Near-maximal Polarisation Entanglement for Device-Independent Quantum Key Distribution at 2.1 μm

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I. Introduction and Motivation

- Quantum-enhanced optical systems operating within the 2–2.5 μm spectral region have the potential to revolutionize emerging applications in communications, sensing and metrology.
- However, until now, sources of entangled photons have been realized mainly in the near-infrared 700–1550 nm spectral window.
- Above 2 μm lies an atmospheric transparency window with nearly one-third of the solar blackbody radiation of what is typical at telecom wavelengths [1] (see Fig. 1).
- This makes the 2–2.5 μm spectral region highly promising for quantum-secured links, such as for daylight satellite-to-ground and satellite-to-satellite quantum communications.
- Guided-wave optics is also rapidly developing into the 2-μm region to satisfy the need for larger bandwidths due to the increasing volumes of data traffic.
- Solutions such as novel hollow-core photonic bandgap fibres working in the mid-infrared offer reduced optical nonlinearities and lower losses and are currently under test for network implementations.

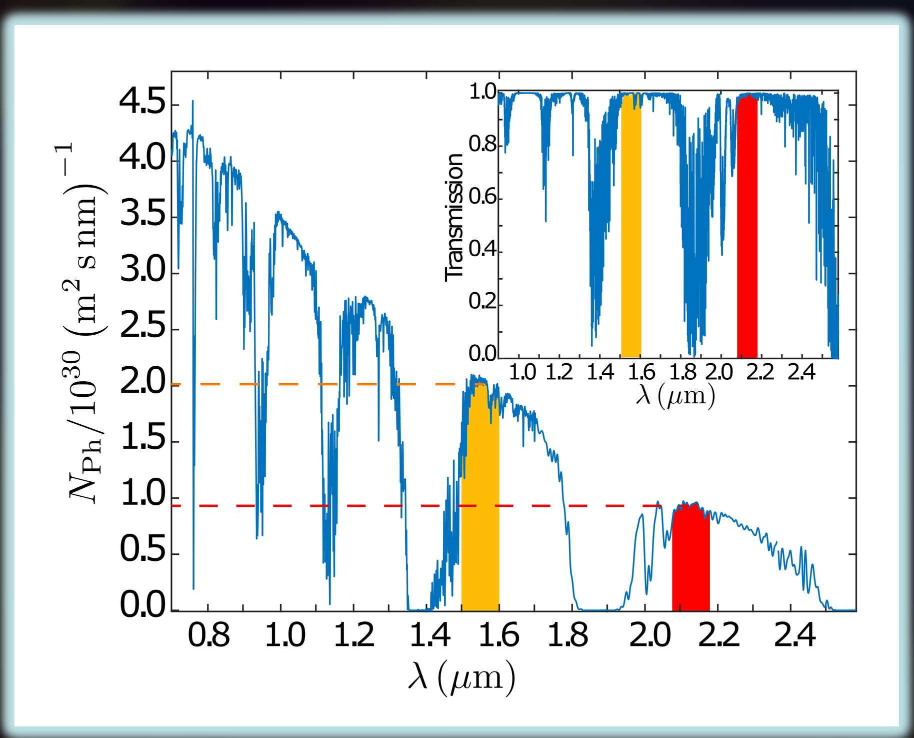


Figure 1: **Solar photon flux density at sea level [1].** Inset: Mauna Kea sky infrared transmission spectrum. In yellow (red) a 100 nm band around 1550 (2100) nm.

II. Summary of Key Results

- Using custom-designed lithium niobate crystals for spontaneous parametric down-conversion and tailored superconducting-nanowire single-photon detectors, we demonstrate:
  - Full-state quantum tomography and near-maximal two-photon entanglement at 2.1μm.
  - Capability of the measured state for device-independent (DI) quantum key distribution (QKD).

III. Experimental Setup

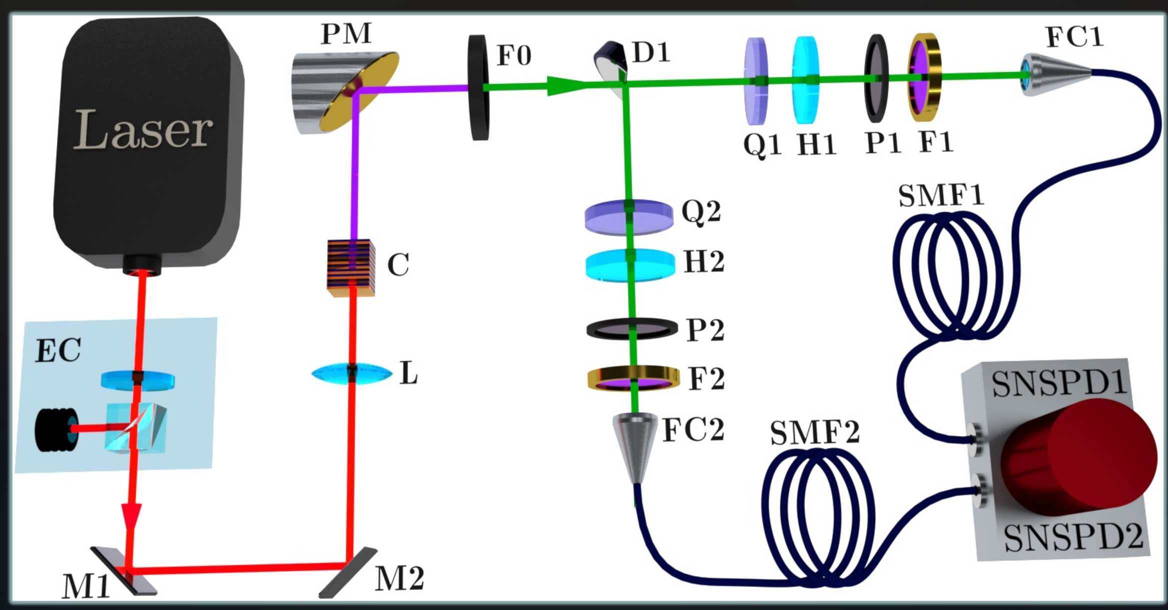


Figure 2: Generation and full tomography of polarization entangled photons at 2.1μm.

- The setup consists of mirrors (M1/2), attenuator/energy controller (EC), lenses (L1 and FC1/2), the PPLN crystal (C), Ge filter (F0), a D-shaped pickoff mirror (D), 50-nm-passband filters (F1/2), halfwave plates (H1/2), quarter-wave plates (Q1/2), polarizers (P1/2), single-mode fibers (SMF1/2), superconducting nanowire single-photon detectors (SNSPD1/2).
- We used periodically poled, magnesium-doped lithium niobate crystals (MgO-PPLN; Covesion Ltd.), with lengths 1 mm and 0.3 mm cut for type-0 and type-2 phase matching, respectively.

IV. Coincidence to Accidentals Ratio

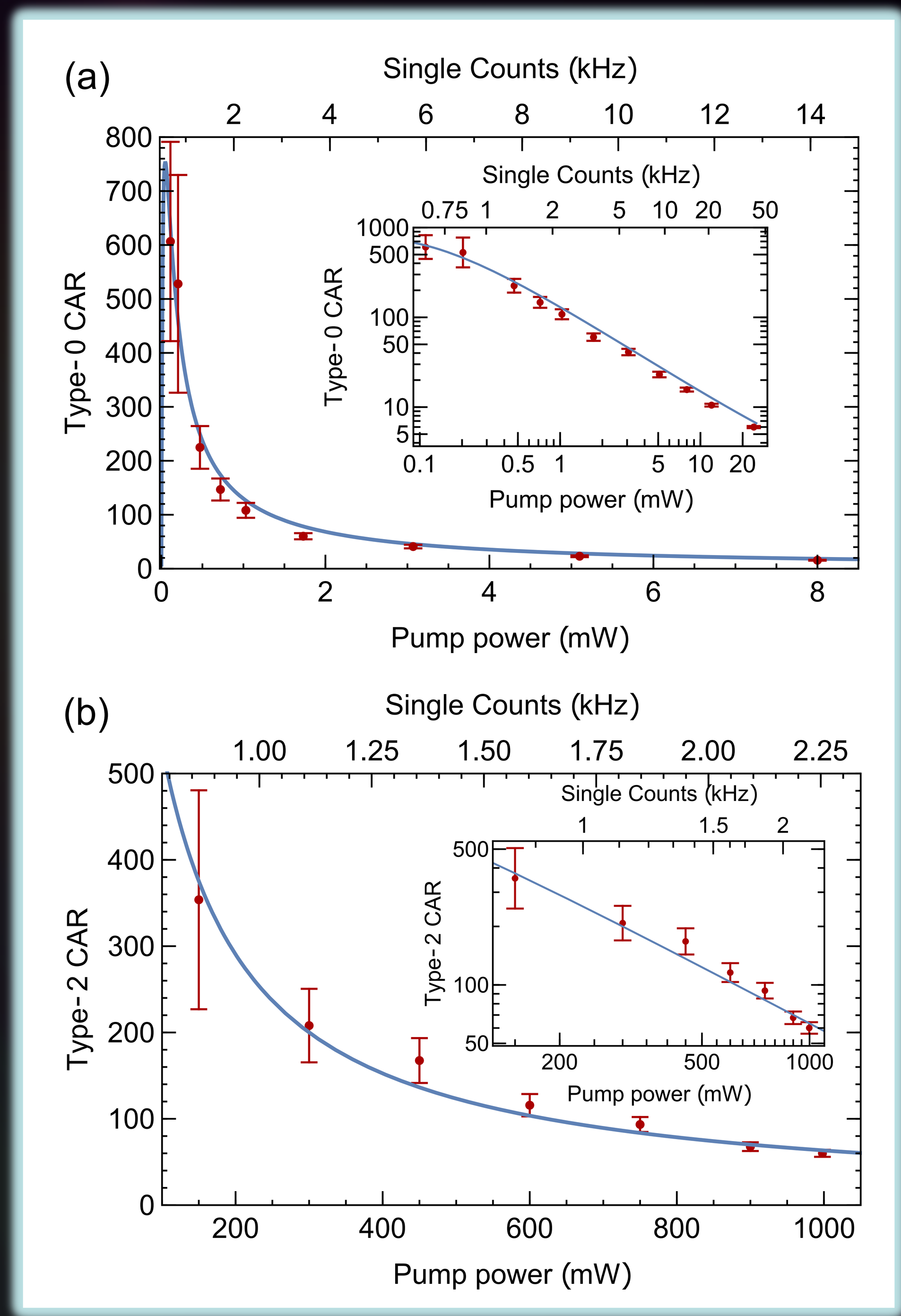


Figure 3. Coincidence measurements at 2.1 μm.

- Measured coincidence-to-accidental ratio (CAR) as a function of the averaged single count rates between detectors 1 and 2, for the (a) type-0 and (b) type-2 sources. The insets show the plots on logarithmic scales. The 'single' counts include the detector dark count rates of ~500 Hz in each arm.
- For the type-0(2) measurement, we projected the state onto |V,V⟩(|V,H⟩) and measure a CAR of 607 ±185 (354±127), ~3 times the state-of-the-art.

V. Quantum State Tomography

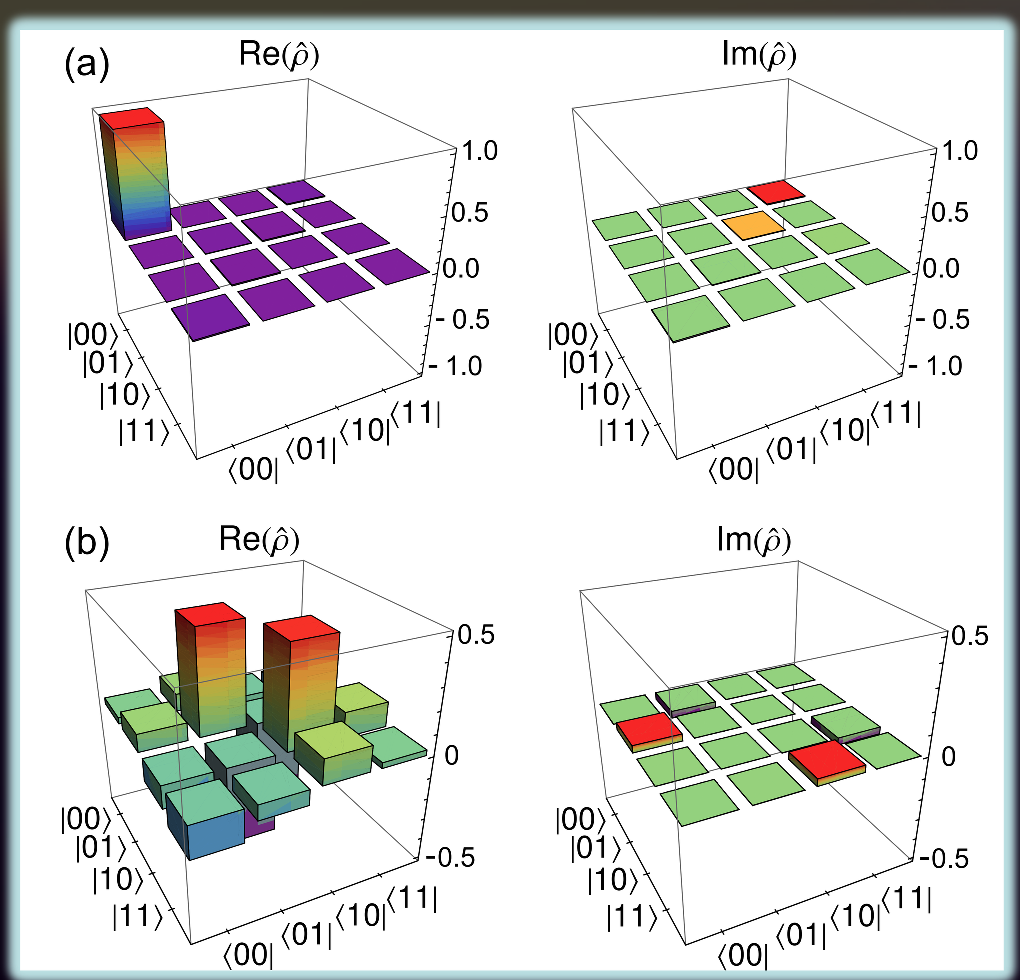


Figure 4: The real (Re) and imaginary (Im) parts of the reconstructed density matrices of the generated states measured by quantum state tomography using the setup in Fig. 2 for (a) type-0 SPDC source (b) type-2 SPDC source, respectively. Here "0" ≡|V⟩ and "1" ≡|H⟩.

(a) Type-0 state: |V,V⟩
Pair detection rate: 13 Hz
State purity: 99%
Fidelity: 99.5%

(b) Type-2 state: (|H,V⟩-|V,H⟩) /√2
Pair detection rate: 2.27 Hz
State purity: 82.55%
Fidelity: 83.13%

- The integration time was 30 minutes for each measurement.

VI. Entanglement @ 2.1μm & Suitability for DI QKD

We obtain:

- **CHSH-Bell parameter**
  S = 2.7 ± 0.03 > 2 (local bound)
- **Entanglement of Formation: E_F = 0.6746**
- **Concurrence: C = 0.7642**

Self-testing for singlet state:
Threshold for CHSH Bell parameter
S' = (16 + 14√2/17) ≈ 2.11, and S=2.7 > S'

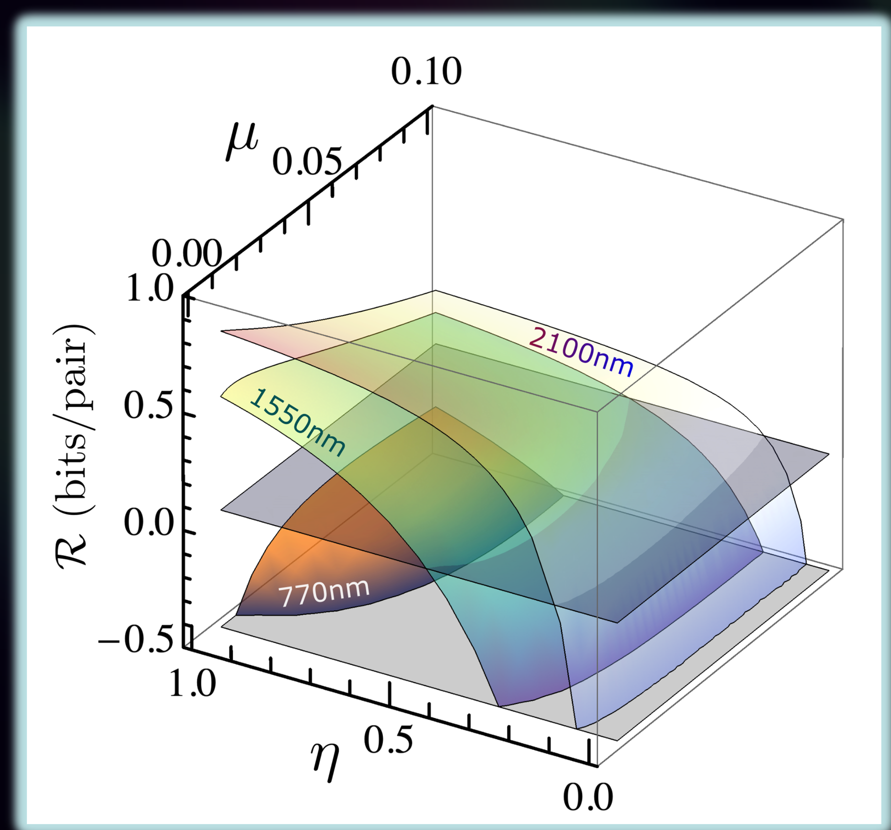
Weak form of Self-testing [6]

- Certifies the quantum state without full determination of the measurement.
- Not previously been addressed experimentally
- We show a violation of the three-setting inequality with **β = 4.77 > 4** (local bound)

For an Ekert91-based QKD protocol [7], we compute

- **Quantum bit error rate (QBER): 5.43%**
- **Lower bound on the DI secure key rate: R = 0.417 bits/pair > 0**

Figure 5: Motivation for future QKD work at 2.1 μm. Simulation of lower bounds on secure key rates for DI QKD at 2.1 μm, 1.55 μm and 770 nm in free-space at day-time, based on the data in Fig. 1. Secure key rates R for DIQKD [4,5] as functions of the number of photons per pulse μ and total channel efficiency η at different wavelengths.



References: [1] ASTM, Standard Solar Constant and Zero Air Mass Solar Spectral Irradiance Tables (ASTM International, 2006); [2] S. Prabhakar, T. Shields, A. C. Dada, *et al.*, Science Advances **6**, eaay5195 (2020) [3] A. C. Dada, *et al.*, arXiv preprint arXiv:2106.10194 [quant-ph] (2021). [4] A. Acín, *et al.*, Phys. Rev. Lett. **98**, 230501 (2007). [5] S. Pironio, *et al.*, New Journal of Physics **11**, 045021 (2009) [6] J. Kaniewski. Phys. Rev. Research **2**, 033420 (2020) [7] A. Acin, *et al.*, New Journal of Physics **8**, 126 (2006)

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For more details, please see [1] or scan the **QR code** to read **the paper** >>>>>>>>>>