QuICHE

Quantum Information and Communication with High-Dimensional Encoding

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The consortium

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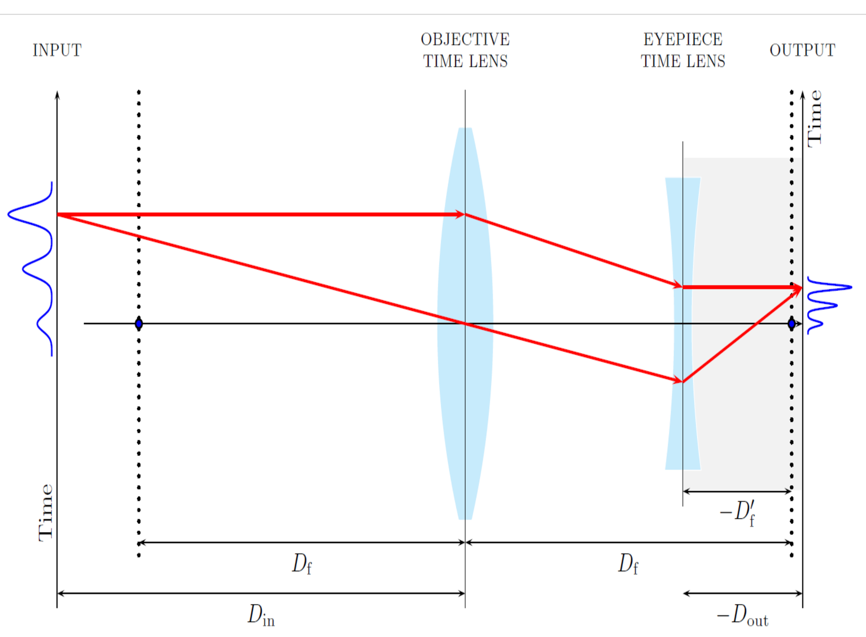
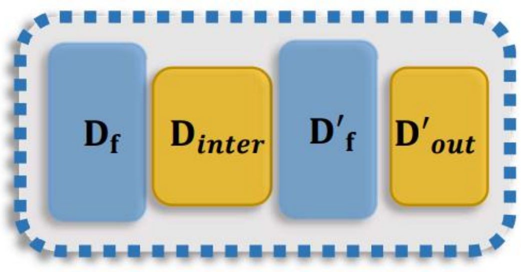
Quantum temporal imaging: an erecting time telescope

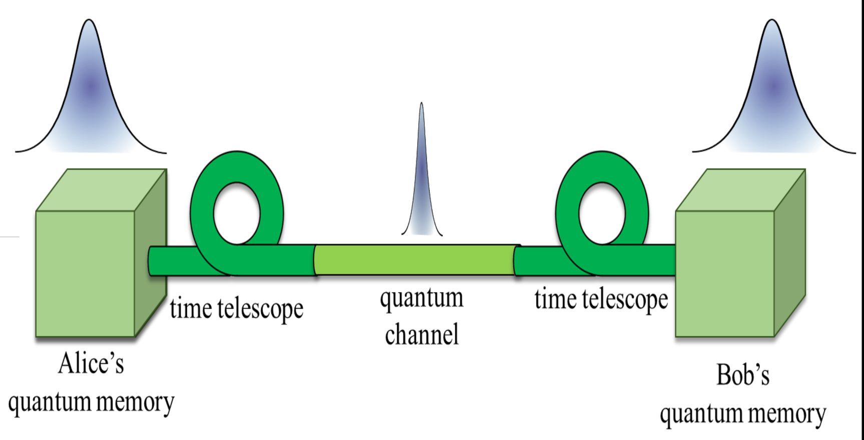
Université de Lille



Geometrical optics representation of the erecting compressing time telescope. The grey area shows a dispersive medium with a negative GDD, resulting in the creation of a real image at the output. This element is not possible in the spatial domain because negative diffraction does not exist while negative dispersion does.



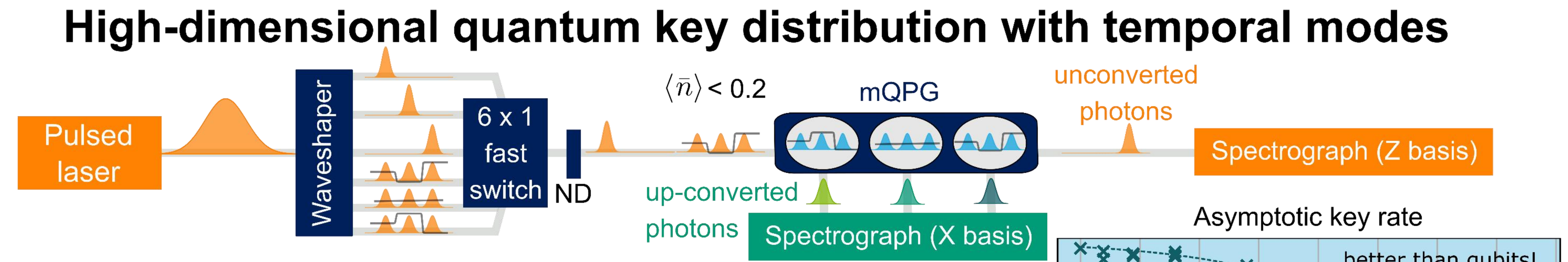
Erecting compressing time telescope with no input dispersive medium. Either D_{in} or D_{out}' can be made equal to zero to minimize the number of elements.



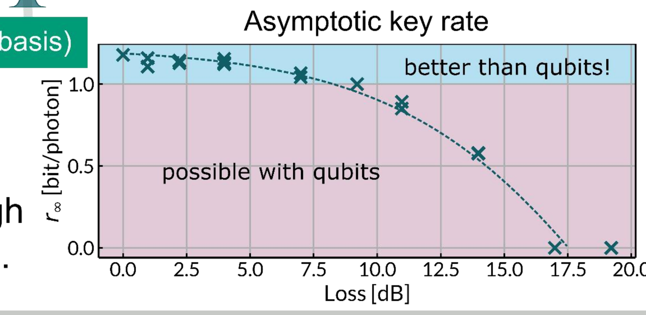
Converting ps-scale pulses in the telecom band, optimal for high-rate fiber transmission, to nanosecond scale pulses in the visible range processed by quantum memories. The pulses can be made identical leaving the encoded quantum information untouched.

S. Srivastava, D. B. Horoshko, M. I. Kolobov, Opt. Express 31, 38560-38577 (2023)
Recent experimental realization at Bar Ilan Univ.: O. Raphaely et al., Opt. Laser Technol. 192, 113912 (2025).

High-dimensional quantum key distribution with temporal modes

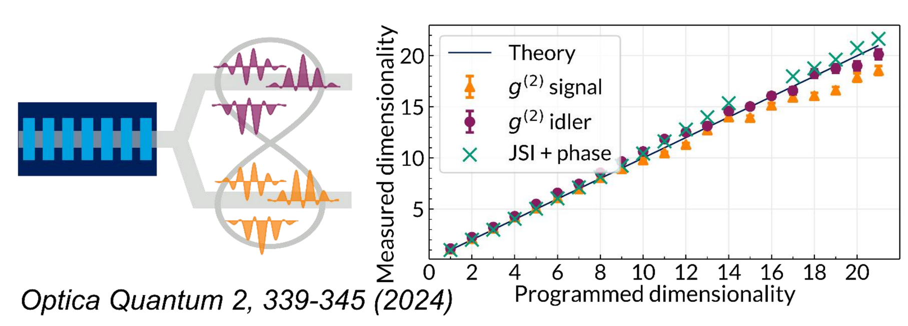


The multi-output quantum pulse gate (mQPG) simultaneously projects the input state onto arbitrary superpositions of frequency bins and maps the results onto different output frequencies through sum-frequency generation. Unconverted light remains unchanged.

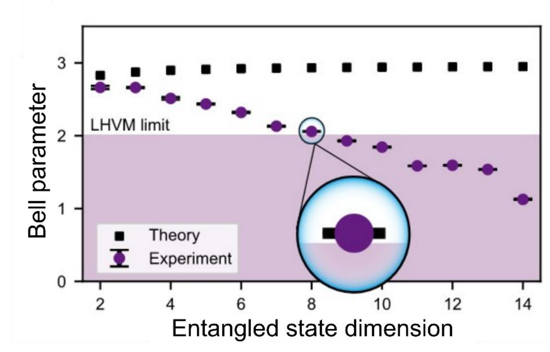


High-dimensional entanglement

Programmable source of photons in controlled high-dimensional entangled temporal modes



Optica Quantum 2, 339-345 (2024)

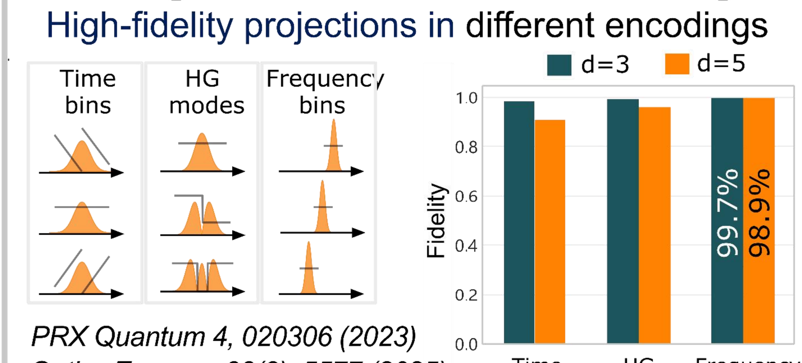


Bell inequality violation in up to d=8 dimensions

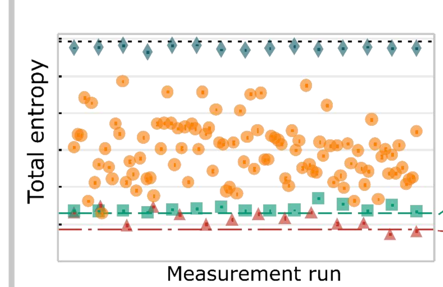
arXiv:2506.20796 (2025)

Programmable mode-sorting

High-fidelity projections in different encodings



PRX Quantum 4, 020306 (2023)
Optics Express, 33(3), 5577 (2025)



Measured entropic uncertainty relations in high dimensions

Predicted bound

New uncertainty bound!

PRR 7, 033152 (2025)

PADERBORN UNIVERSITY

Construction of efficient Schmidt number witnesses

Motivation

- Modern setups (Quantum phase gate, time-frequency encoding, ...) prepare high-dimensional quantum states.
- Problem: **Certify dimensionality** of prepared states.

Schmidt number

- Decompose pure state: $|\psi\rangle = \sum_{i=0}^{k-1} \sqrt{\lambda_i}|i\rangle_A|i\rangle_B$
- k is called **Schmidt rank**, measures dimension of state.
- For mixed states: convex roof yields Schmidt number

$$\mathrm{SN}(\rho) = \min_{\rho=\sum p_i|\psi_i\rangle\langle\psi_i|} \max_i \mathrm{SR}(|\psi_i\rangle)$$

- Detect using Schmidt number witness W:

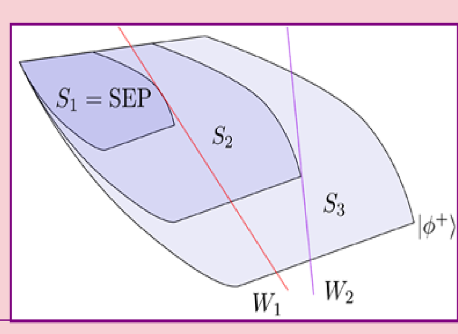
$\mathrm{Tr}(W\rho_k) \geq 0 \quad \forall \rho \in S_k$,

$\mathrm{Tr}(W\rho) < 0$ for some ρ.

- Simple witness:

$W = \mathbb{1} - \frac{d}{k}|\phi^+\rangle\langle\phi^+|$

with $|\phi^+\rangle = \frac{1}{\sqrt{d}}\sum_{i=0}^{d-1}|ii\rangle$



The algorithm

- Problem: requires O(d^2) measurements in standard basis.
- Construct witness that uses measurements M with $|M|$ =

1. Choose k, subset M and some constant $C \in (-1,1)$.
2. Run semidefinite program

find $\tilde{W}^{(1)}$

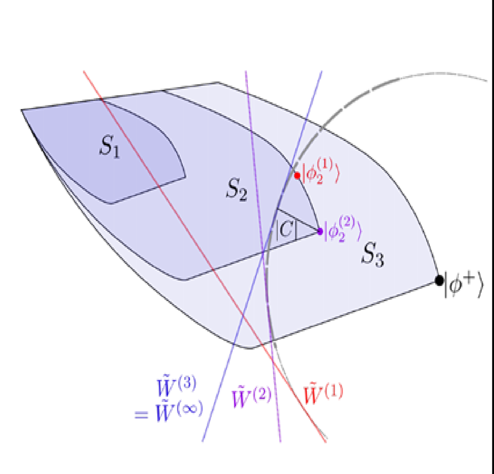
s.t. $\langle\phi^+|\tilde{W}^{(1)}|\phi^+\rangle = -1$,

$-1 \leq \tilde{W}^{(1)} \leq 1$.

3. Find $\min_{|\phi_k^{(1)}\rangle} \langle\phi_k^{(1)}|\tilde{W}^{(1)}|\phi_k^{(1)}\rangle$.
4. Go back to 2., add constraint

$\langle\phi_k^{(1)}|\tilde{W}^{(2)}|\phi_k^{(1)}\rangle \geq C$.

5. Stop if infeasible (decrease C) or converged (increase C) and repeat.



Result

- Measuring $\mathrm{Tr}(\tilde{W}\rho) < -\sqrt{\frac{d^2-4d+4k}{d^2}}$ with

$$\tilde{W} = \left(1-\frac{2}{d}\right)|00\rangle\langle00| - \frac{2}{d}\sum_{i=1}^{d-1}(|00\rangle\langle ii| + |ii\rangle\langle00|) - \left(1-\frac{2}{d}\right)\sum_{i=1}^{d-1}|ii\rangle\langle ii|$$

- certifies Schmidt rank $k+1$.

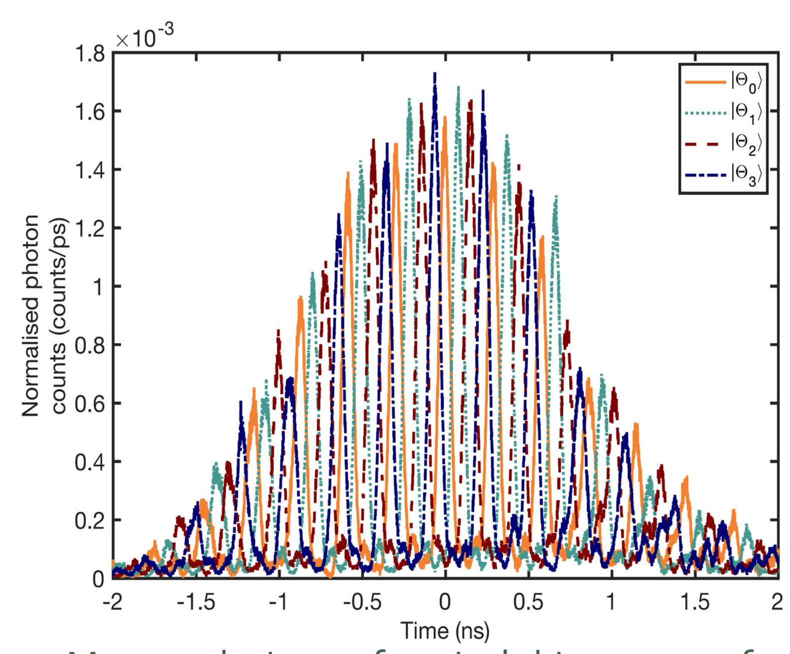
N. Wyderka, G. Chesi, H. Kampermann, C. Miacchiavello, D. Bruß, Phys. Rev. A **107**, 022431 (2023)

Efficient detection of multidimensional single-photon time-bin superpositions

FACULTY OF PHYSICS UNIVERSITY OF WARSAW

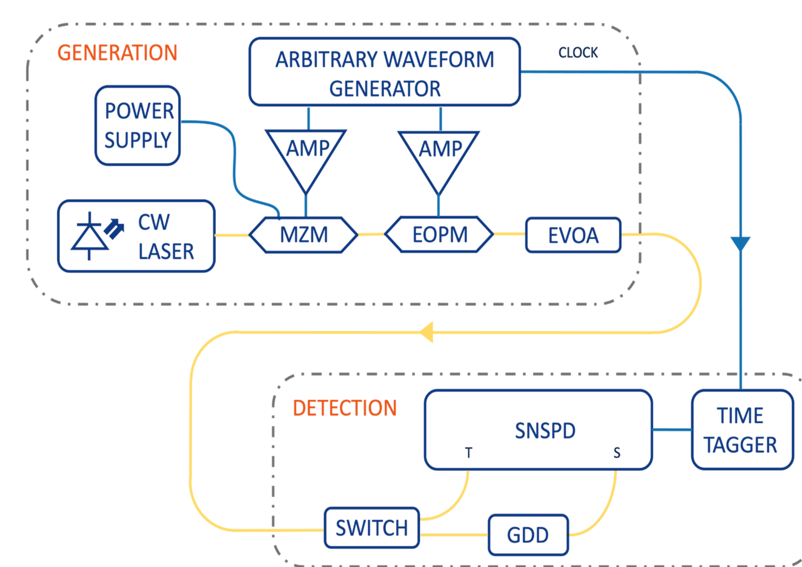
photon.fuw.edu.pl

With dispersive medium we can detect time-bin superpositions in the single-photon-counting regime in an all-fiber setup without the use of interferometers. We showed that we can do that efficiently thanks to the temporal Talbot effect. Currently we are working on using this method for high-dimensional quantum key distribution.



Measured time of arrival histograms for superpositions of four pulses with equal time separation.

$$|\Theta_n\rangle = \frac{1}{\sqrt{d}}\sum_{m=0}^{d-1} e^{\frac{-2\pi i nm}{d}}|t_m\rangle$$



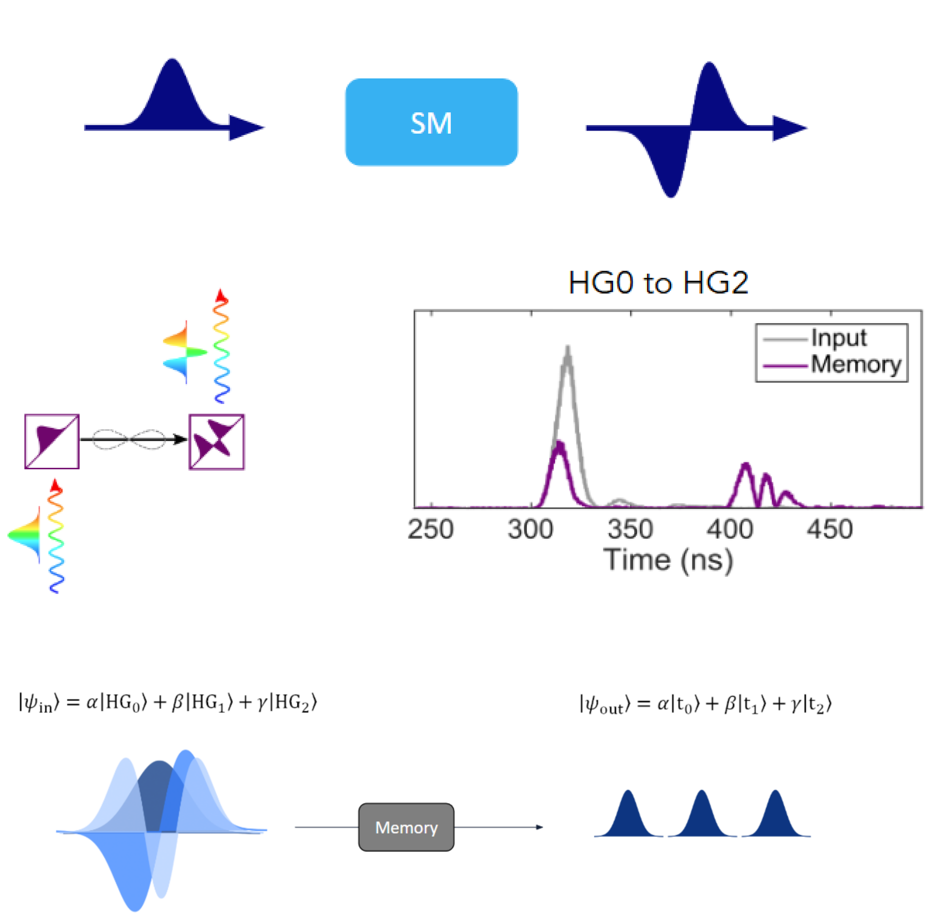
Pulses in time-bins are carved with Mach-Zehnder modulator (MZM) and phases are given by electro-optic phase modulator (EOPM). To detect superpositions pulses are transmitted through group delay dispersion medium (GDD).

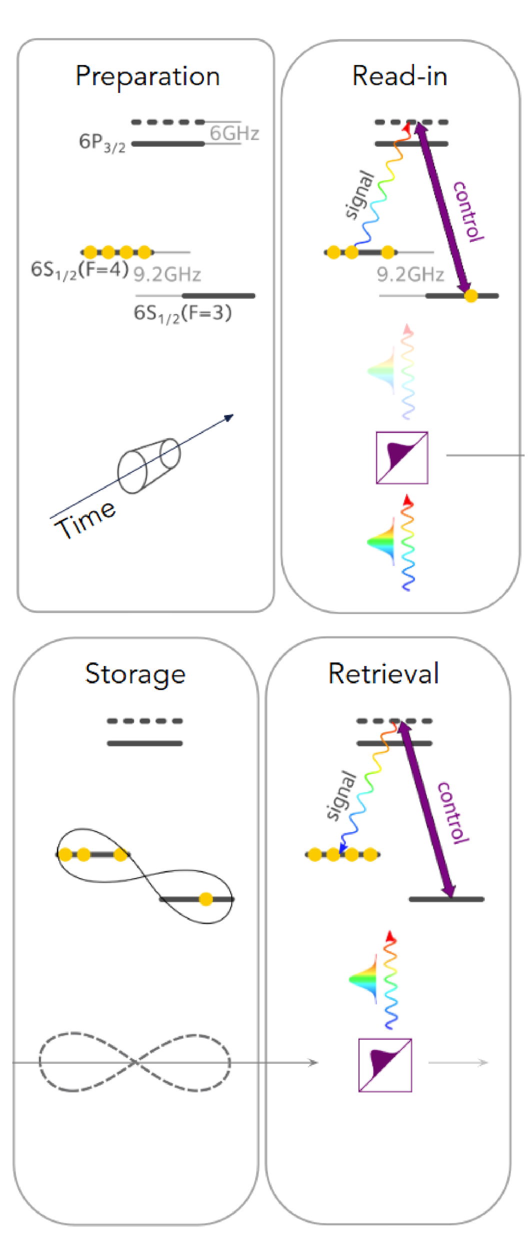
A. Widomski, M. Ogrodnik, M. Karpiński, Optica 11, 926 (2024).

Temporal mode manipulation using a quantum memory

Imperial College London

FACULTY OF PHYSICS UNIVERSITY OF WARSAW

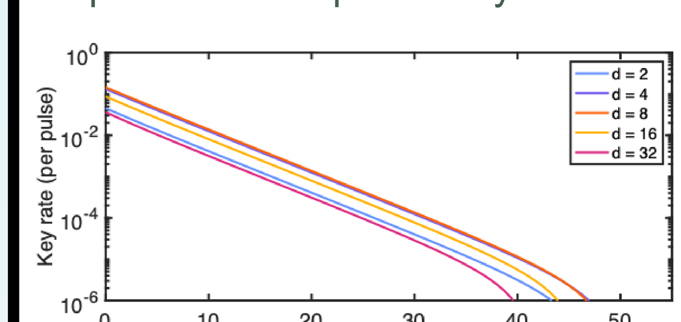




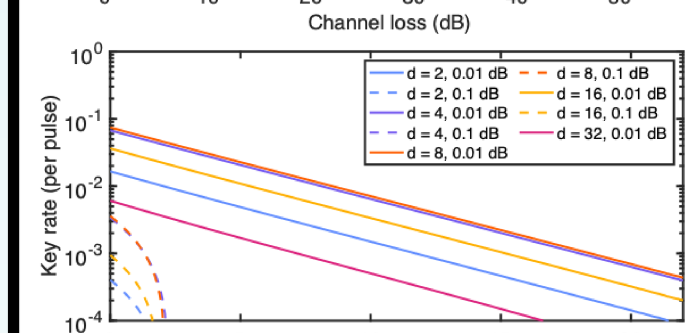
Multipass quantum memory approach was used to convert between overlapping temporal modes and nonoverlapping time bins.

High-dimensional quantum key distribution with resource-efficient detection

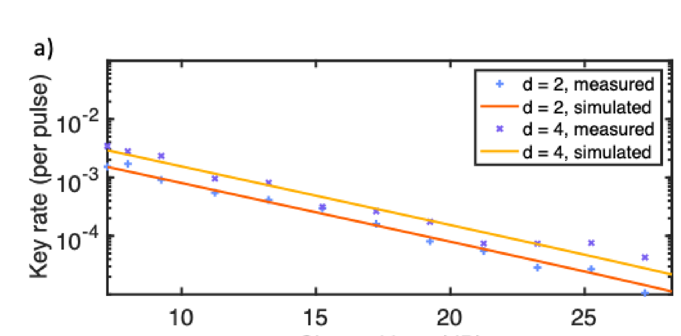
By employing a detection scheme based on the temporal Talbot effect, we can perform QKD experiments using only a single detector per measurement, irrespective of the encoding dimension. We present experimentally-obtained secret key rates for both two-dimensional and four-dimensional scenarios, showing that a 4-dimensional encoding offers higher resistance to noise and information entropy then a qubit-based scheme. We show key rates according to two different security proofs – a standard BB84 protocol and a new tunable beam splitter (TBS) protocol [Grasselli2025], developed witin QuICHE, which allows dropping assumption about equal detection probability in the two bases.

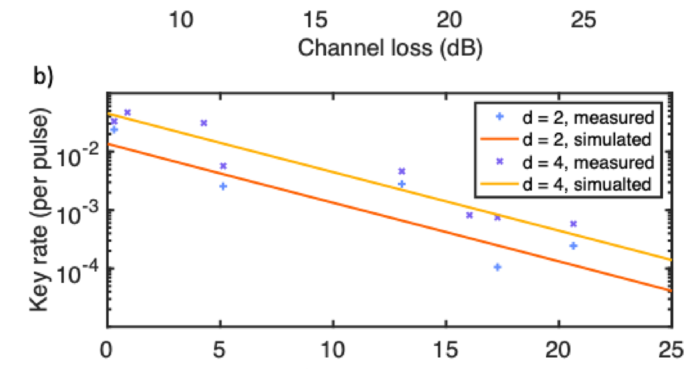


Key rates simulated using BB84 protocol for 25 ps jitter



Key rates simulated using TBS protocol for different imbalances and 25 ps jitter





Measured BB84 key rates: a) in-lab b) over urban dark fibers in Warsaw

Ogrodnik et.al. Optica Quantum (2025),
Grasselli et al.., Phys. Rev. Applied 23, 044011 (2025)