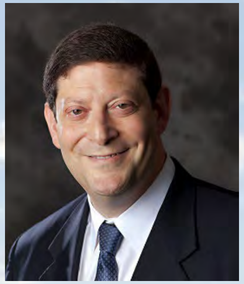
Université d'Ottawa | University of Ottawa



Robert W. Boyd
Yiyu Zhou
Jiapeng Zhao
Boris Braverman

Zhimin Shi
Alexander Fyffe

Alan E. Willner
Runzhou Zhang
Kai Pang

Vectorial Phase Conjugation for High-Fidelity Spatial Mode Transmission

<u>Jeremy Upham</u>[1], Zhimin Shi[3], Robert W. Boyd[1,2], and Alan E. Willner[4]

Presented by Jeremy Upham

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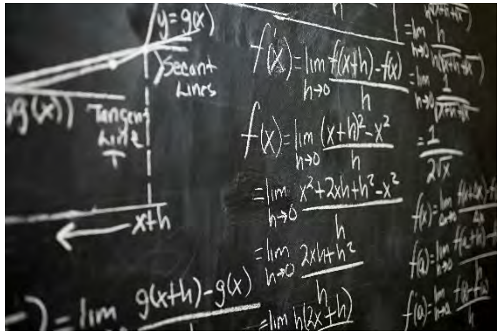
The Value of Quantum information

Conventional Information



Can be observed without changing it

Can be shared at will

Can be copied

Quantum Information

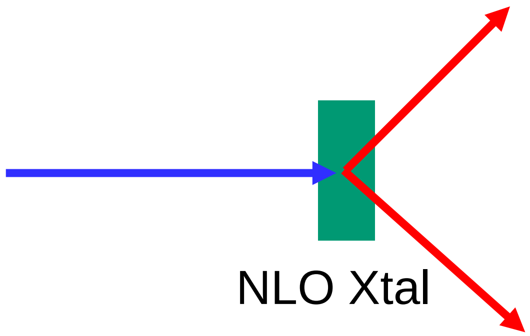
Can be tasted, but this leaves a mark.

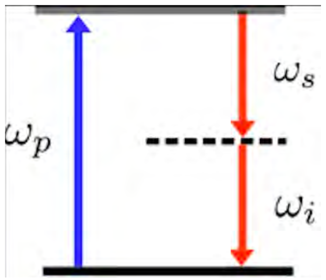
Can be shared, but there is a total of 1 item to be shared.

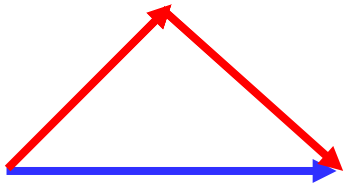
Cannot be copied.

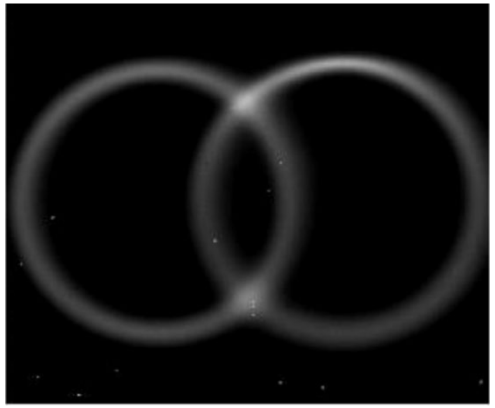
Anne Broadbent
https://youtu.be/ZKGSgWSRLSk

Spontaneous Parametric Down Conversion







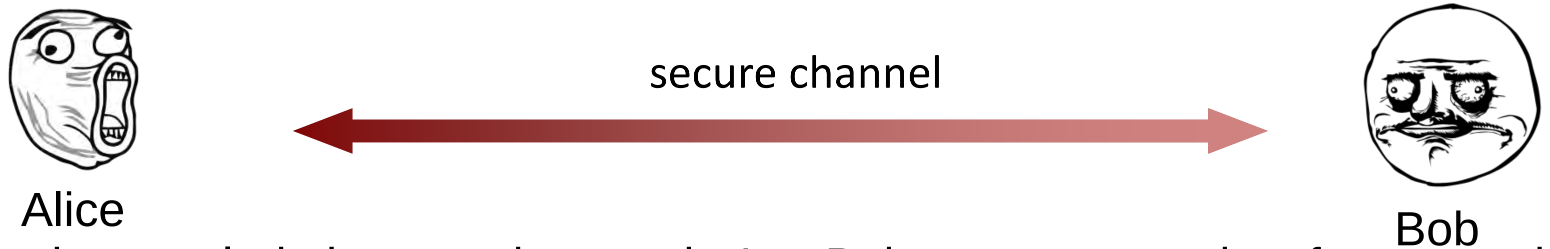


Resulting photon pairs can be entangled in different degrees of freedom

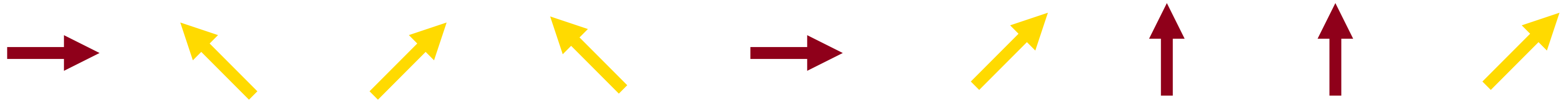
Example: Type 1 Polarization entanglement $|\psi\rangle = \frac{1}{\sqrt{2}}\left(|H_1H_2\rangle + e^{i\phi(\omega_p,\omega_s,\omega_i,\mathbf{k}_p,\mathbf{k}_s,\mathbf{k}_i)}|V_1V_2\rangle\right)$

The entangled photon pairs are nonseperable, a single quantum state of light

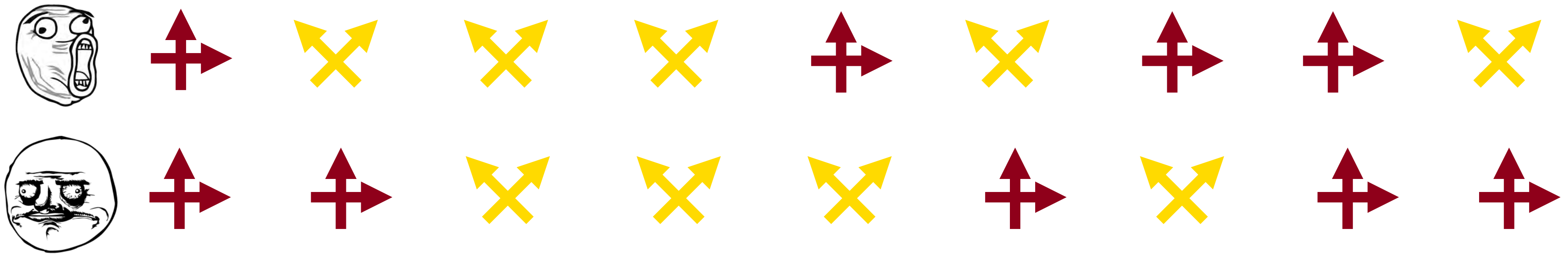
Quantum Key Distribution (BB84)



1) Alice produced entangled photon pairs, sends 1 to Bob to generate a key for encryption



2) Alice and Bob each measure their photon randomly in 2 unbiased bases



3) Alice and Bob share their bases they used openly, use the common values to produce a key

Sohrab Ganjian
Robert Fickler

Quantum Key Distribution

An eavesdropper intercepting a the message introduces a minimum rate of errors dictated by the quantum nature of the system

As long as Bob gets Alice's message with fewer errors than that threshold, we are certain the channel is secure

Drawbacks of QKD

Slow: The secure key rate of QKD is many orders of magnitude slower than the data rate of classical communication.

We can’t distinguish between lost information (lossy channel) and stolen information (eavesdropper).
If the channel loss exceeds the Quantum Bit Error Rate, we assume not secure

Polarization: 2-dimension = 1 bit/photon

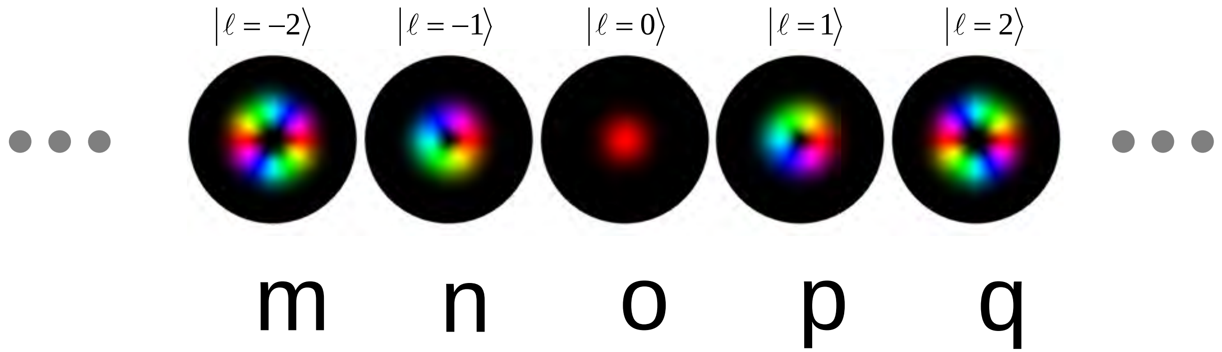
$$\left\{\overset{0}{\leftrightarrow}, \overset{1}{\updownarrow}\right\} \text{ or } \left\{\overset{0}{\swarrow\!\!\!\!\nearrow}, \overset{1}{\nwarrow\!\!\!\!\searrow}\right\}$$

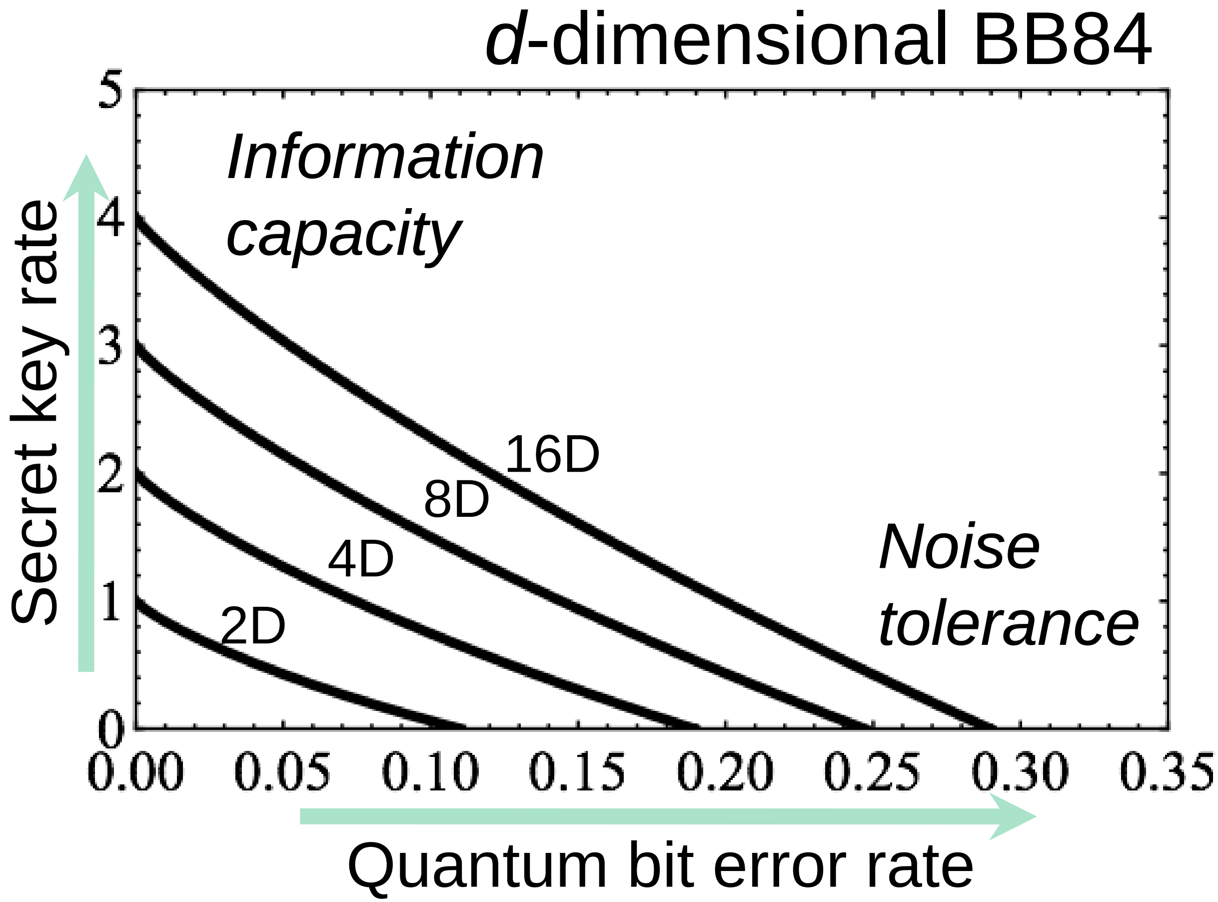
BB84 protocol with polarization

QBER > 0.11 Unsecure

More information per photon?

Spatial modes offer a larger basis for information





High dimensional QKD wants channels supporting many (>100) spatial modes.
over long distances with low losses.

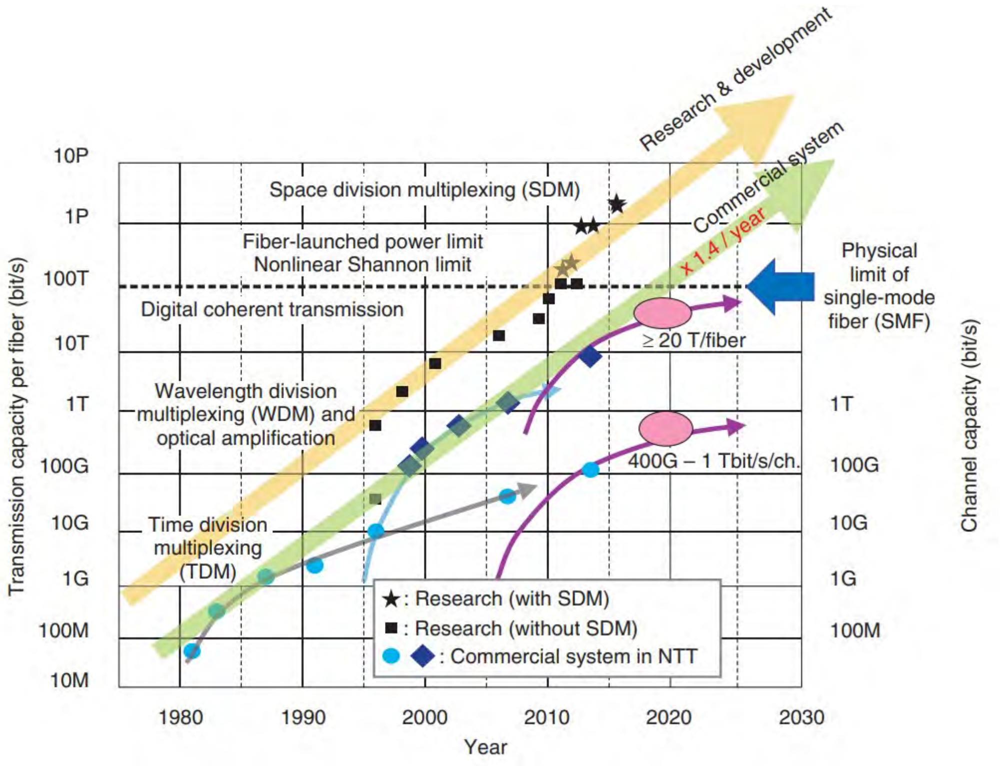
How do we mitigate loss in our channel?

Learned a lot from telecom

Lower fidelity of the structured light
-> Cross-talk loss to other modes

Forget perfect media: real-world factors (temperature, strain, turbulence) induce crosstalk

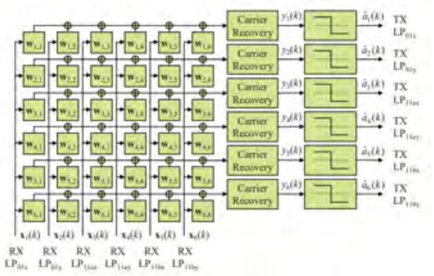
Solution must be tailored to the medium, adaptable to changes during transmission



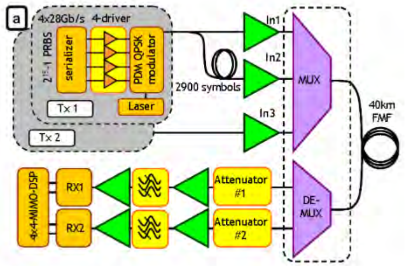
Y. Miyamoto et al. NTT Technical Review **15.6** 1 (2017)

SDM in Fibers – Existing Approaches

MIMO algorithms



Randel et al., Opt. Exp., **19**, 16697 (2011)



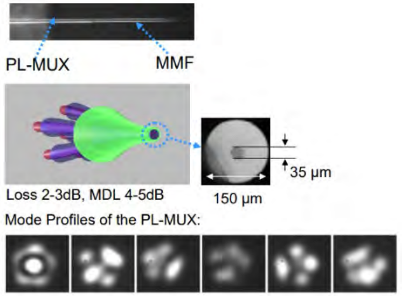
Koebele et al. Opt. Exp., **19**, 16593 (2011)

Long fibres

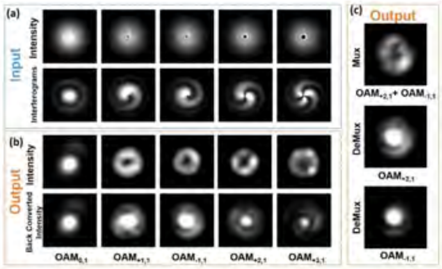
Needs high SNR for digital signal processing.

SDM in Fibers – Existing Approaches

Mode-group excitation



Ryf et al., Opt. Exp., **23**, 235 (2015)



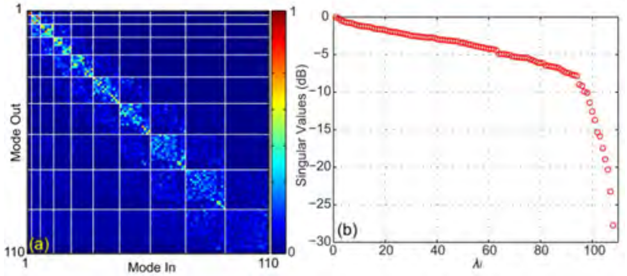
Zhu et al., Opt. Exp., **25**, 25637 (2017)

Group modes to limit coupling

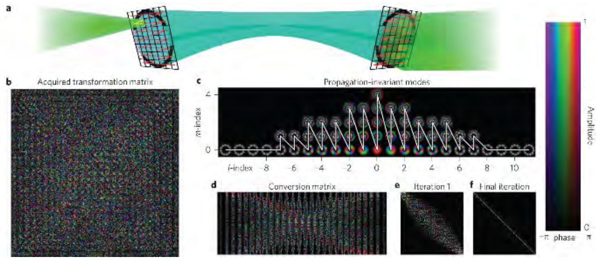
Typically restricts n modes to $\sqrt{n}$

SDM in Fibers – Existing Approaches

Transfer matrix inversion



Carpenter et al., Opt. Exp., **22**, 96 (2014)

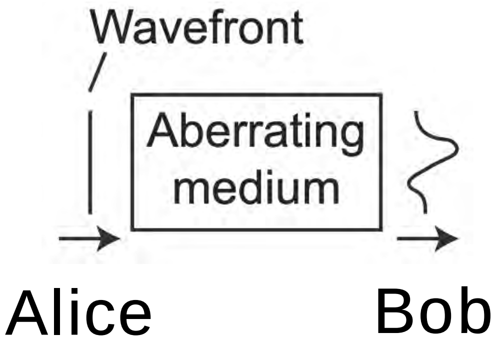


Plöschner et al., Nat. Photon. **9**, 529 (2015)

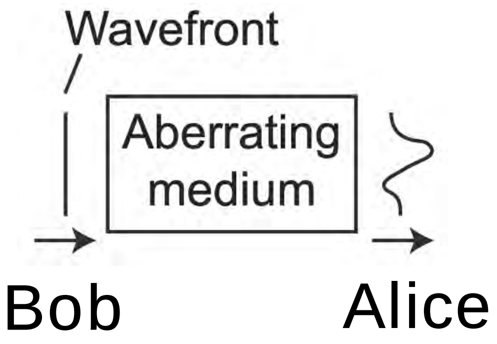
Probe all modes then invert the transfer matrix

100s spatial modes (10^3-10^5 elements)

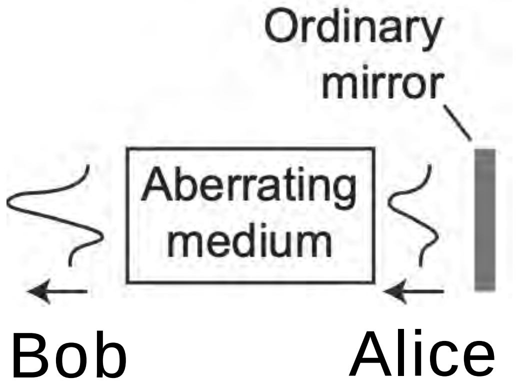
Phase Conjugation (AKA Time-Reversal)



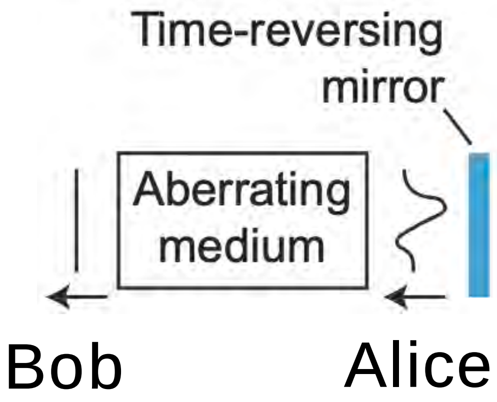
$$E_{probe}(r) = A(r)e^{ik\cdot r}$$



$$E_{probe}(r) = A(r)e^{ik\cdot r}$$



$$E_{probe}(r) = A^2(r)e^{ik\cdot r}$$

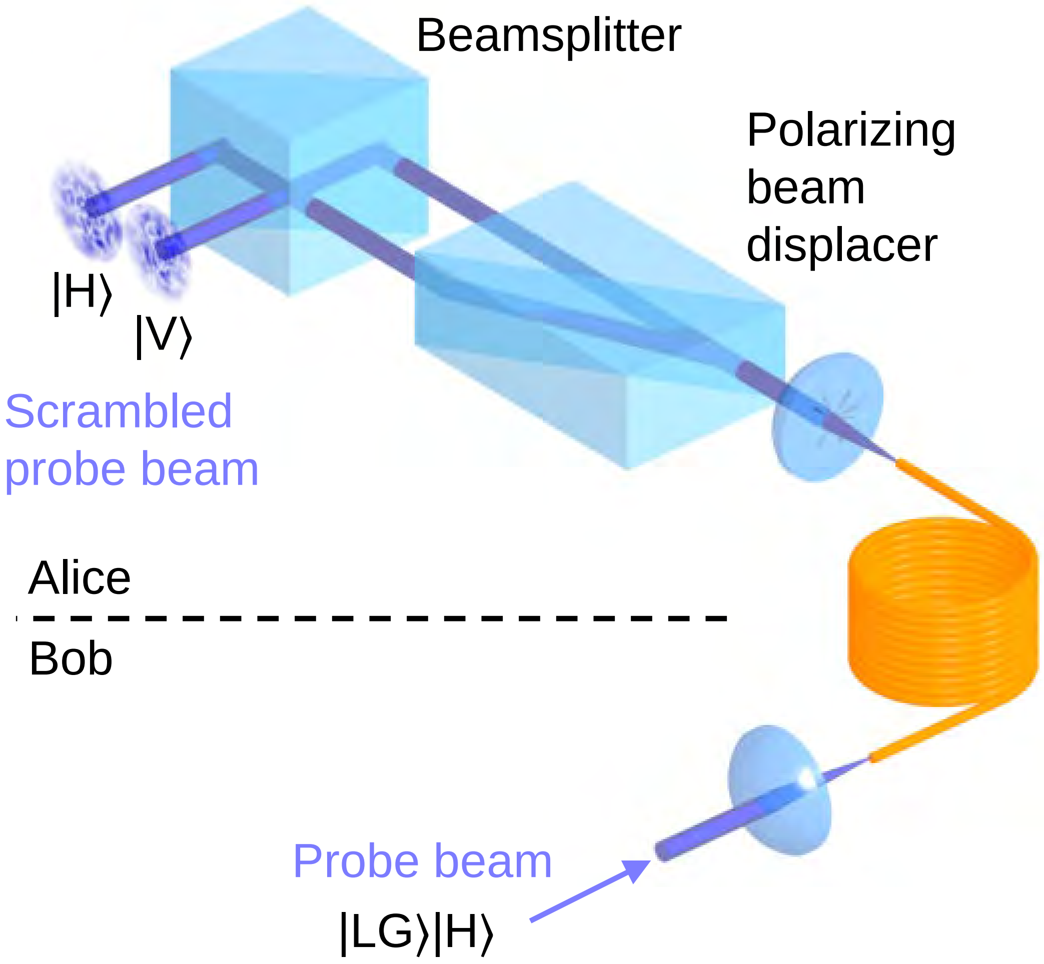


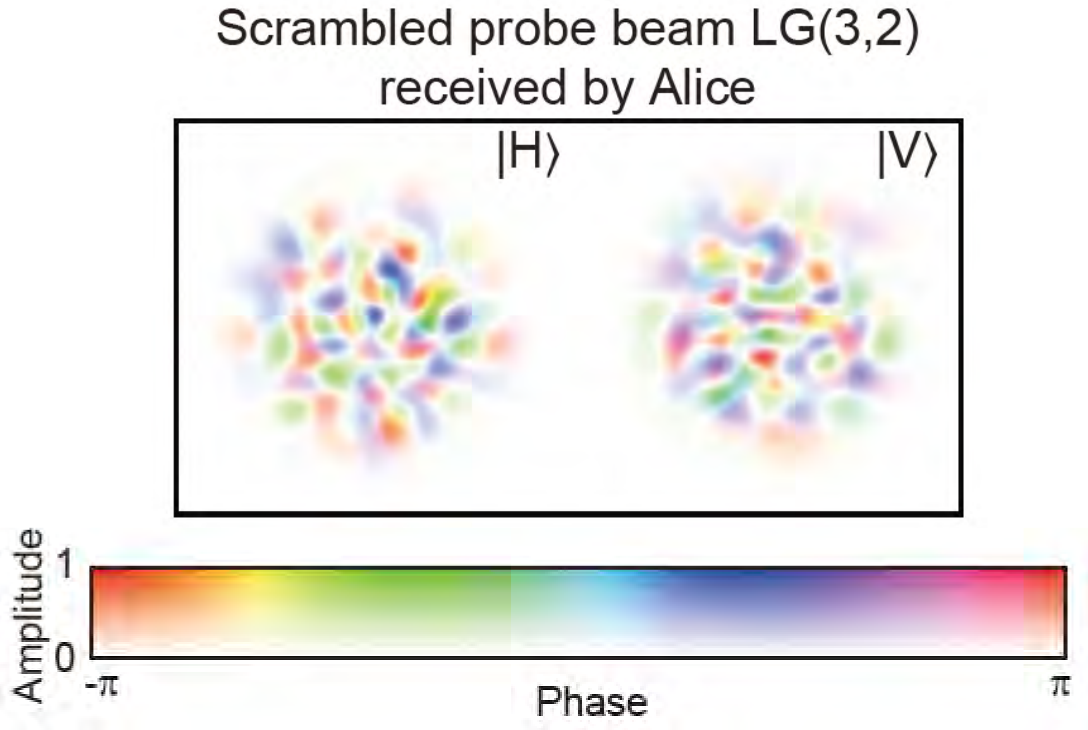
$$E_{probe}(r) = A^*(r)A(r)e^{ik\cdot r}$$

Bob sends Alice the modes they want, Alice learns what to actually send

No extra modes, if medium evolves, just repeat characterization

Vectorial phase conjugation in a 1 km multi-mode fibre



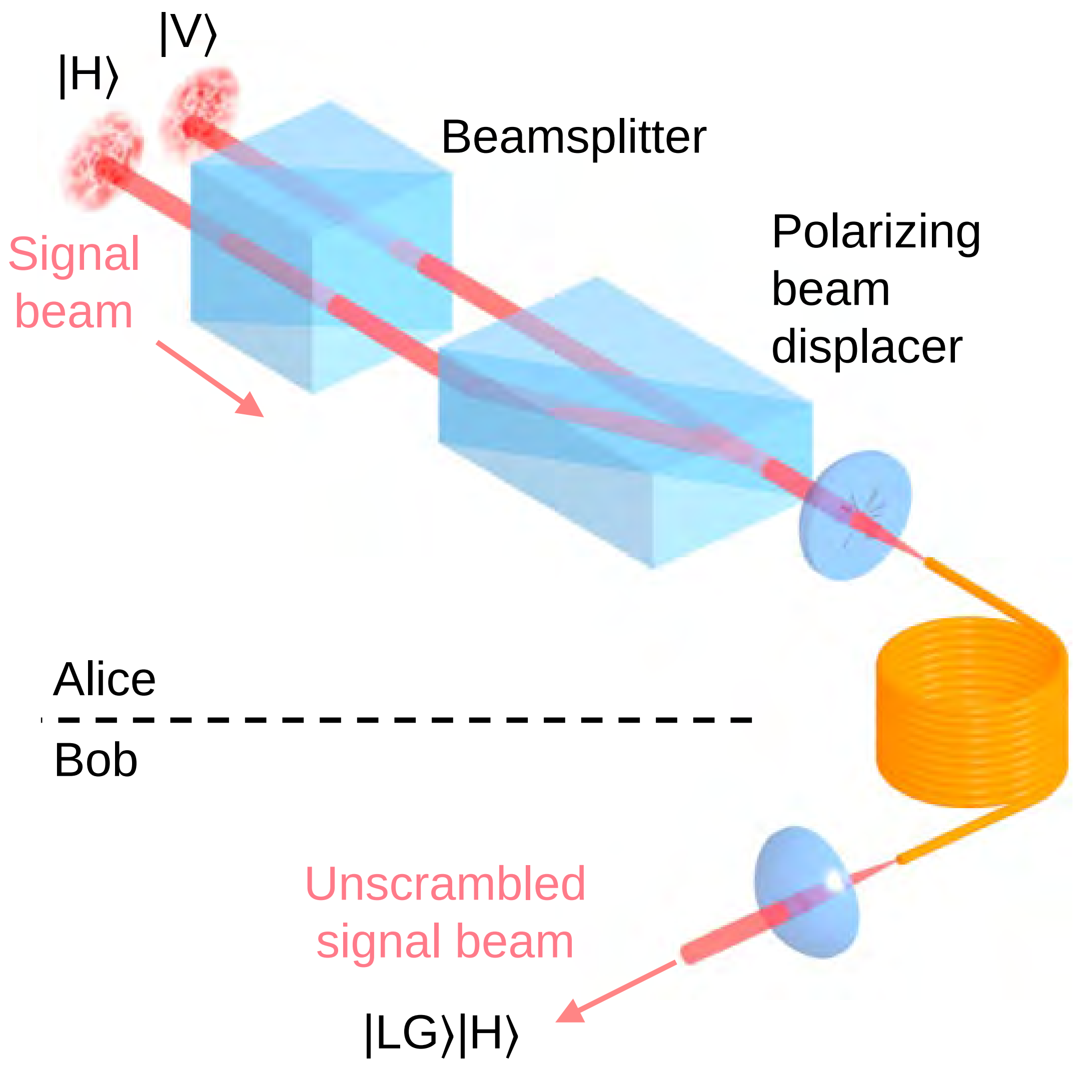


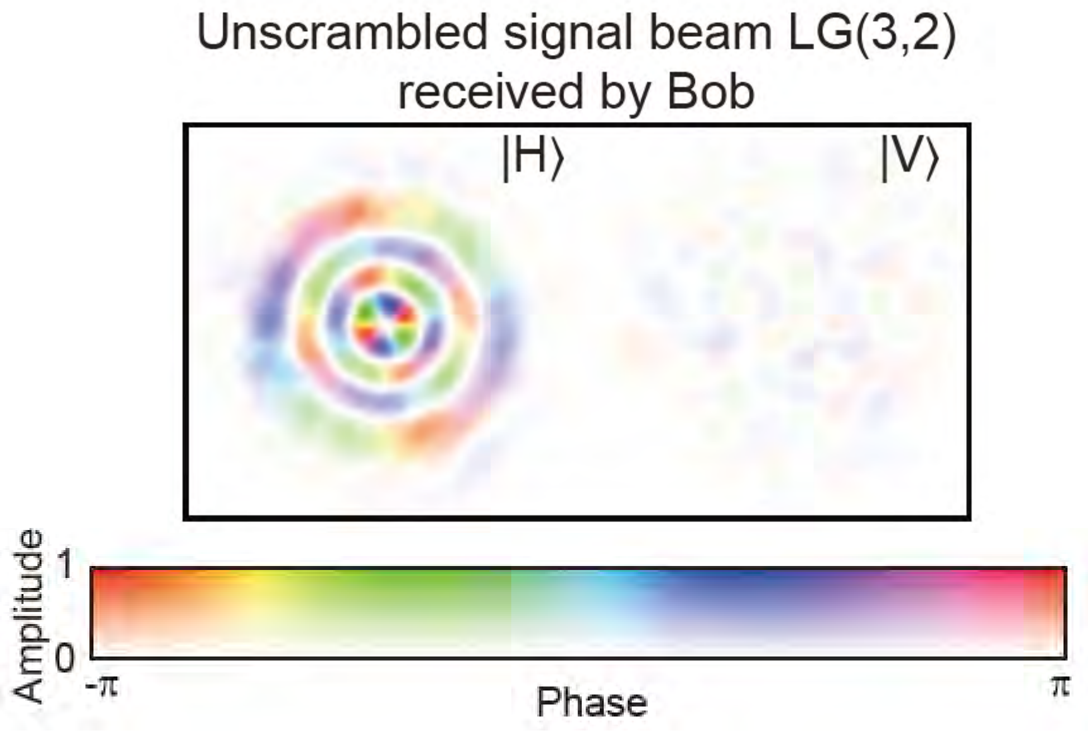
$$E_{scalar}(r) = A(r)e^{ik\cdot r}$$

$$E_{vector}(r) = \hat{x}A_1(r)e^{ik_1\cdot r} + \hat{y}A_2(r)e^{ik_2\cdot r}$$

Y. Zhou et al., Nat. Commun., **12**, 1866, (2021).

Vectorial phase conjugation in a 1 km multi-mode fibre





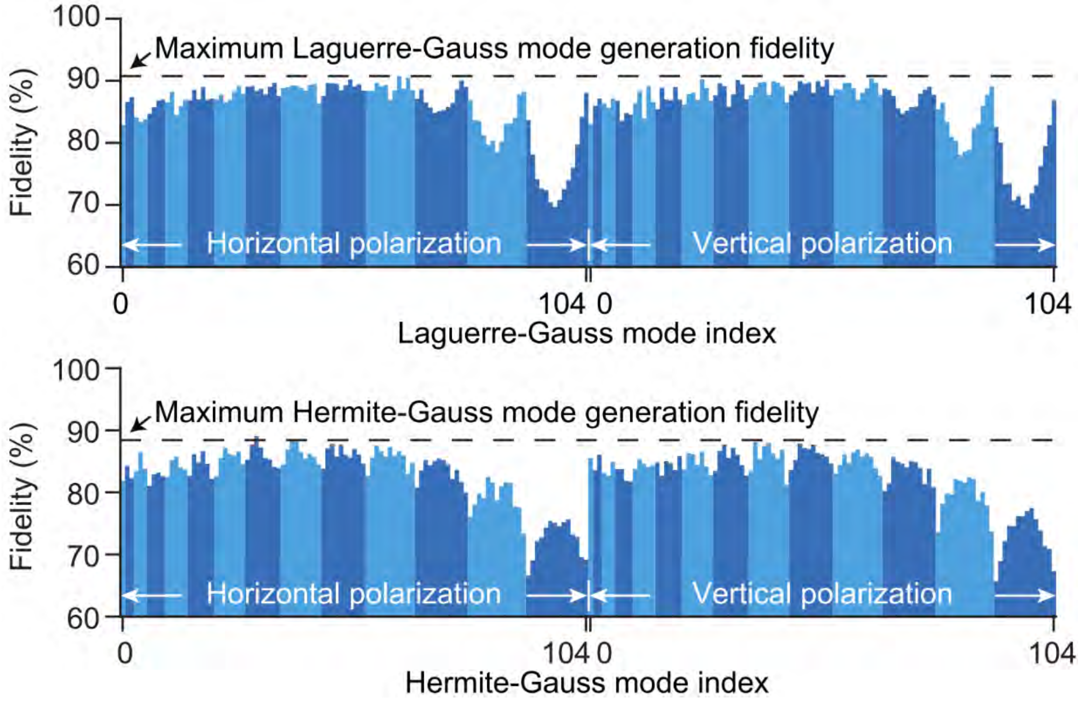
$$E_{vector}(r) = \hat{x}A_1(r)e^{ik_1\cdot r} + \hat{y}A_2(r)e^{ik_2\cdot r}$$

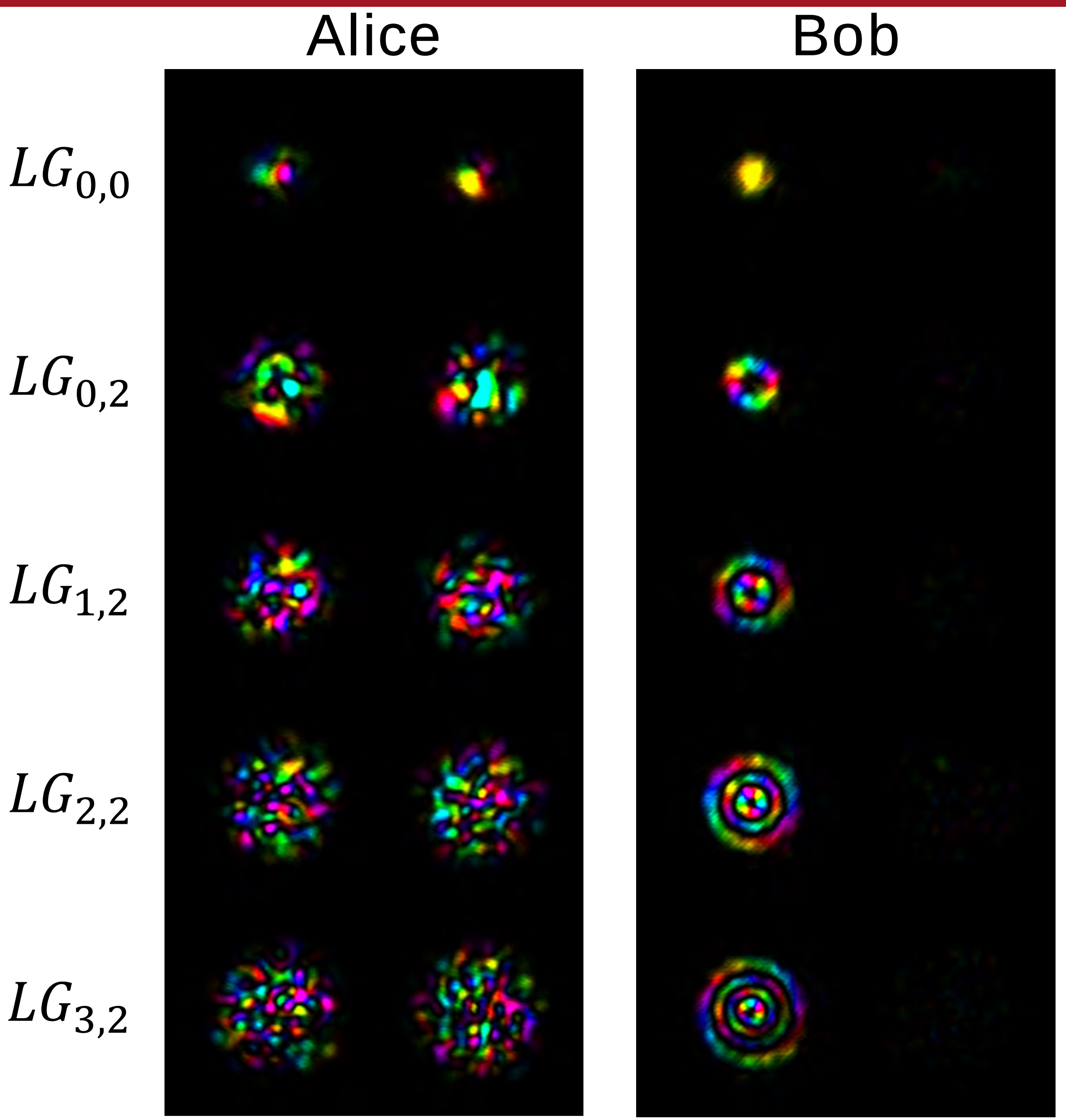
$$E^*_{vector}(r) = \hat{x}A^*_1(r)e^{-ik_1\cdot r} + \hat{y}A^*_2(r)e^{-ik_2\cdot r}$$

Y. Zhou et al., Nat. Commun., **12**, 1866, (2021).

Mode Fidelity

Measured for 210 modes in LG and HG
Average fidelity: 84.1%

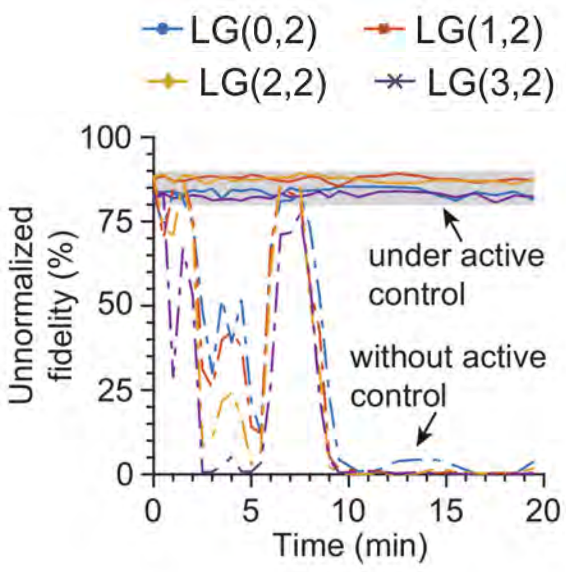




Y. Zhou et al., Nat. Commun., **12**, 1866, (2021).

Stabilization for Fiber Drift

Procedure is fast enough to allow for real-time link stabilization!

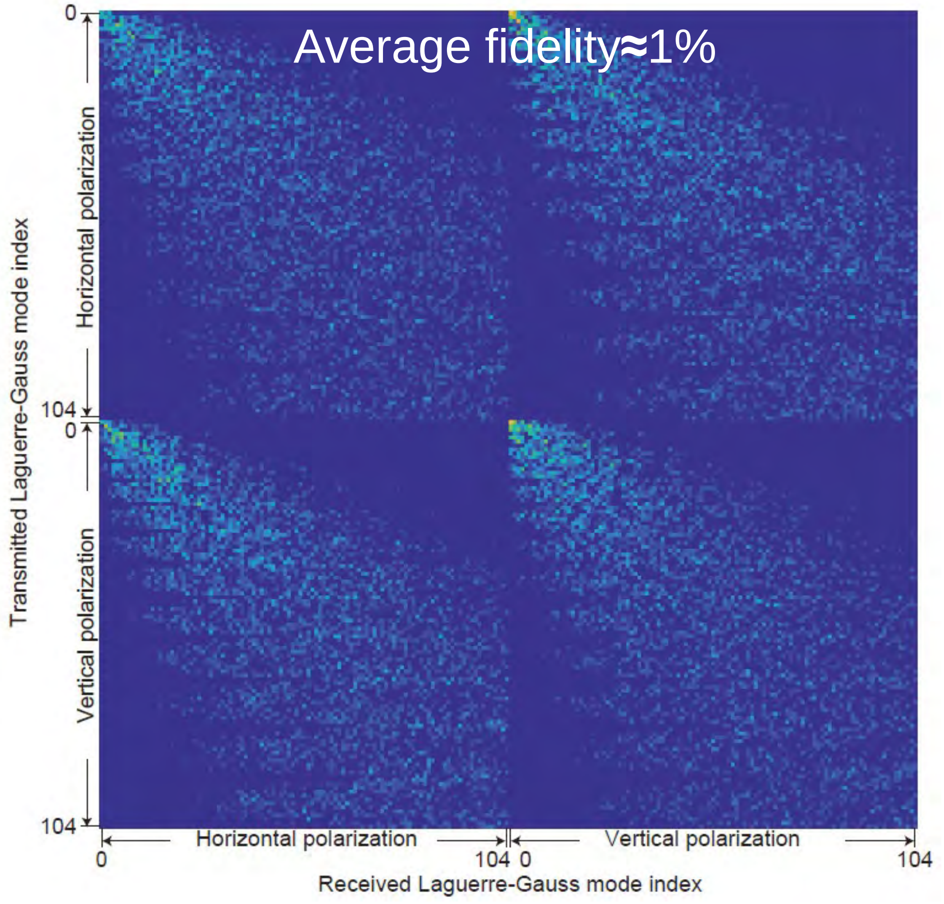


	Alice	Bob
Active feedback		
No feedback		

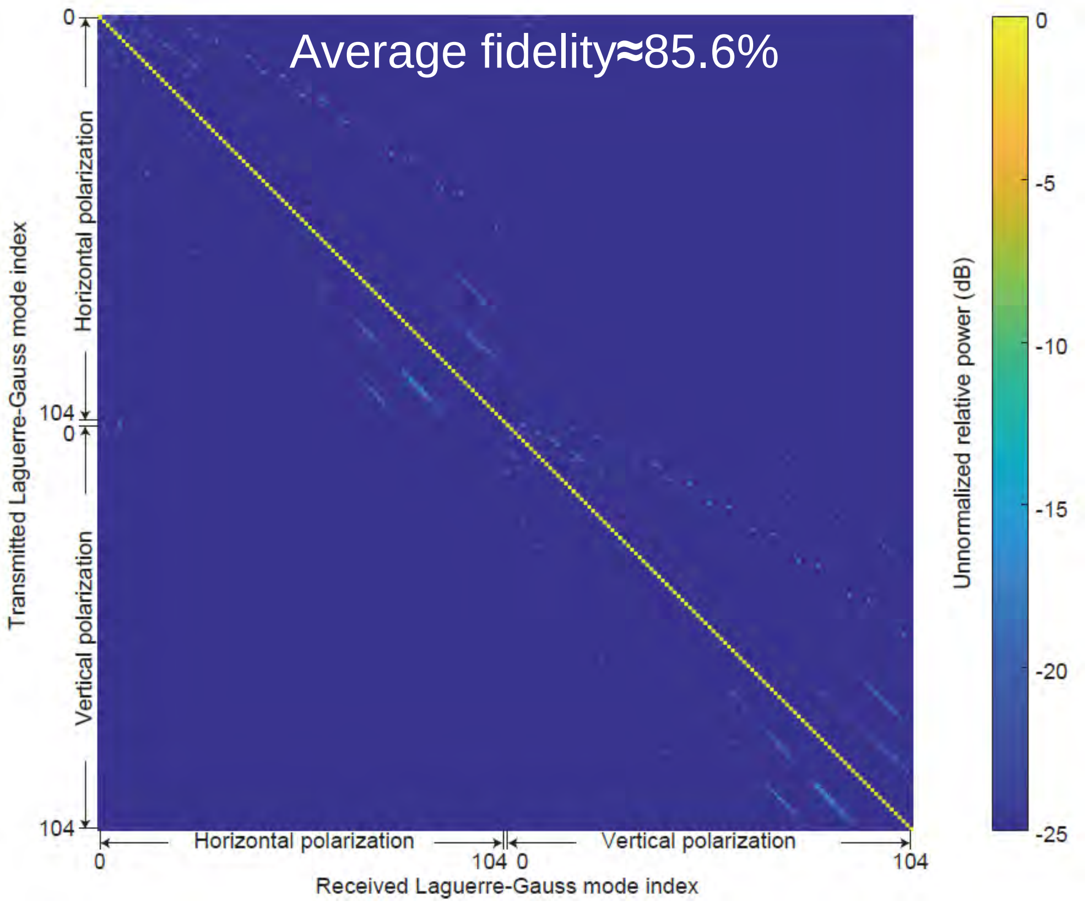
Y. Zhou et al., Nat. Commun., **12**, 1866, (2021).

210x210 crosstalk matrix

Without time reversal

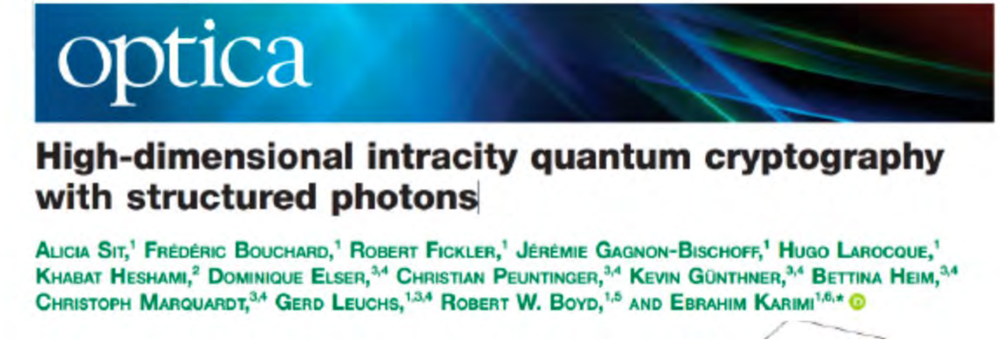


With time reversal



Y. Zhou et al., Nat. Commun., **12**, 1866, (2021).

Free space transmission


optica

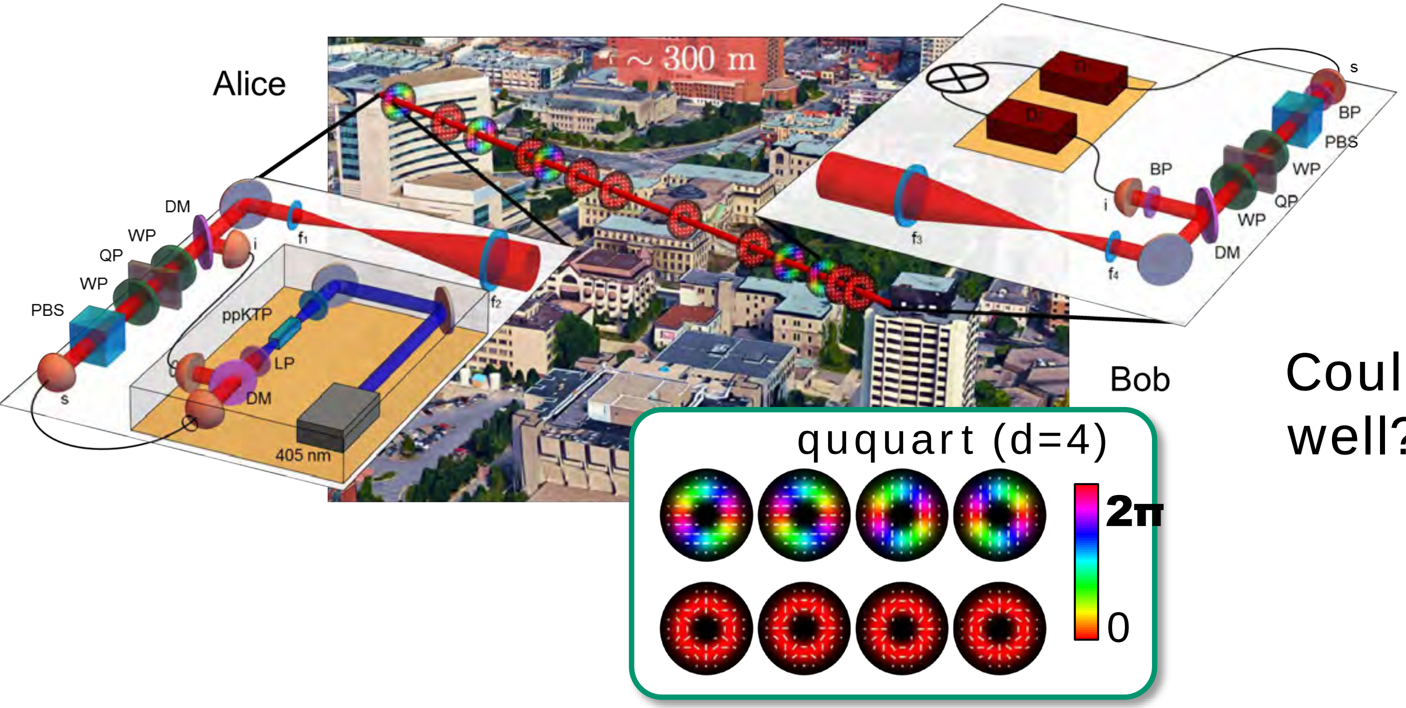
High-dimensional intracity quantum cryptography with structured photons

Alicia Sit,[1] Frédéric Bouchard,[1] Robert Fickler,[1] Jérémie Gagnon-Bischoff,[1] Hugo Larocque,[1] Khabat Heshami,[2] Dominique Elser,[3,4] Christian Peuntinger,[3,4] Kevin Günthner,[3,4] Bettina Heim,[3,4] Christoph Marquardt,[3,4] Gerd Leuchs,[1,3,4] Robert W. Boyd,[1,5] and Ebrahim Karimi[1,6,*]

We've shown QKD with spatial modes in free space

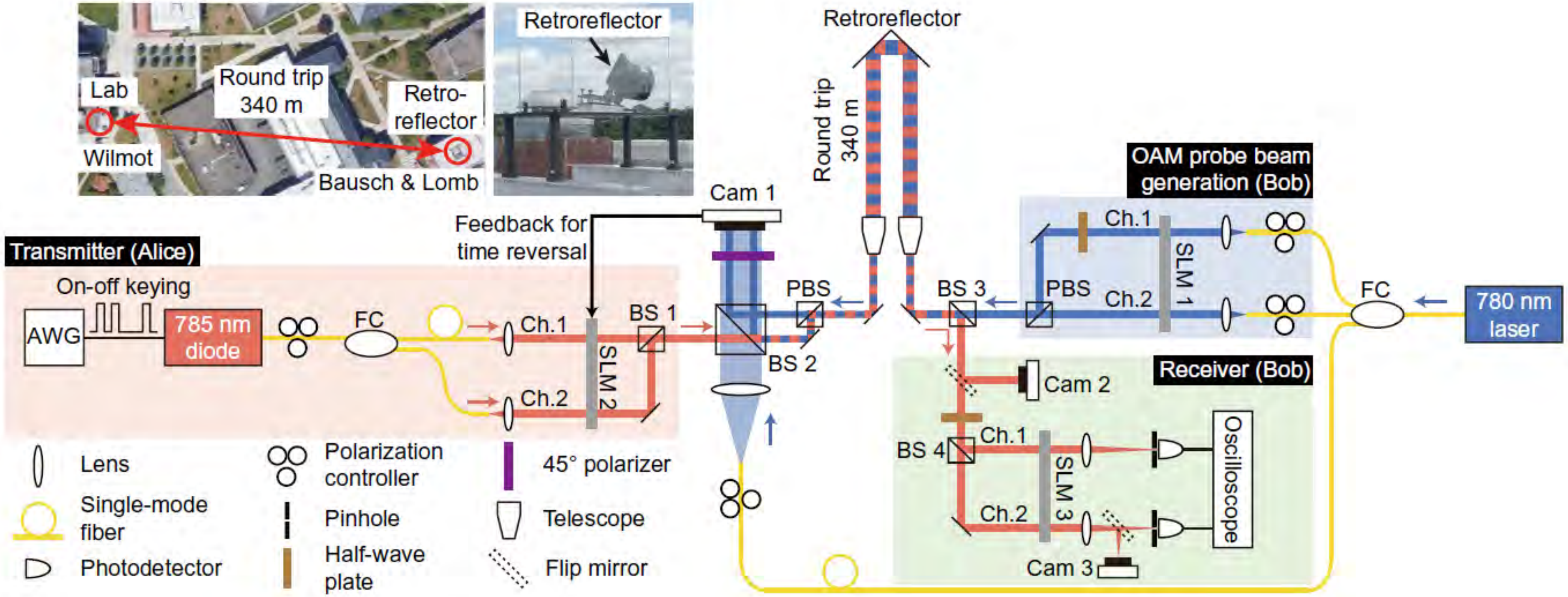
Turbulence was the principal source of cross talk

No turbulence mitigation,
still achieved QBER of 0.11 in 4D



Could digital phase conjugation assist here as well?

Digital phase conjugation in free-space

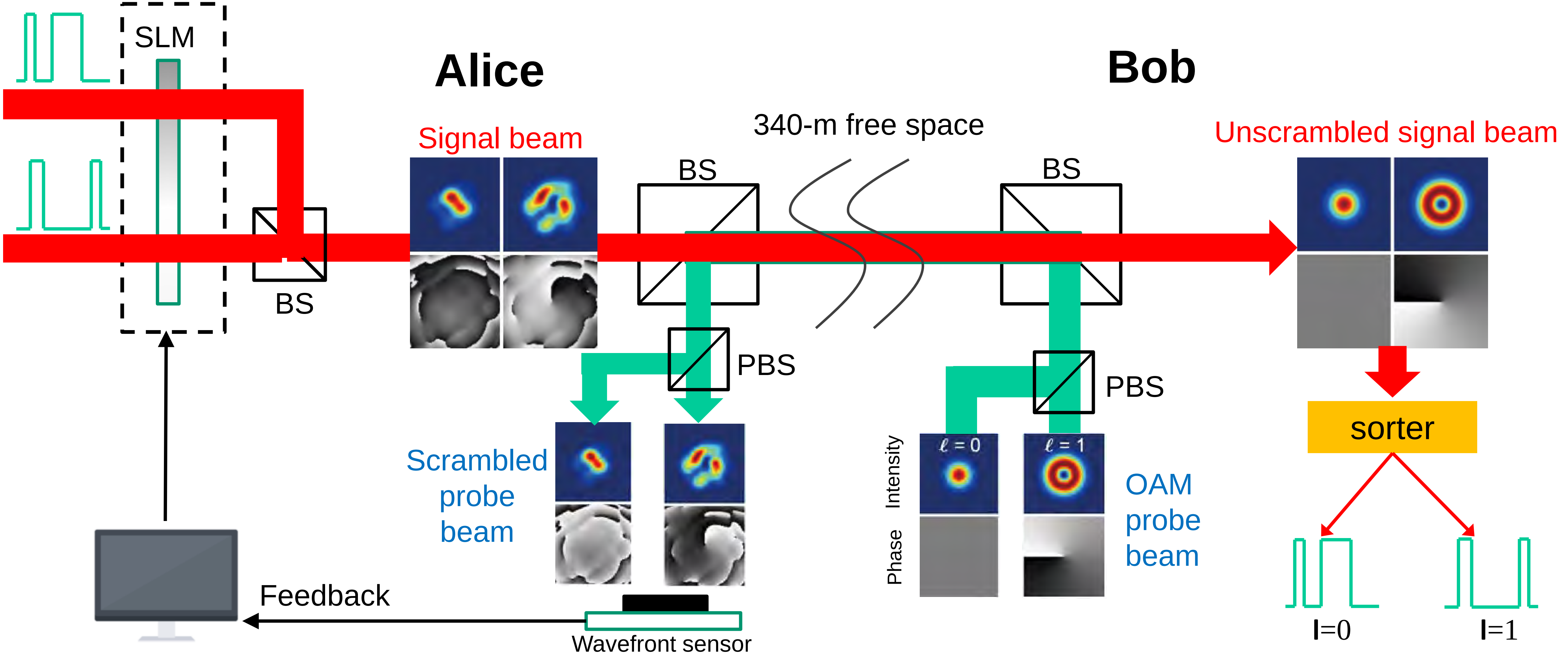


Conceptually the same set-up as in MMF

Turbulence requires in re-characterization by Bob on 10s of ms timescale

Phys. Rev. Applied 15, 034011, (2021)

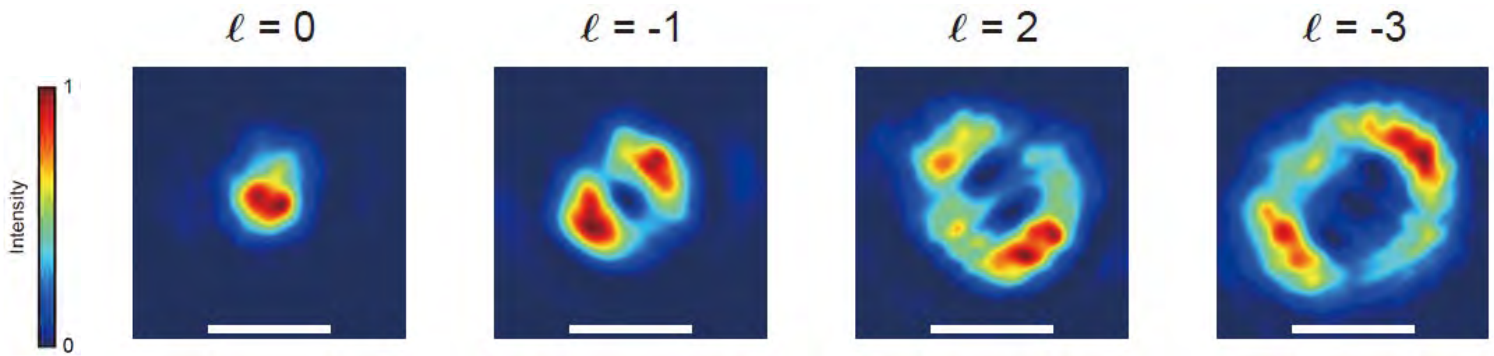
Digital phase conjugation in free-space



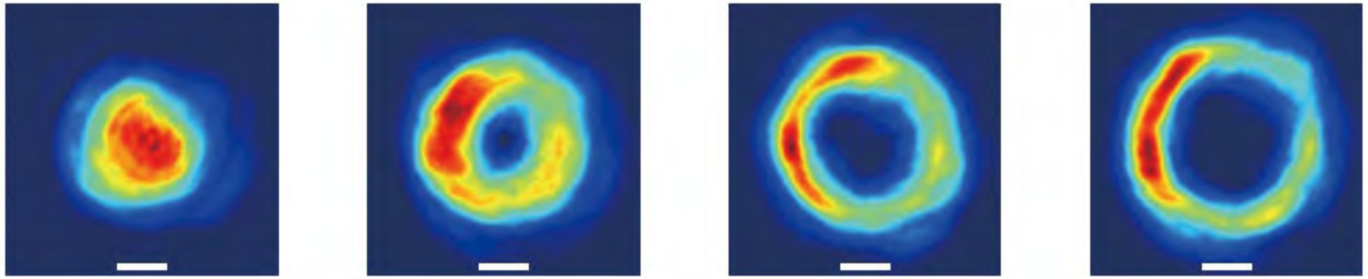
Phys. Rev. Applied 15, 034011, (2021)

Digital phase conjugation in free-space

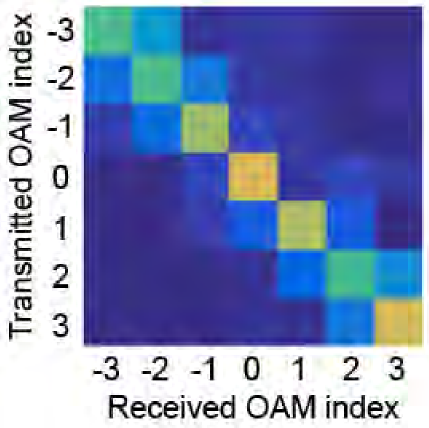
Without time reversal



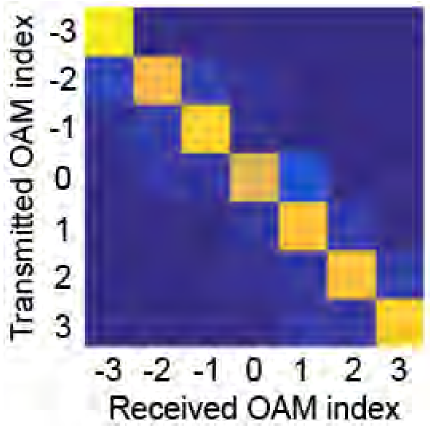
With time reversal



Crosstalk matrix without time reversal
Average fidelity=63.0%



Crosstalk matrix with time reversal
Average fidelity=86.8%



Phys. Rev. Applied 15, 034011, (2021)

Conclusions

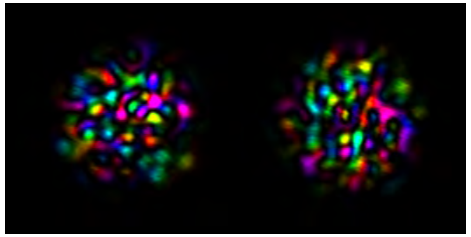
Digitial vectorial phase conjugation with real-time link stabilization achieves high-fidelity mode transmission:

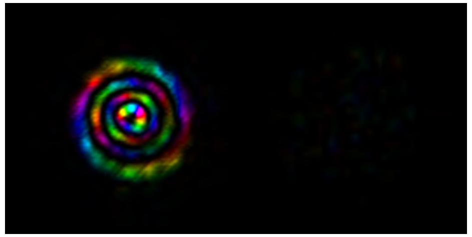
1 km of multimode fibre

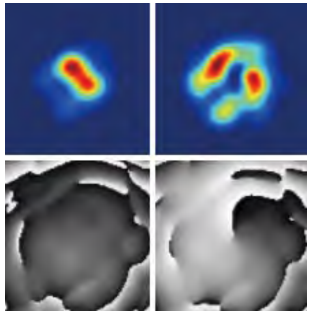
>80% average fidelity for 210 LG modes

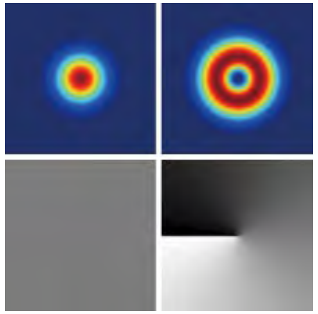
340 m of free space

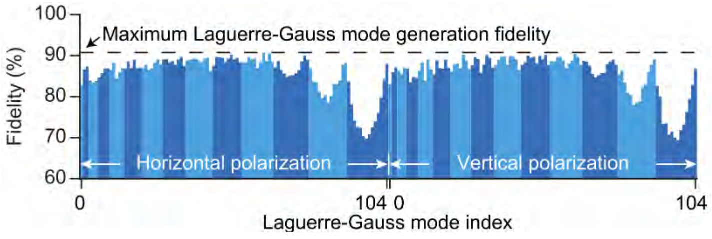
>80% average fidelity for 7 LG modes

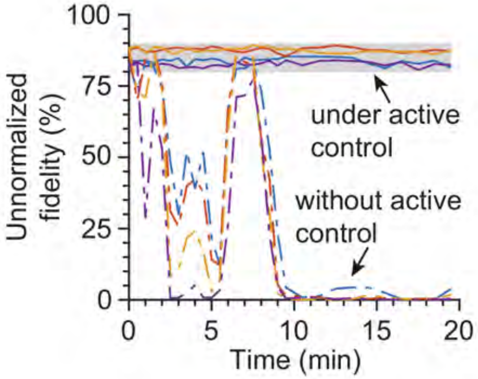












Response time constrained by SLMs

Poster Today!
Fast Generation and Detection of Spatial Modes of Light by Acousto-Optic Modulation
-Mahdieh Jabbari PS-40