFLN) technology, designed for PSL-free Bell tests with time-bin entangled states. The system features a high-speed Mach-Zehnder modulator (MZM) functioning as an active switch, which directs early (late) entangled photon pairs along the long (short) arm of an unbalanced Franson interferometer. By exploiting the electro-optic modulation properties of TFLN, the device not only closes the PSL but also minimizes dependence on high-speed detectors and time-tagging systems, facilitating the practical deployment of photon-based time-bin entanglement while operating at GHz-level generation rates.

The device performance was evaluated both in the absence and presence of modulation applied to the optical switch. When no modulation is applied, the switch operated as a 50:50 beam splitter, producing three peaks in the correlation histogram (Fig. 1b). In this configuration, the theoretical upper limit for two-photon quantum interference visibility is 25 % [5], and we experimentally observed a visibility of (22.30 ± 0.62) % (Fig. 1c). By applying a sinusoidal modulation signal with a peak-to-peak voltage of V_π = 4.35 V at 5 GHz, photons experienced same time delays, suppressing the spurious sidebands resulting in a single-peak histogram (Fig. 1b). This setup yielded a visibility of (86.11 ± 0.68) % (Fig. 1c), corresponding to a Bell inequality violation by more than 20 standard deviations.

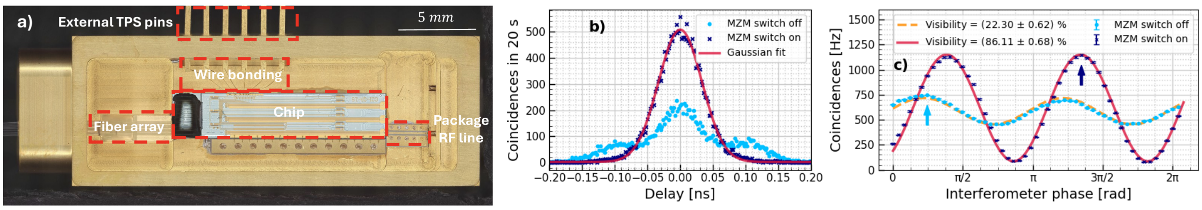

Fig. 1 (a) Micrograph of the packaged device. TPS: Thermal Phase Shifter. (b) Correlation histograms in the maximum of the two-photon interference (indicated by light and dark blue arrows in panel c). The histogram width is limited by the detector jitter (70 ps). (c) Bell curves measured without modulation (light blue) and with modulation (dark blue) applied to the optical switch. Coincidence counts were obtained by summing all detection events in the temporal histograms, without applying any post-selection.

References

[1] S. Aerts, P. Kwiat, J. A. Larsson, and M. Żukowski, "Two-Photon Franson-Type Experiments and Local Realism, Phys. Rev. Lett., 83, 2872 (1999).

[2] F. Vedovato, C. Agnesi, M. Tomasin, M. Avesani, J. A. Larsson, G. Vallone, and P. Villoresi, "Postselection-Loophole-Free Bell Violation with Genuine Time-Bin Entanglement", Phys. Rev. Lett., 121, 190401 (2018).

[3] I. Marcikic, H. de Riedmatten, W. Tittel, V. Scarani, H. Zbinden, and N. Gisin, "Time-bin entangled qubits for quantum communication created by femtosecond pulses", Phys. Rev. A, 66, 062308 (2002).

[4] F. B. L. Santagiustina, C. Agnesi, A. Alarcón, A. Cabello, G. B. Xavier, P. Villoresi, G. Vallone, "Experimental post-selection loophole-free time-bin and energy-time nonlocality with integrated photonics", Optica, 11(4), (2024).

[5] I. Marcikic, H. de Riedmatten, W. Tittel, V. Scarani, H. Zbinden, and N. Gisin, "Time-bin entangled qubits for quantum communication created by femtosecond pulses", Phys. Rev. A, 66, 062308 (2002).