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Centre for Silicon Photonics for Optical Communications

2018.qcrypt.net
QCrypt
8th International Conference on Quantum Cryptography

Fibre-based high-dimensional quantum communications

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Karsten Rottwitt, and Leif Katsuo Oxenløwe

High-Speed Optical Communication Group (HSOC)

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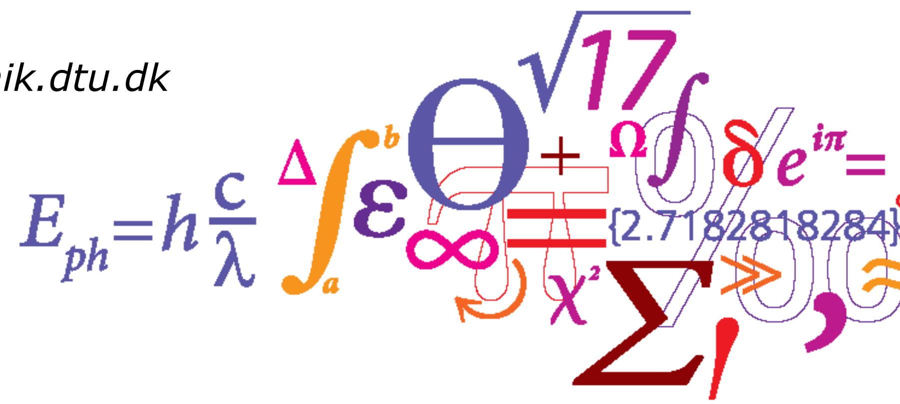


29 August 2018

DTU Fotonik
Department of Photonics Engineering

Niels Bohr Institutet

Danmarks Grundforskningsfond
Danish National Research Foundation

Outline

- SPOC centre (DTU Fotonik)
- Quantum communications with Hi-D (qudits)
- Examples: Multicore and OAM fibres for QCs
- Application: Hi-D Quantum key Distribution
- Comparison between Hi-D encoding and key multiplexing
- Conclusion

SPOC
CENTRE FOR SILICON PHOTONICS FOR OPTICAL COMMUNICATIONS

DTU

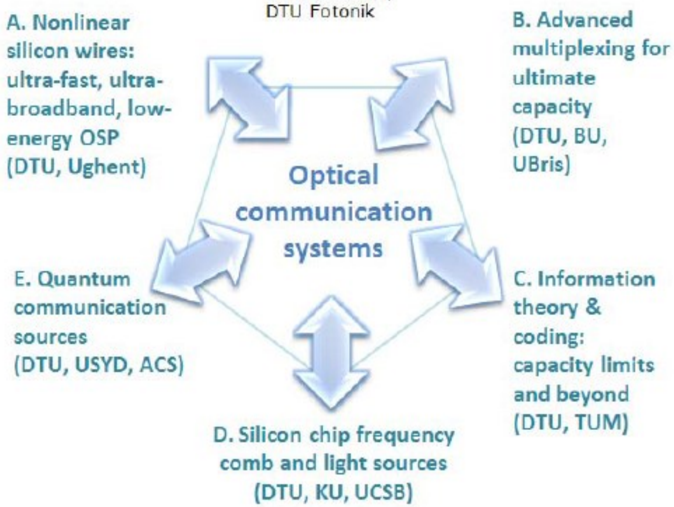
Centre of excellence for **Silicon Photonics for Optical Communication**

Aim: find solutions to the major challenges of communication systems – security, energy consumption and capacity

Leif K. Oxenløwe, Centre Leader, DTU Fotonik

Kresten Yvind, Assoc. Professor, DTU Fotonik

Toshio Morioka, Professor, DTU Fotonik



Karsten Rottwitt, Professor, DTU Fotonik

Søren Forchhammer, Professor, DTU Fotonik

Jan W. Thomsen, Assoc. Professor, Niels Bohr Institute

29 August 2018

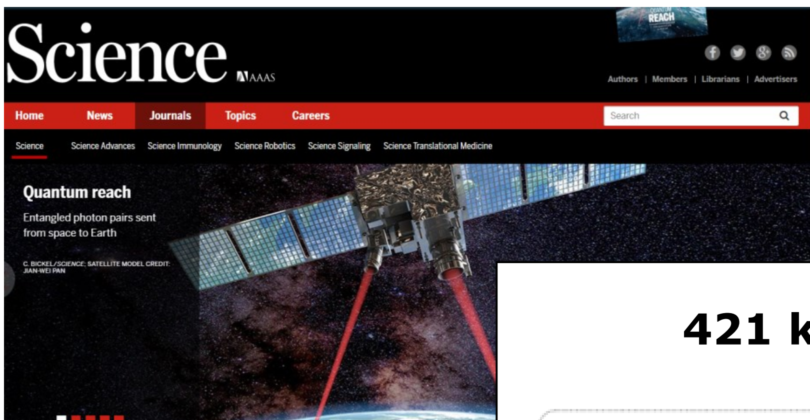
Quantum communication:

$|\psi\rangle$

"The art of transferring a quantum state from one place to another"
[N. Gisin, R. Thew, Nat. Photon. 1(3), 165 (2007)]

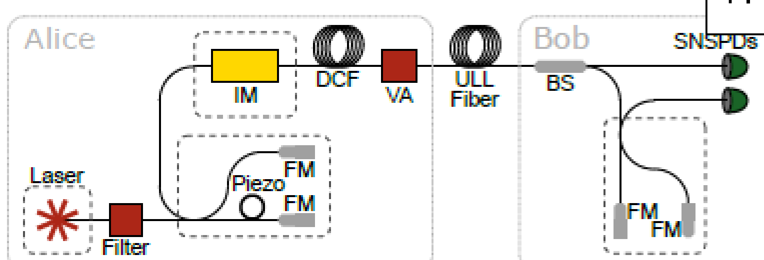
$|\psi\rangle$

Satellite teleportation/QKD



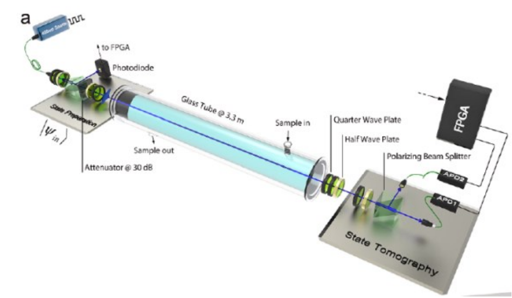
J. Yin et al., Science 356 (1140)
J. G. Ren et al., Nature 549 (70)

421 km QKD in fibre



A. Boaron et al., aRXiv:1807.03222

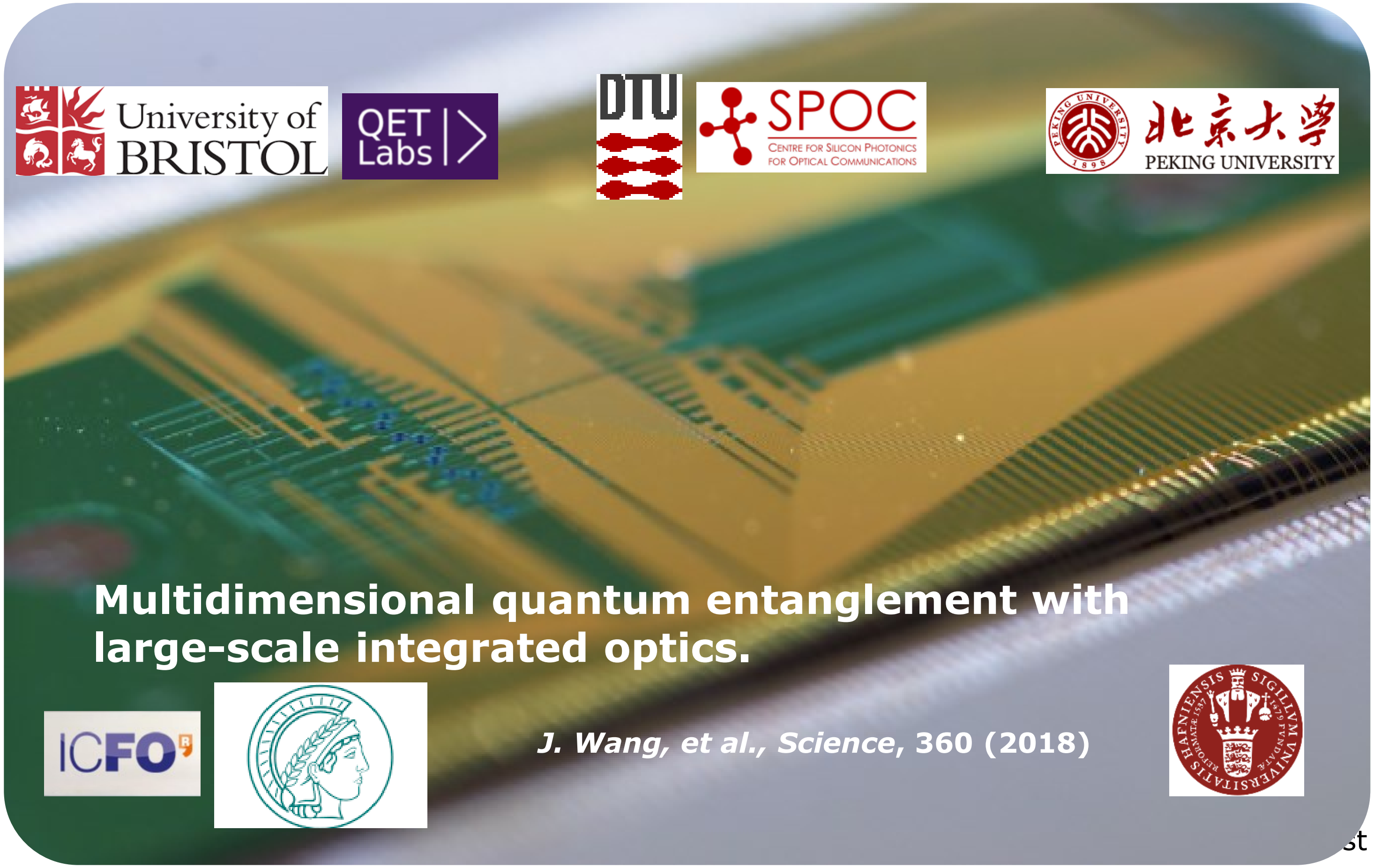
Underwater QCs



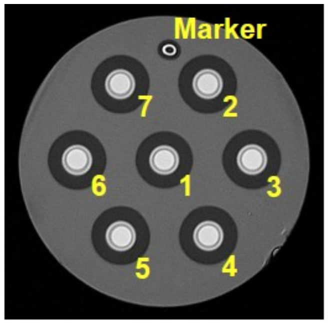
L. Ji et al., Opt. Expr. 25 (17)
F. Bouchard et al., Opt. Expr. 26 (17)

Quantum communications with qudits

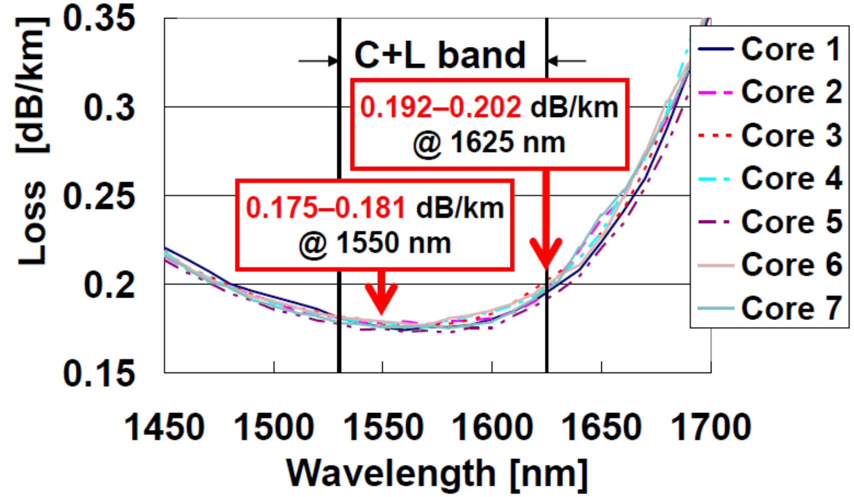
- ✓ larger PIE and noise robustness for quantum communications [N. J. Cerf, et al., *P.R.L.*, *88*(12) 2002]
- ✓ reduction of cloning fidelity in Hi-D quantum states [M. Erhard et al., Light: Science & Applications 7,17146 (2018)]
- ✓ higher efficiency and flexibility in quantum computing [J. Wang, et al., Science, 360 (2018)]



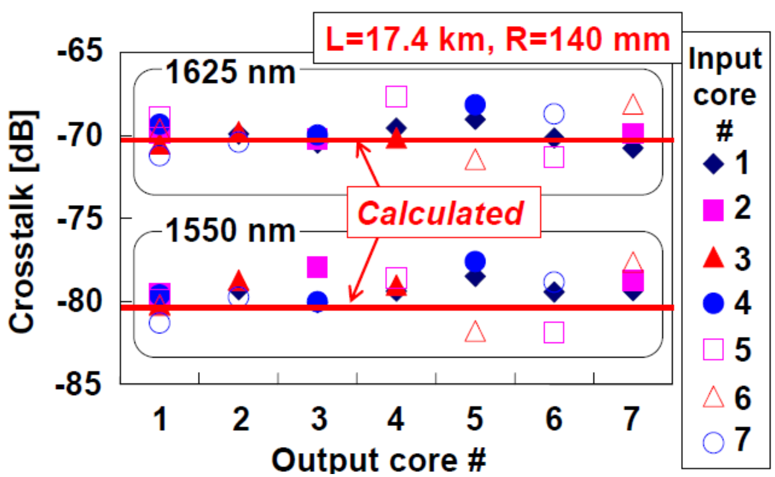
Multicore fibre for QCs



Loss : ~0.2 dB/km



Low crosstalk



SOTA

37 cores heterogeneous MCF

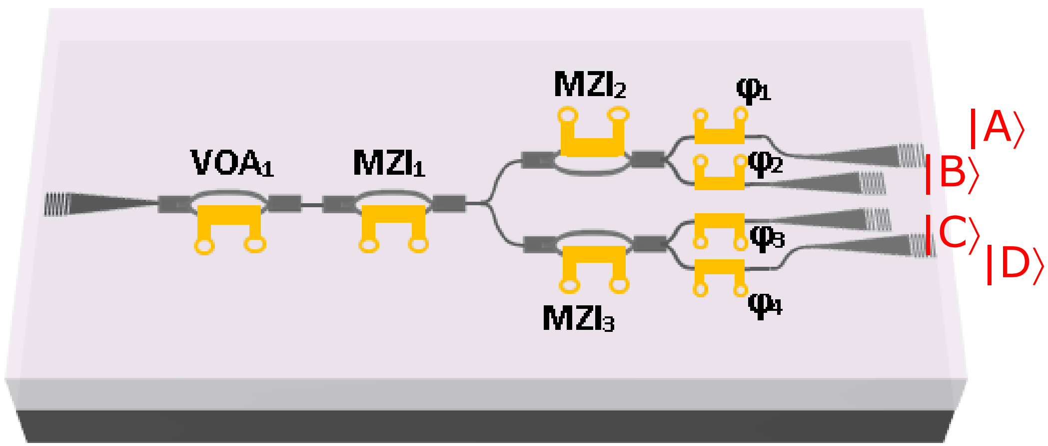
Distance >10 km

Few deployed fibres

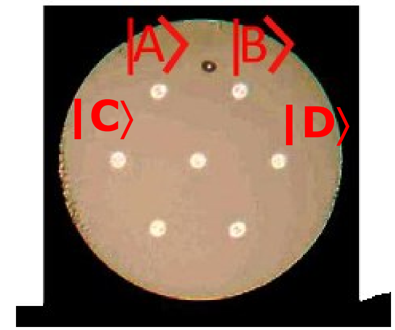
T. Hayashi et al., Opt. Express19, 16576-16592 (2011)

Setup of QCs with MCF

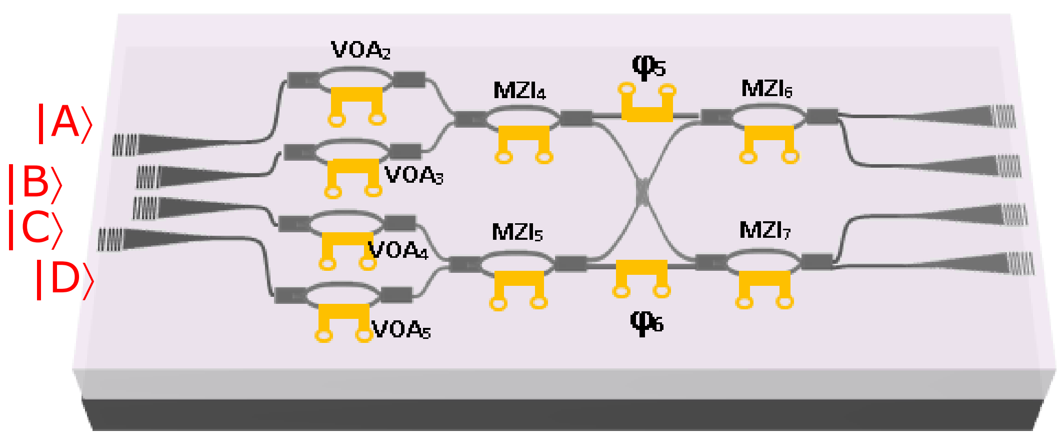
Transmitter



MCF



Receiver



Quantum states

2D

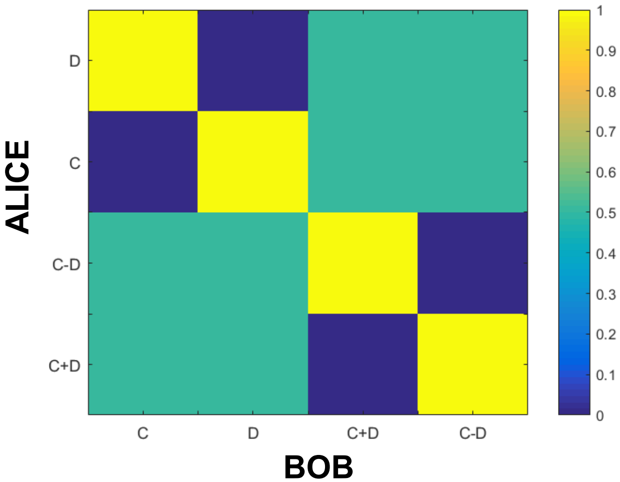
$$\begin{pmatrix}|A\rangle\\|B\rangle\end{pmatrix} \qquad \begin{pmatrix}|A+B\rangle\\|A-B\rangle\end{pmatrix}$$

4D

$$\begin{pmatrix}|A+B\rangle\\|A-B\rangle\\|C+D\rangle\\|C-D\rangle\end{pmatrix} \quad \begin{pmatrix}|A+C\rangle\\|A-C\rangle\\|B+D\rangle\\|B-D\rangle\end{pmatrix} \quad \begin{pmatrix}|A+D\rangle\\|A-D\rangle\\|B+C\rangle\\|B-C\rangle\end{pmatrix}$$

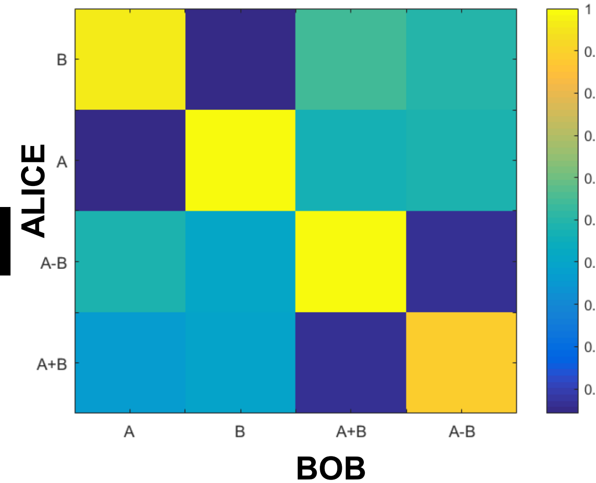
Y. Ding , D. Bacco et al., npj Quantum Information 3 (2017).

Fidelity of MUBs



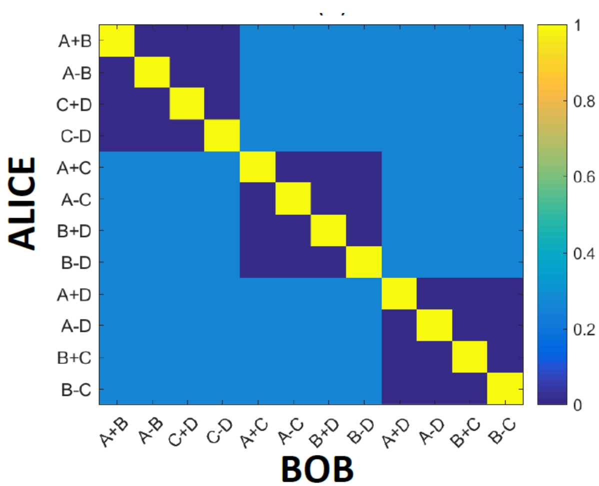
2D

[redacted]



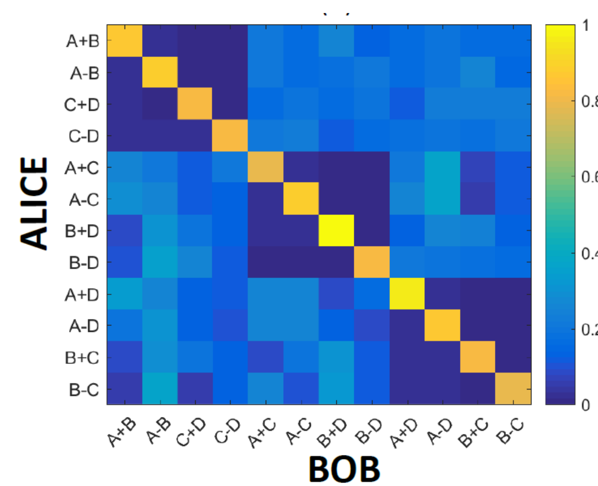
Theory

Experiment



4D

$$F \simeq 98\%$$



Y. Ding , D. Bacco et al., npj Quantum Information 3 (2017).

Application Hi-D QKD (MCF)

Problematics:

- ✓ few meters between transmitter and receiver (5m)
- ✓ Slow repetition rate
- ✓ difficult to keep stability over time

Y. Ding , D. Bacco et al., npj Quantum Information 3 (2017).

OAM for QCs

Free-Space Quantum Key Distribution by Rotation-Invariant Twisted Photons

Giuseppe Vallone,[1] Vincenzo D'Ambrosio,[2] Anna Sponselli,[3] Sergei Slussarenko,[4,*] Lorenzo Marrucci,[4] Fabio Sciarrino,[2] and Paolo Villoresi[1,†]
[1]Dipartimento di Ingegneria dell'Informazione, Università di Padova, I-35131 Padova, Italy
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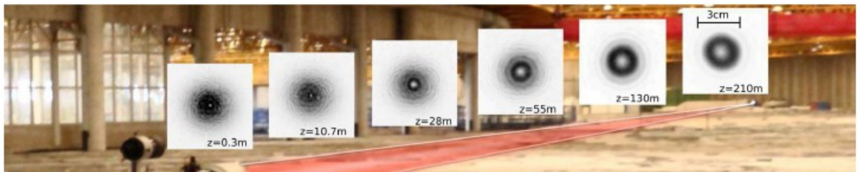
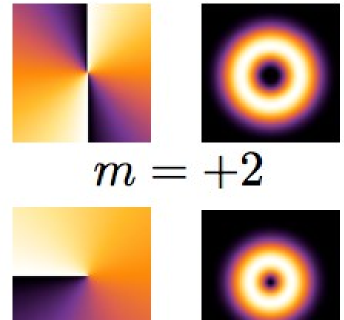
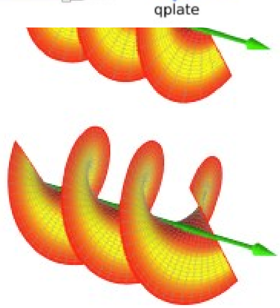
(Received 29 April 2014; published 8 August 2014)



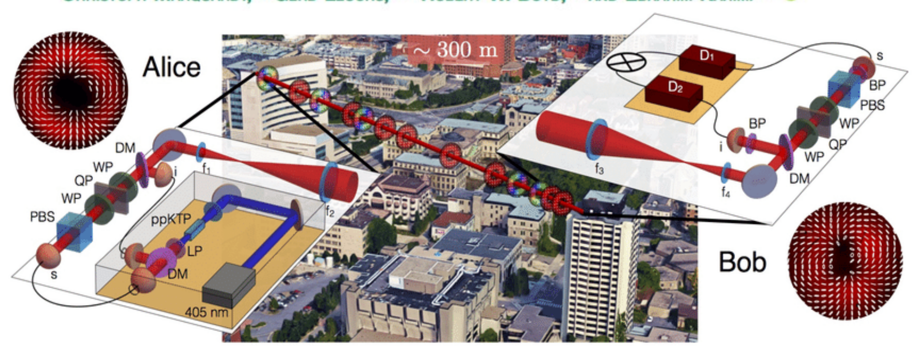


Fibre based QC with twisted photons was not demonstrated!

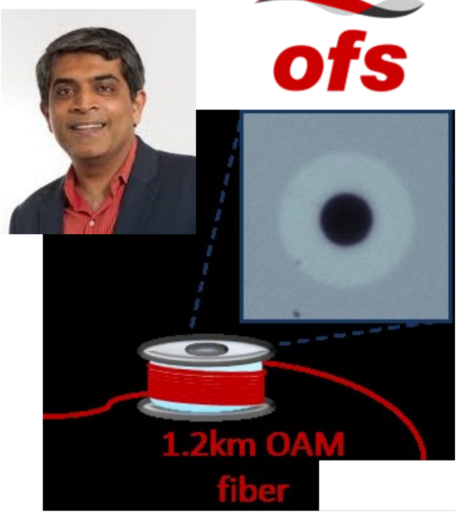


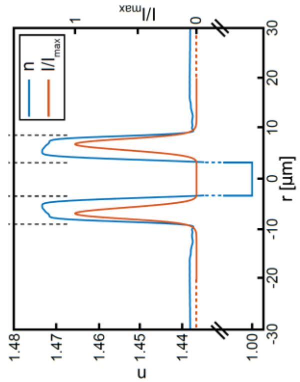
High-dimensional intracity quantum cryptography with structured photons

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,*]

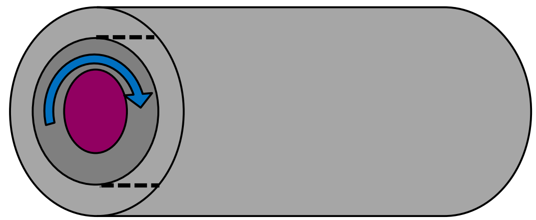


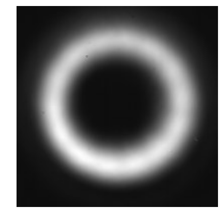
HOM fibre for QCs

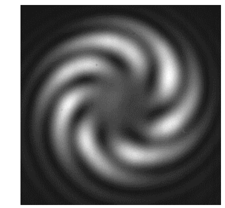




Loss : ~1 dB/km







Terabit-Scale Orbital Angular Momentum Mode Division Multiplexing in Fibers, **S. Ramachandran, A. Willner groups**

Science 2013, **340 (**6140), DOI: 10.1126/science.1237861

Orbital Angular Momentum Conserved: OAM more robust against mode-mixing

Mode Division Multiplexing Using Orbital Angular Momentum Modes Over 1.4-km Ring Core Fiber **Uni. Laval,**

Journal of Lightwave Technology 34(18), 2016, DOI: 10.1109/JLT.2016.2594698

18 km low-crosstalk OAM + WDM transmission with 224 individual channels enabled by a ring-core fiber with large high-order mode group separation, **Siyuan Yu group**

Optics Letters **43**(8), 2018 DOI: 10.1364/OL.43.001890

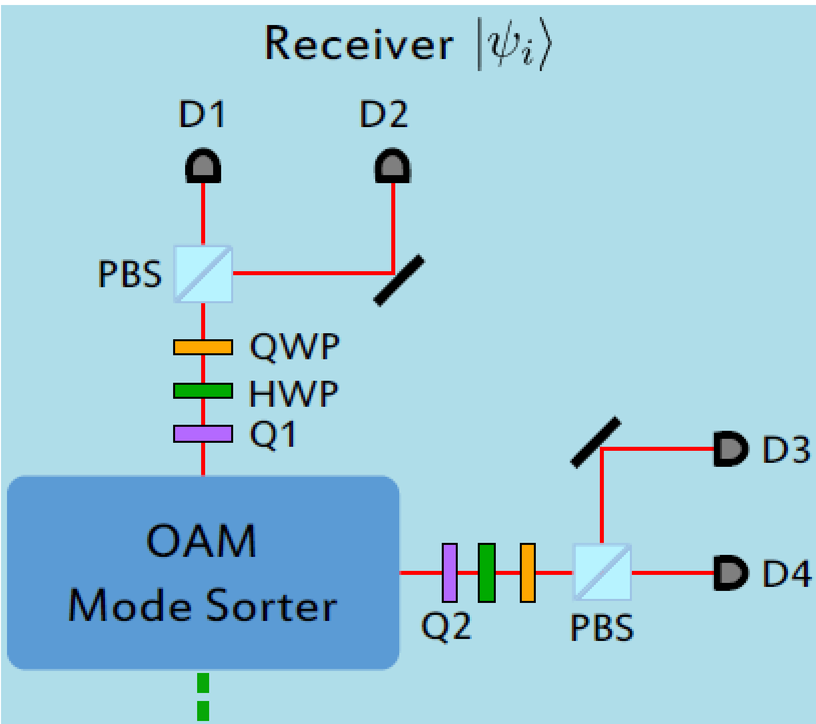
12 mode, WDM, MIMO-free orbital angular momentum transmission, **DTU, BU, OFS, Uni.Napoli**

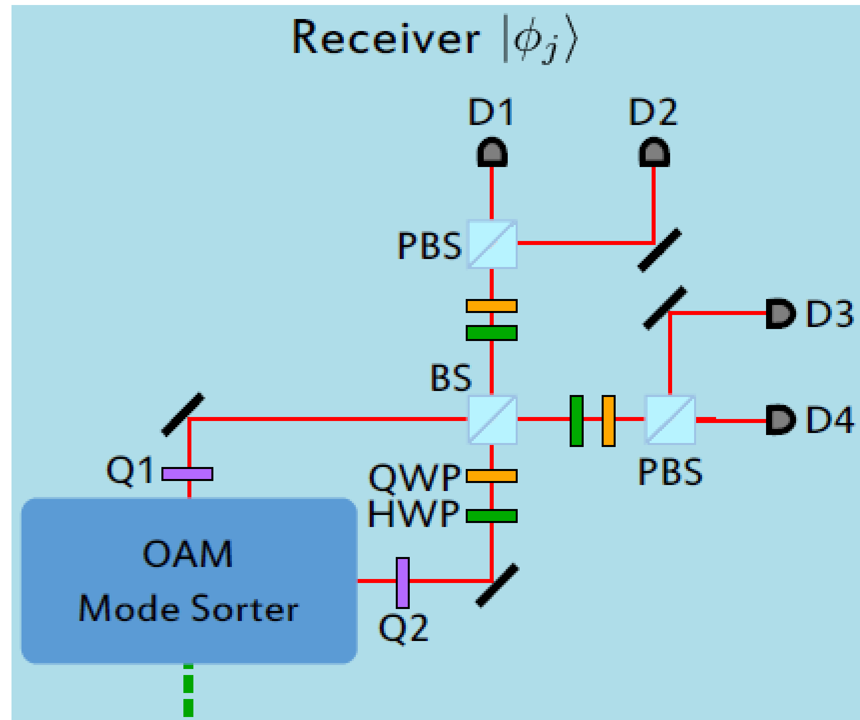
Optics Express **26** (16) 2018, DOI: 10.1364/OE.26.020225

Fibre based QCs with twisted photons

Vortex half plate (q-plate)

L. Marrucci et al., P.R.L. 96.16 (2006)



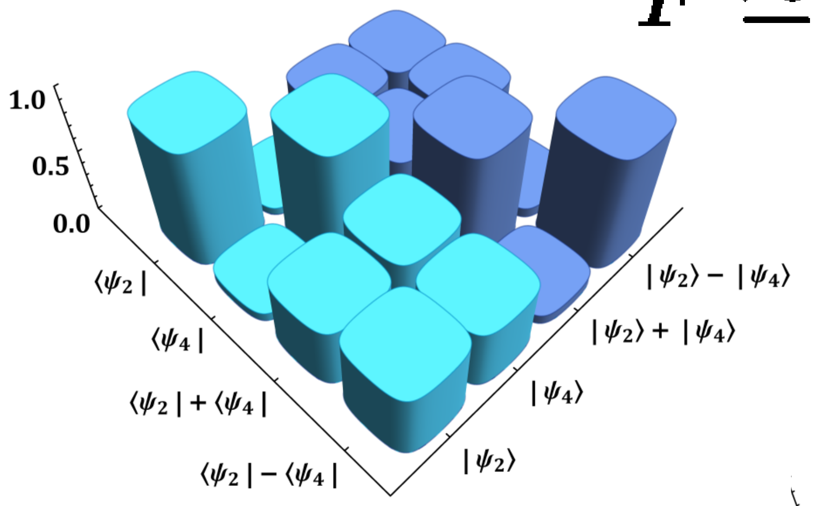


D. Cozzolino, D. Bacco et al., arXiv:1803.10138 [quant-ph]

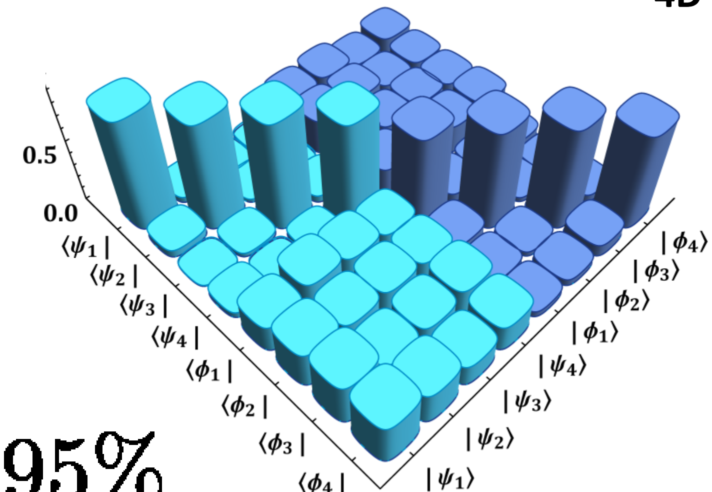
Results with OAM fibre

2D

$$F \simeq 98\%$$



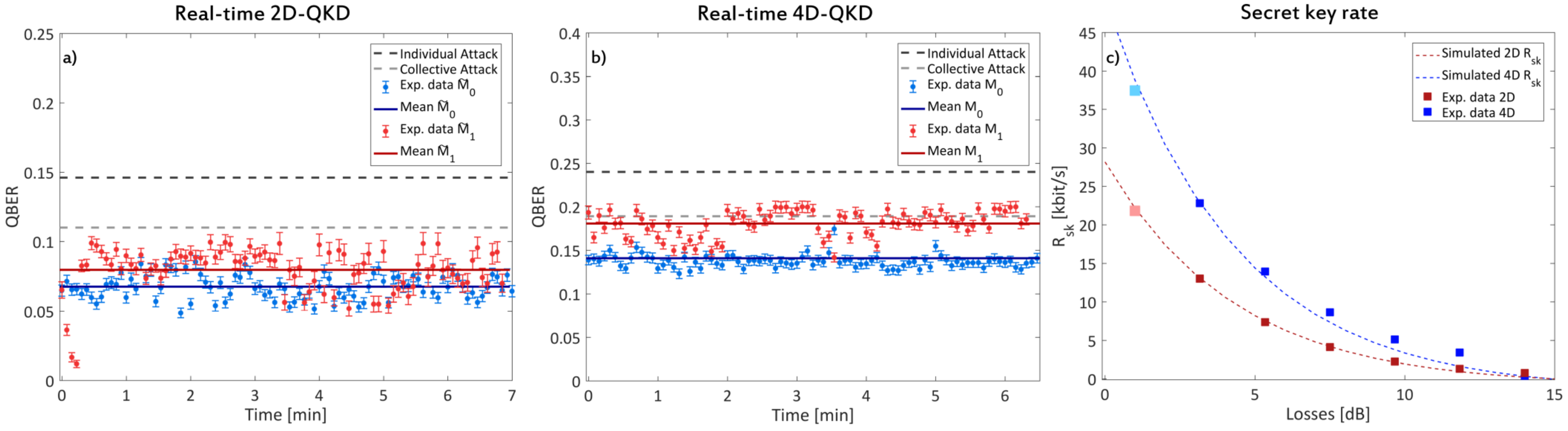
4D



$$F \simeq 95\%$$

D. Cozzolino, D. Bacco et al., arXiv:1803.10138 [quant-ph]

Application Hi-D QKD (OAM)



- First demonstration of Hi-D-QKD at 600 MHz using OAM fibre of 1.2 km
- Enhancement of 71% in key generation compared to 2D case
- Proved feasibility of OAM Quantum Communications in a fibre

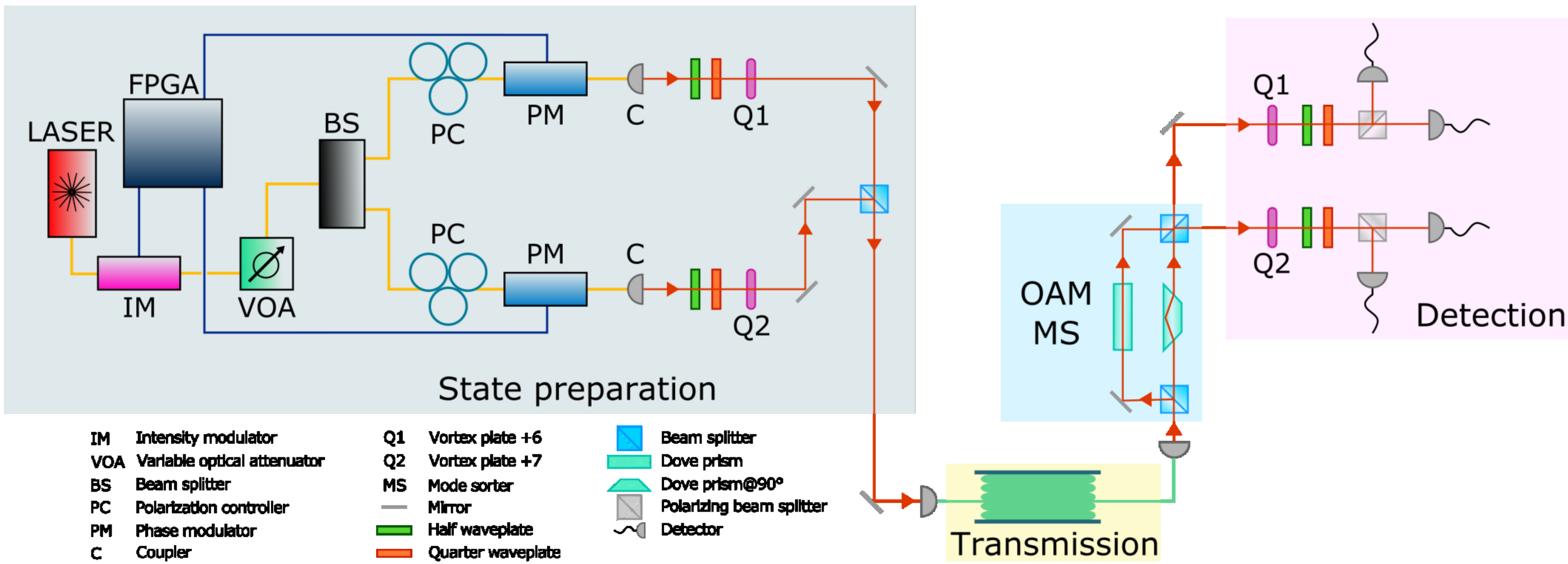
D.Cozzolino, D.Bacco, et al., PDP CLEO Pacific RIM (2018)

D. Cozzolino, D. Bacco et al., arXiv:1803.10138 [quant-ph]

OAM key multiplexing

Independent decoy state BB84 QKD over OAM

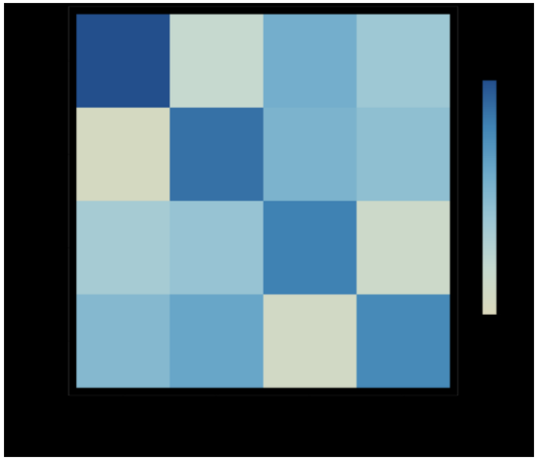
OAM order mode	$\lvert\ell\rvert=6$	$\lvert\ell\rvert=7$
***Z* bases polarizations**	R , L	R , L
***X* bases polarizations**	D , A	D , A



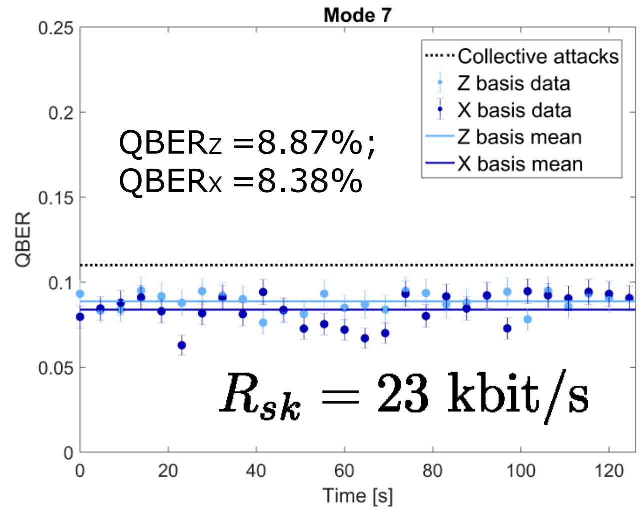
D. Bacco, D. Cozzolino et al., in preparation

Experimental results MUX OAM

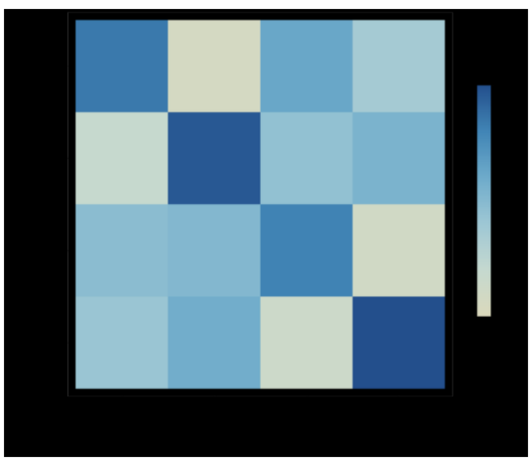
MODE 7



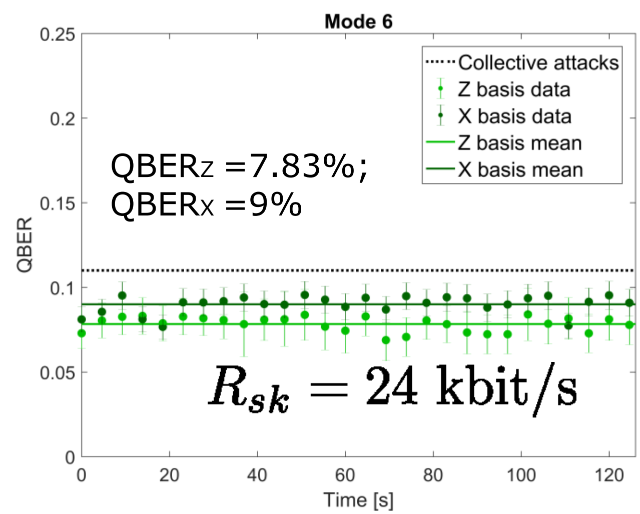
$F \simeq 96.6\%$



MODE 6



$F \simeq 96.7\%$

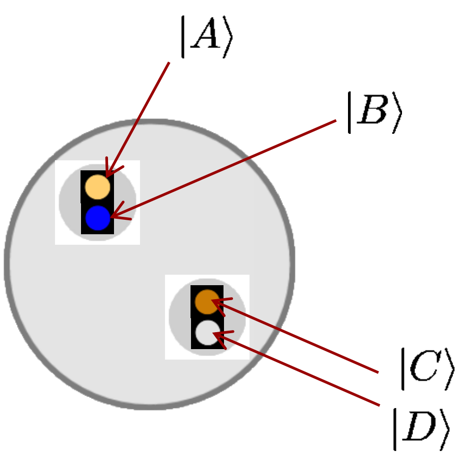


D. Bacco, D. Cozzolino et al., in preparation

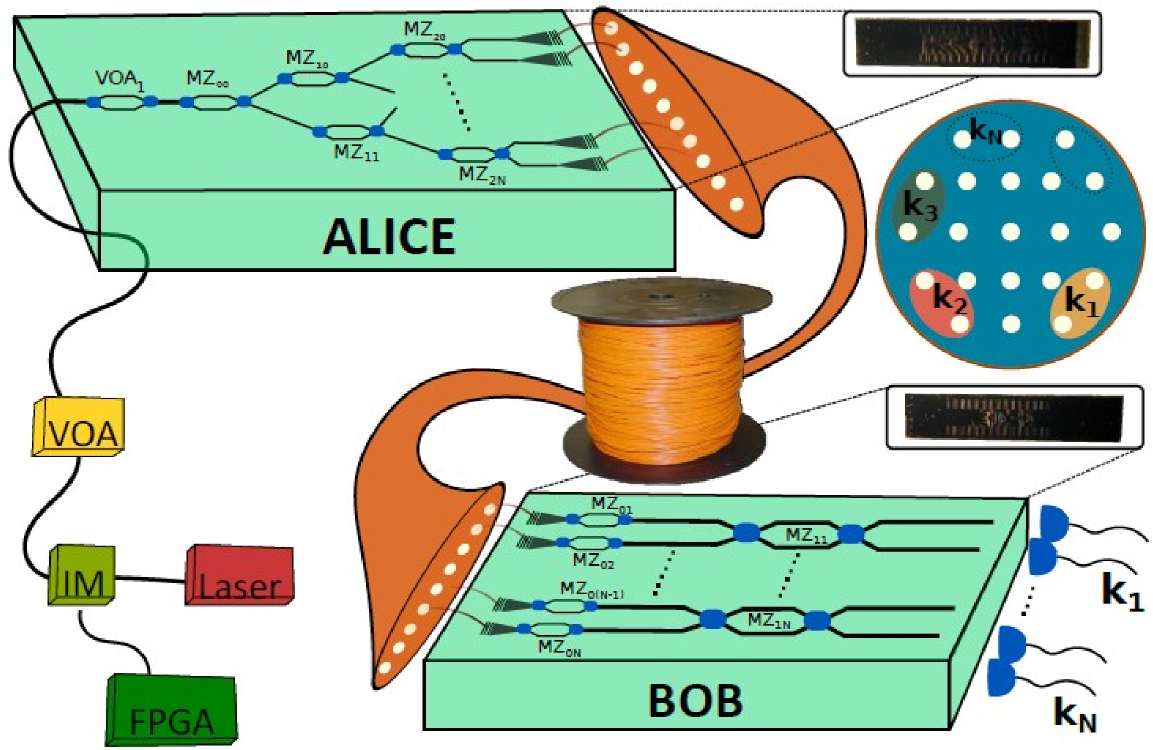
Chip-to-chip key multiplexing

Independent decoy state BB84 QKD over MCF

Base 1	Base 2
$\begin{pmatrix} \vert A\rangle \\ \vert B\rangle \end{pmatrix}$	$\begin{pmatrix} \vert A+B\rangle \\ \vert A-B\rangle \end{pmatrix}$



Base 1	Base 2
$\begin{pmatrix} \vert C\rangle \\ \vert D\rangle \end{pmatrix}$	$\begin{pmatrix} \vert C+D\rangle \\ \vert C-D\rangle \end{pmatrix}$

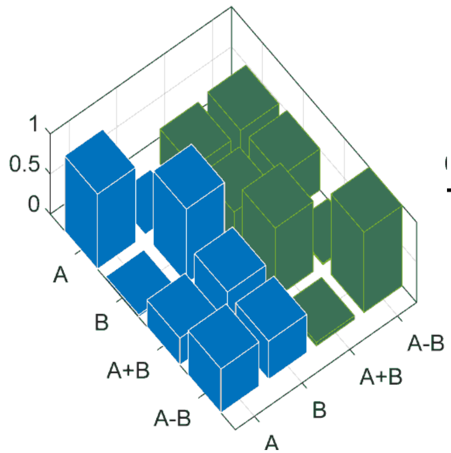


Experimental results MUX MCF

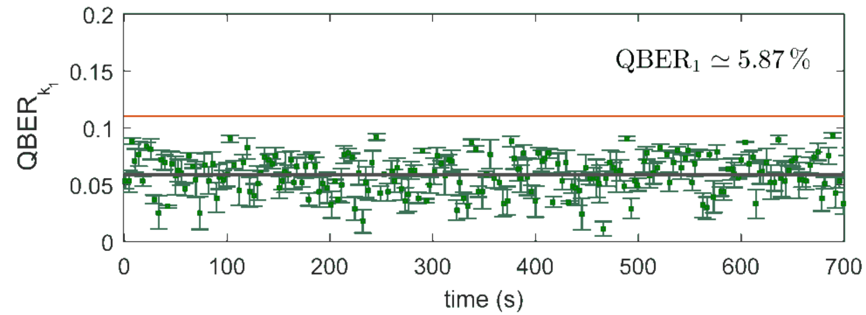
- SDM: Two parallel decoy state BB84 protocol

BER vs TIME
stability of the system

k1

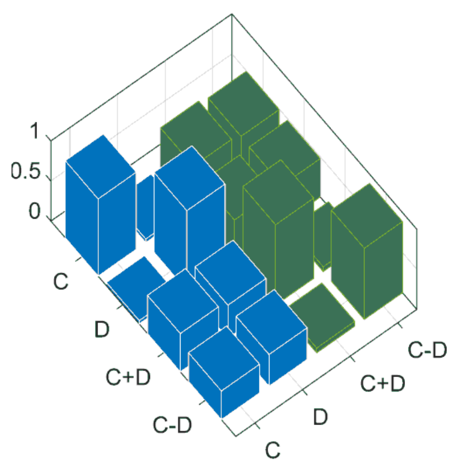


$F \simeq 93\%$

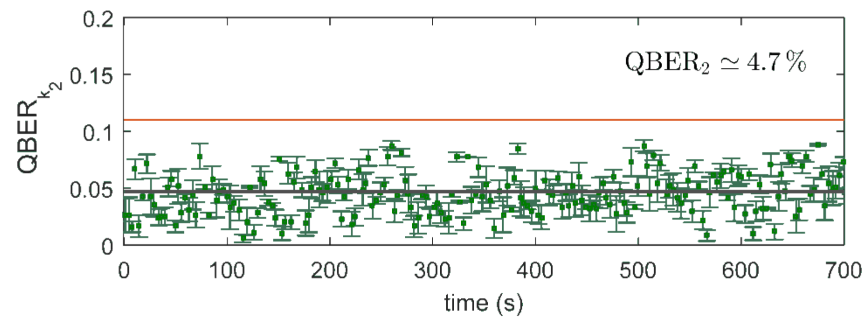


$$R_{sk} = 150 \text{ bit/s}$$

k2



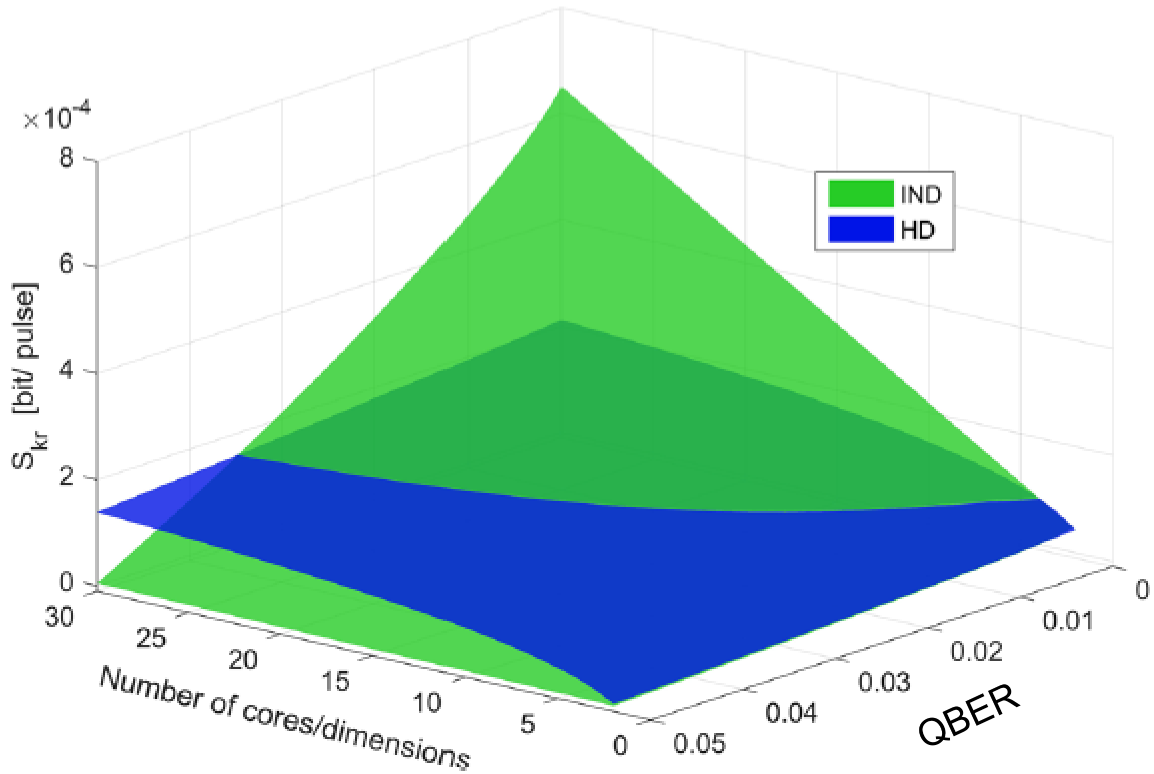
$F \simeq 96\%$



$$R_{sk} = 162 \text{ bit/s}$$

D. Bacco et al., Scientific Reports 7, 12459 (2017)

Comparison HD-QKD and keys MUX



-High noise HD gain compared to IND

-Low noise better to use MUX technique

D. Bacco et al., Scientific Reports 7, 12459 (2017)

Conclusions

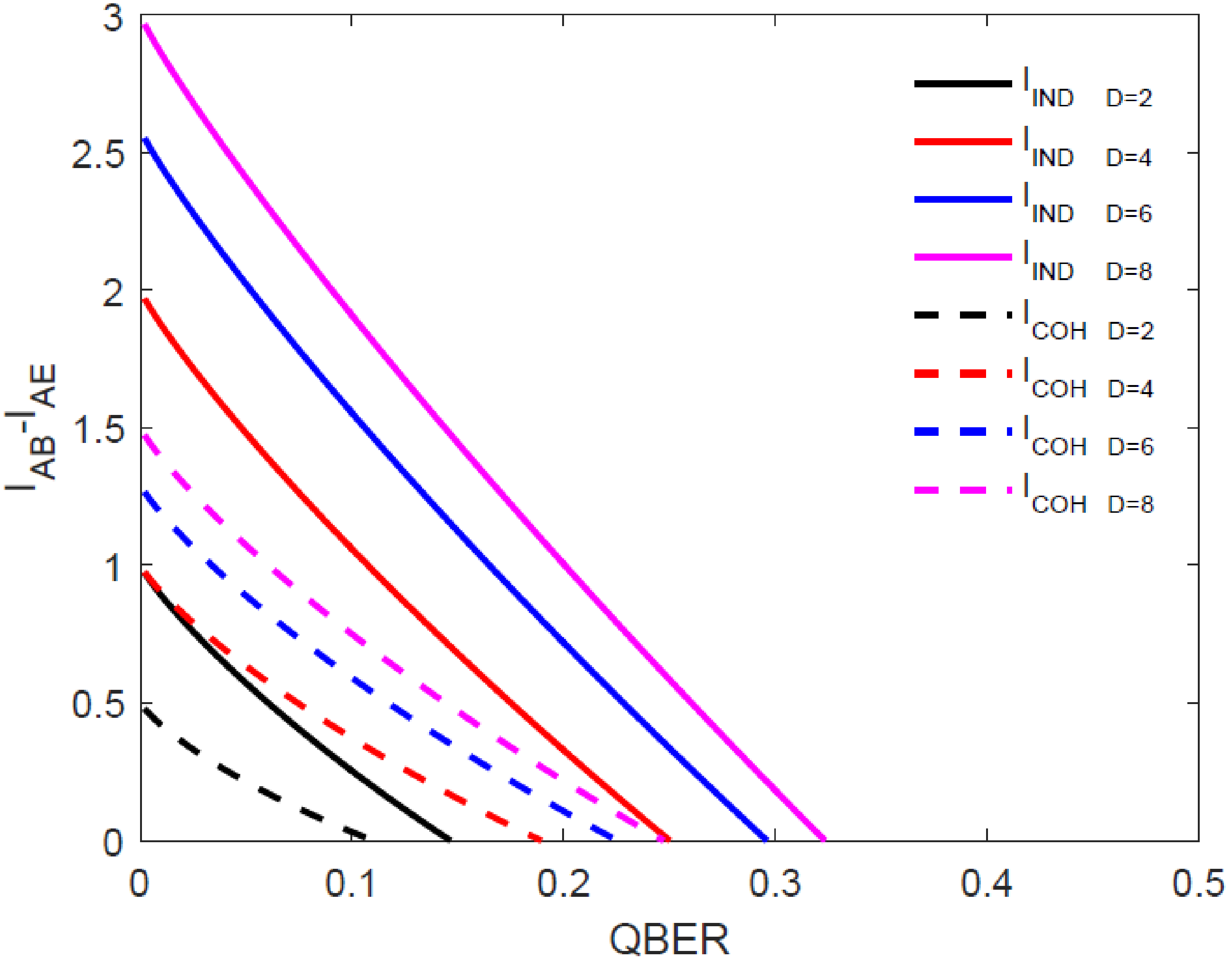
- space encoding qudits can be transferred over fibre
  - demonstration of a ququart through a MCF
  - first transmission of a ququart over an OAM fibre
- applications of qudits
  - Decoy state chip-to-chip Hi-D QKD over MCF fibre
  - Decoy state Hi-D QKD over 1.2 km OAM fibre
- Hi-D or keys multiplexing?
  - low channel noise convenient key MUX
  - high noise, only qudits allow key distillation

Thanks for your attention!

Additional Slides

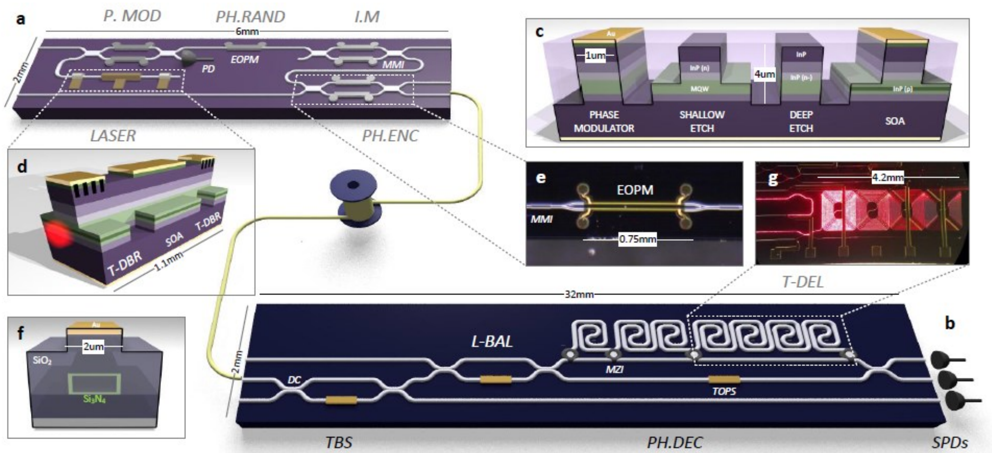
Qudits encoding

More robust against noise [N. J. Cerf, et al., *P.R.L.*, *88*(12) 2002]

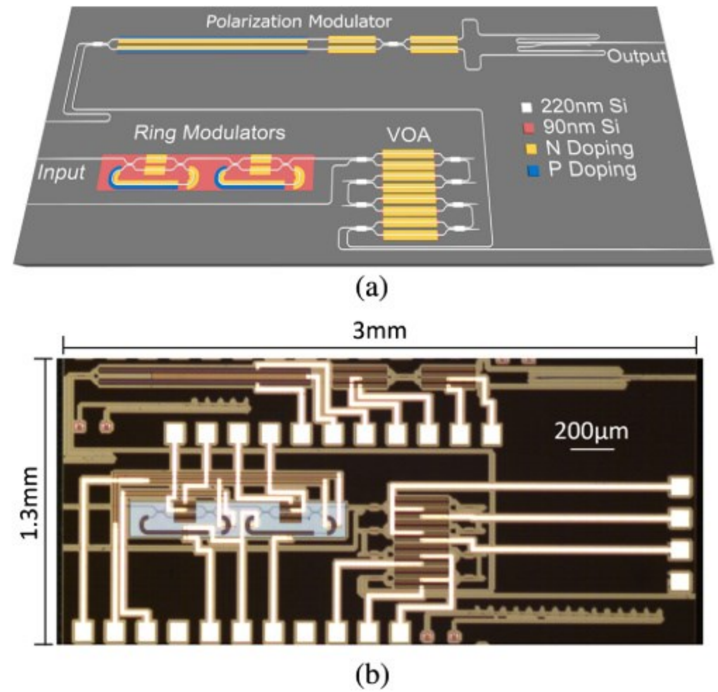


Y. Ding , D-. Bacco et al., npj Quantum Information 3 (2017).

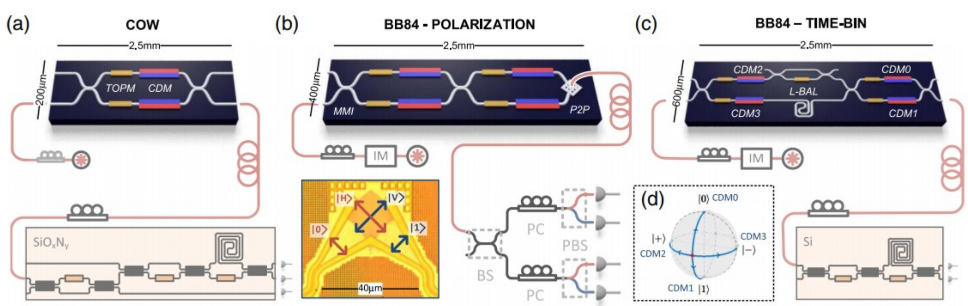
Integrated devices for QCs



P. Sibson et al., Nat. Commun. 8:13984 (2017)

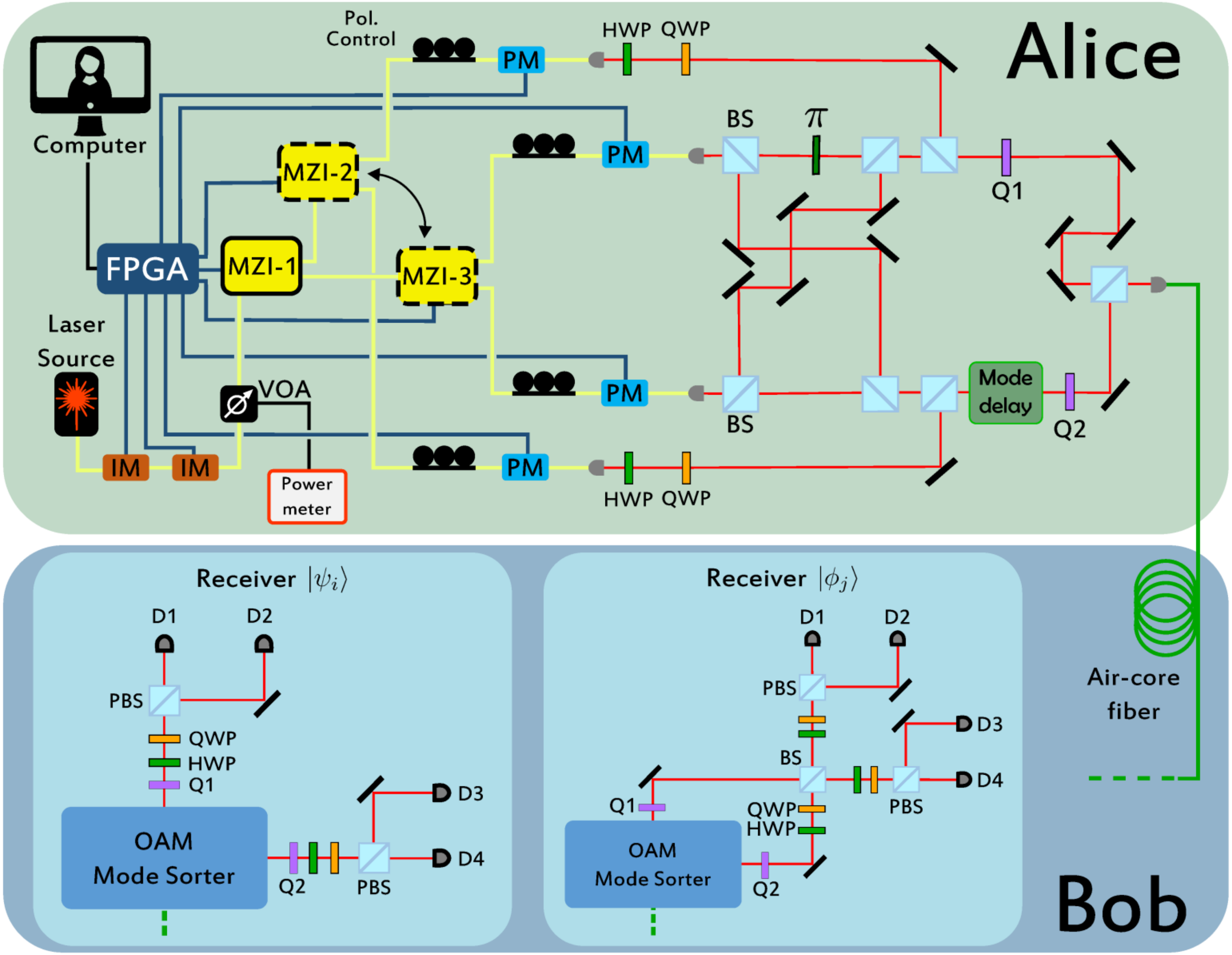


C. Ma et al, Optica 3, 1274-1278 (2016)



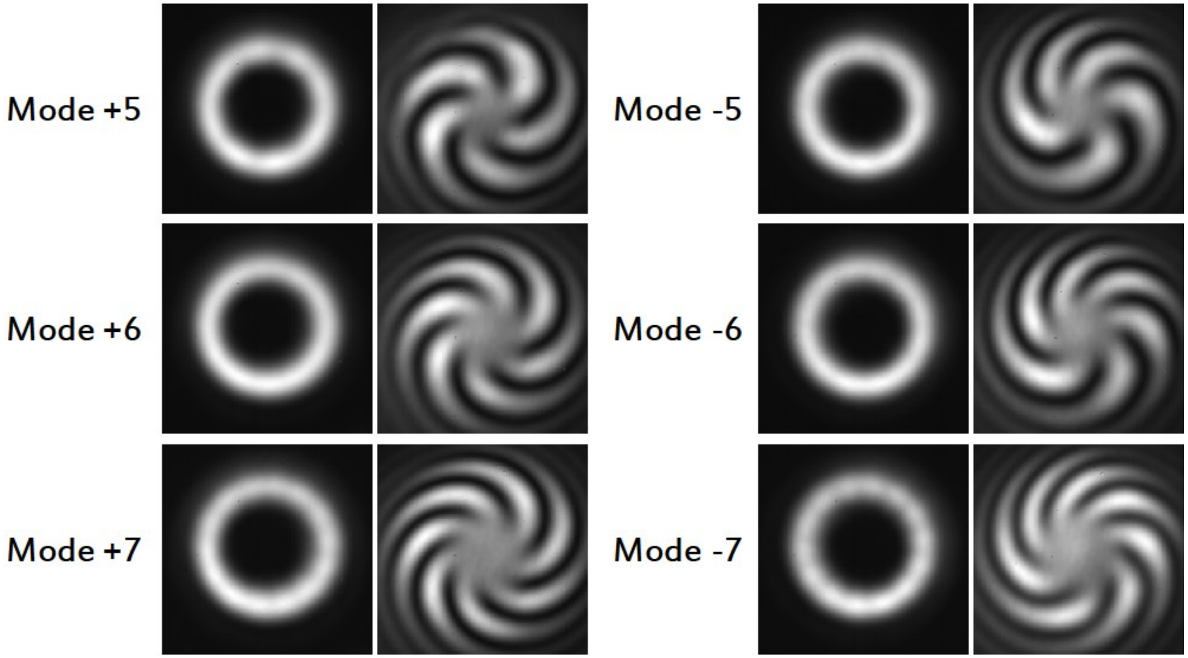
P. Sibson et al, Optica 4, 172-177 (2017)

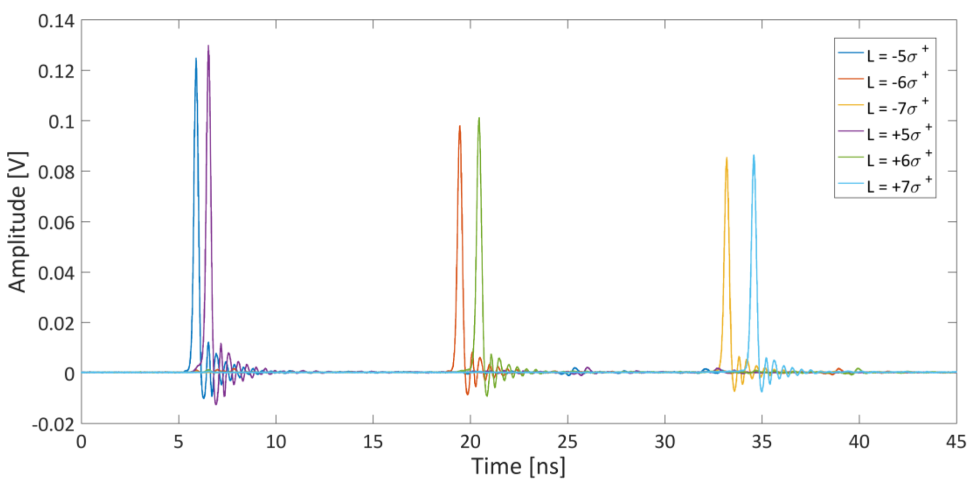
Main setup OAM



D. Cozzolino, D. Bacco et al., arXiv:1803.10138 [quant-ph]

Modes characterization

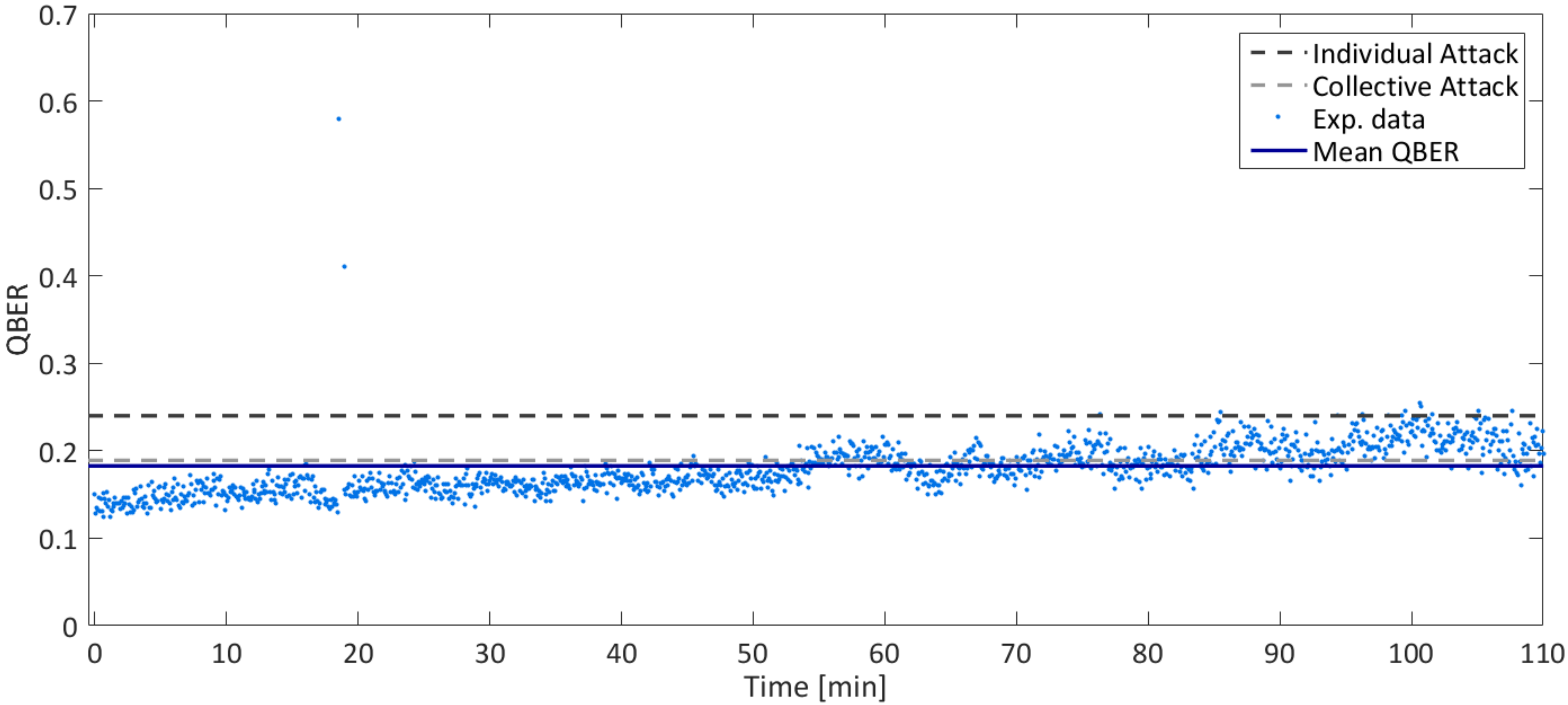




D. Cozzolino, D. Bacco et al., arXiv:1803.10138 [quant-ph]

Experimental Results Hi-D OAM

Stability measurement in the M0 basis



D. Cozzolino, D. Bacco et al., arXiv:1803.10138 [quant-ph]