Integrated Photonic Technologies for Quantum Communications

Mark G Thompson, colleagues & collaborators:

University of BRISTOL P. Sibson, J. Wang, C. Erven, J. L. O'Brien, M. G. Thompson

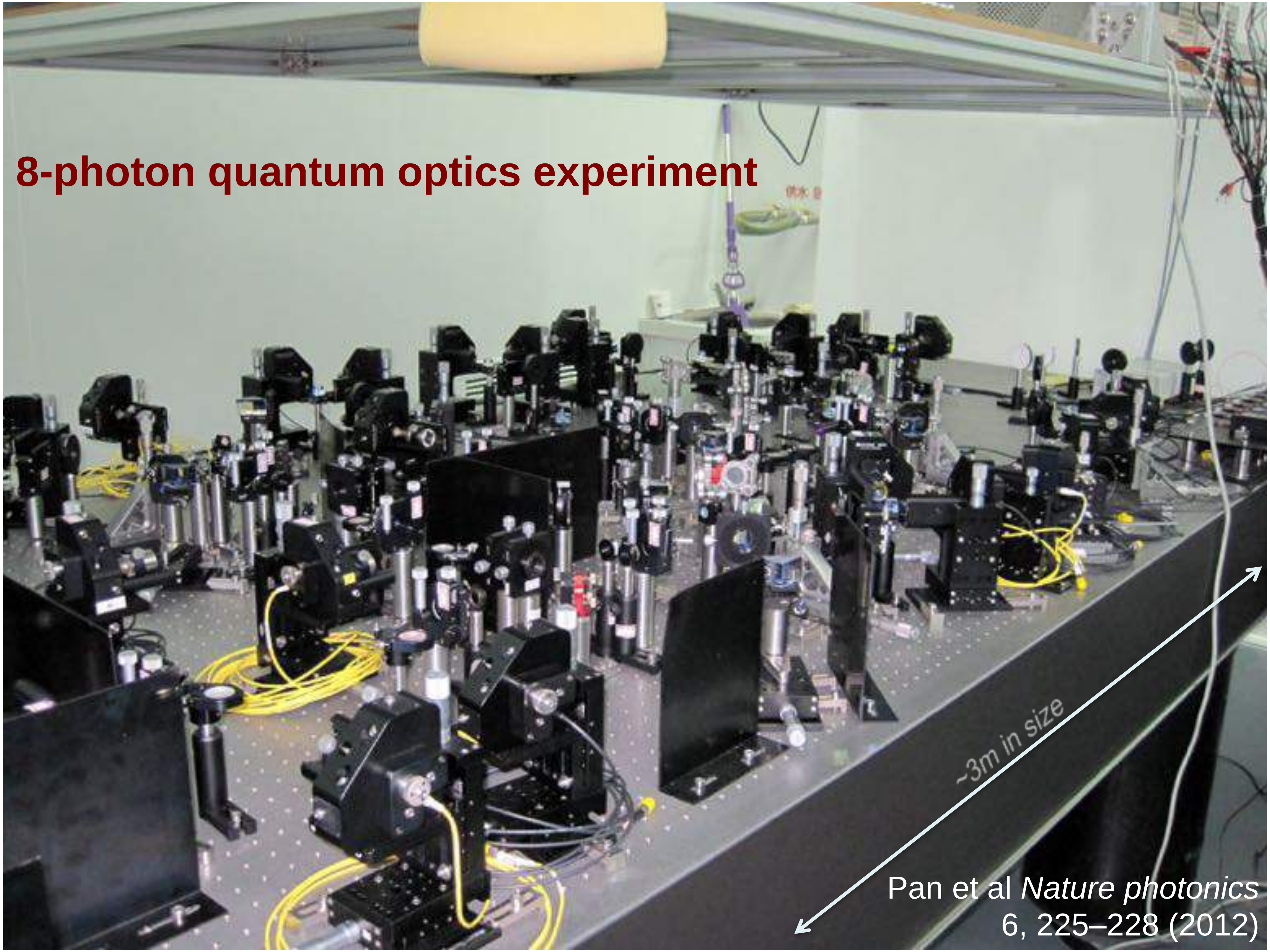
University of Glasgow M. G. Tanner, C. M. Natarajan, R. H. Hadfield,

NICT S. Miki, T. Yamashita, M. Fujiwara, M. Sasaki, H. Terai,

Centre for Quantum Photonics
Schools of Physics and Electrical Engineering
University of Bristol

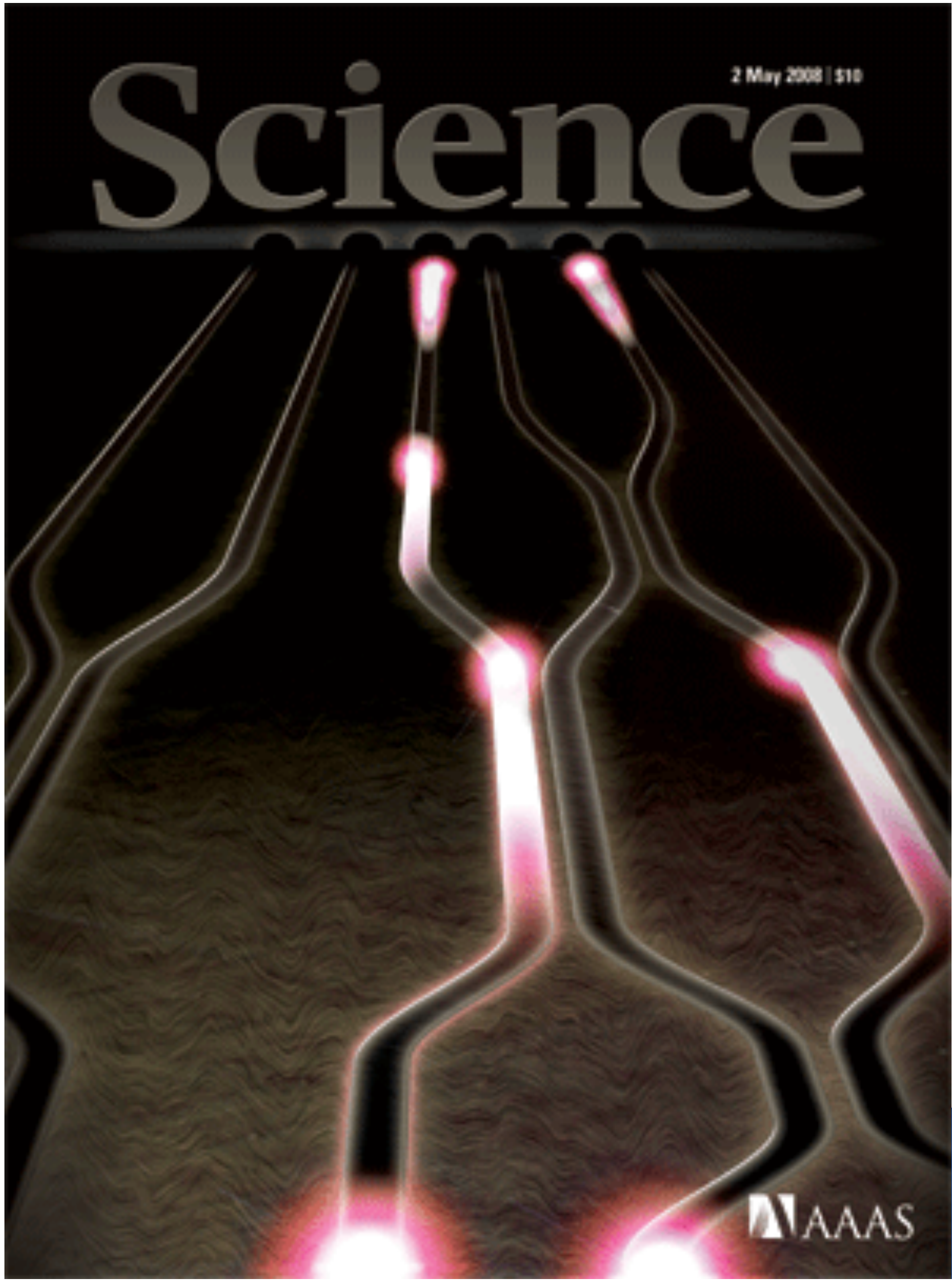
QUANTUM COMMUNICATIONS HUB
erc
UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME
EPSRC
dstl

8-photon quantum optics experiment

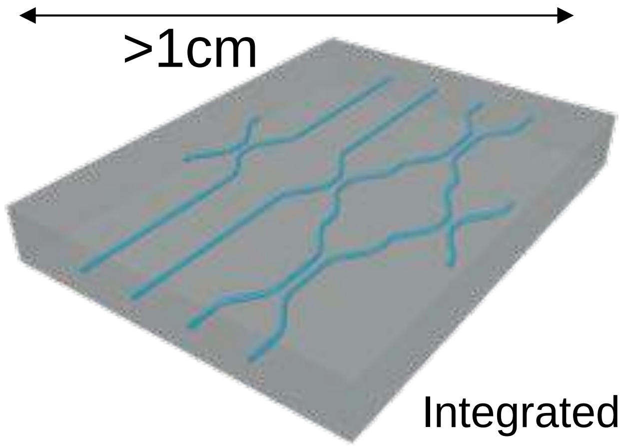


Pan et al *Nature photonics* 6, 225–228 (2012)

Integrated Quantum Photonics



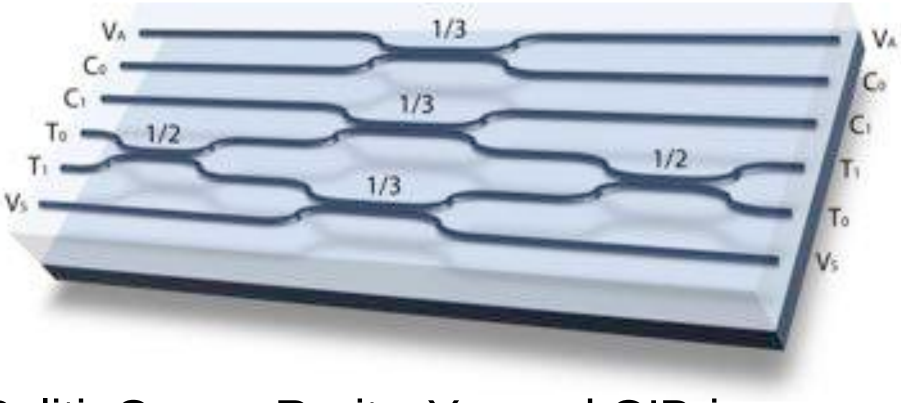
- Size / Compactness
- Stability
- Complexity
- Route to scalability



Integrated device

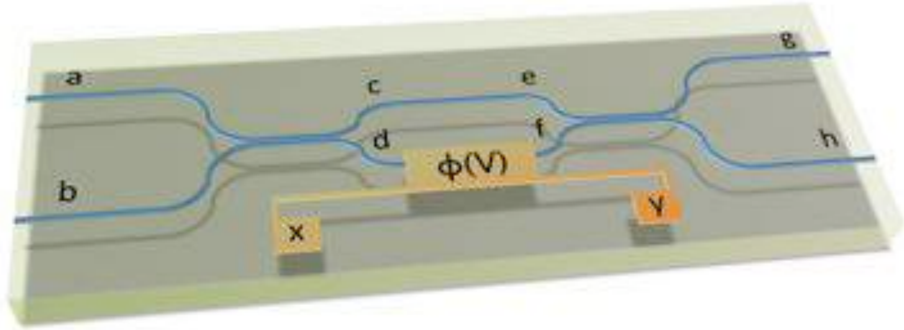
A. Politi, et al. *Science*,**320**,5876 (2008).

CNOT gate



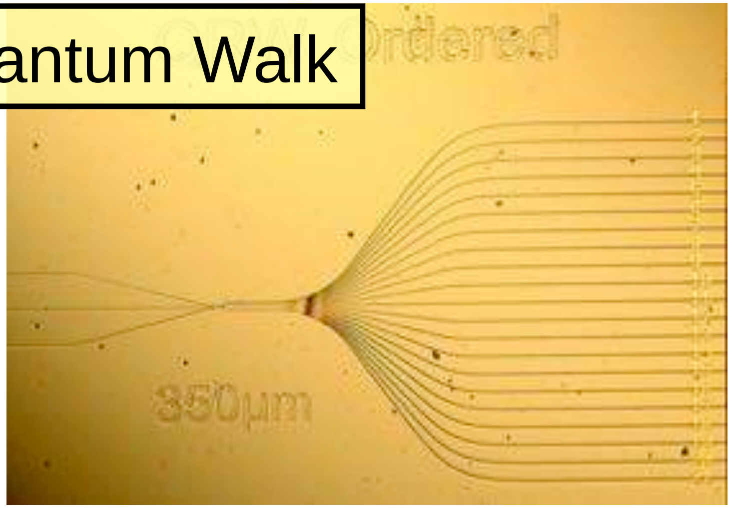
Politi, Cryan, Rarity, Yu, and O'Brien
***Science* 320**, 5876 (2008)

1-Qubit operations



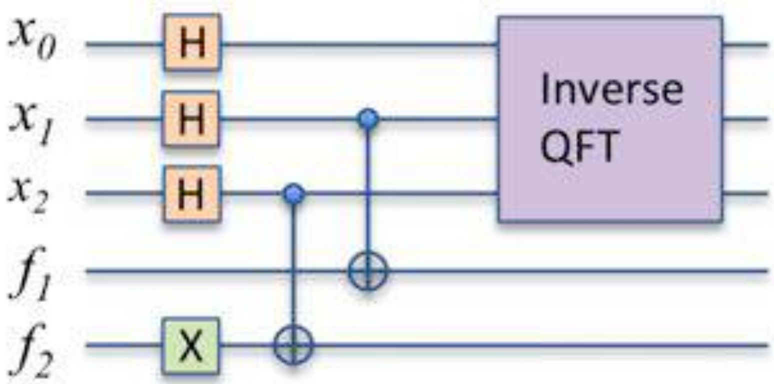
Matthews, Politi, Stefanov, O'Brien
***Nature Photonics* 3**, 346 (2009)

Quantum Walk



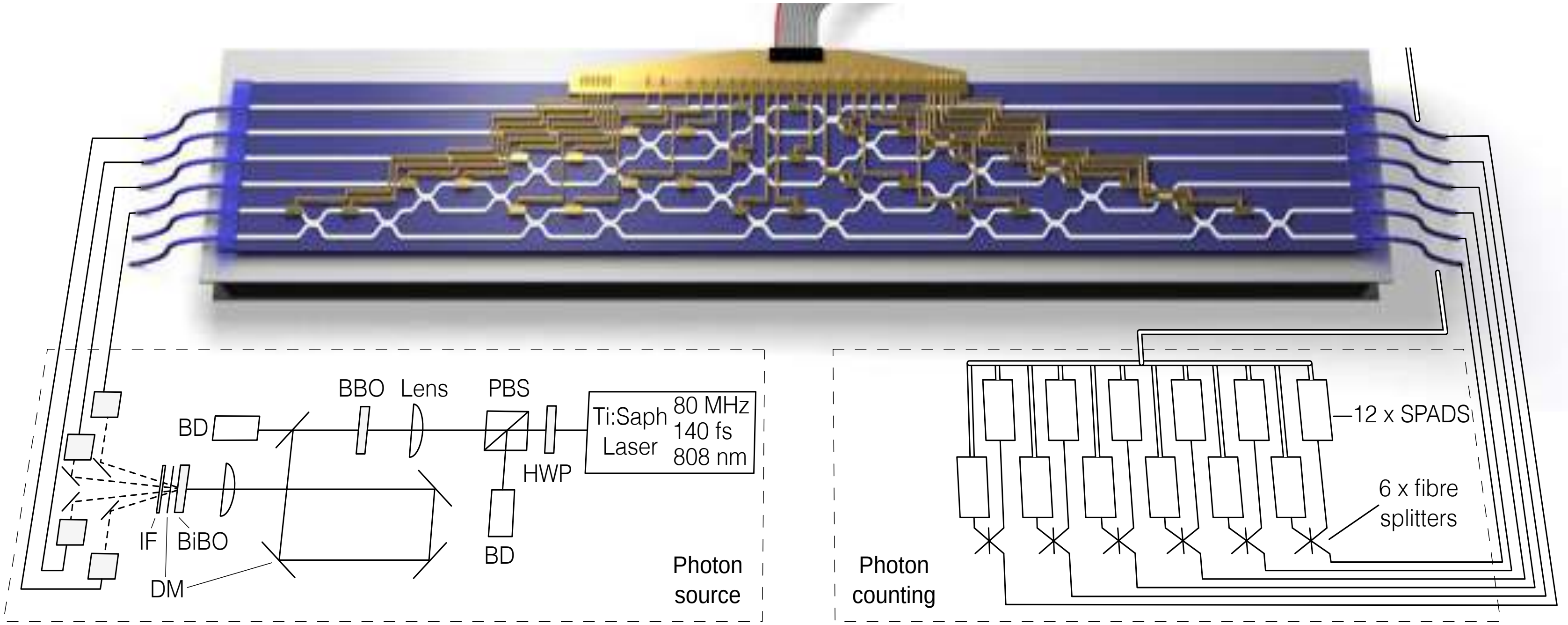
Peruzzo, Lobino, Matthews, Matsuda, *et al.*
***Science* 329** 1500 (2010)

Shor's Factoring Algorithm



Politi, Matthews, O'Brien
***Science* 325** 1221 (2009)

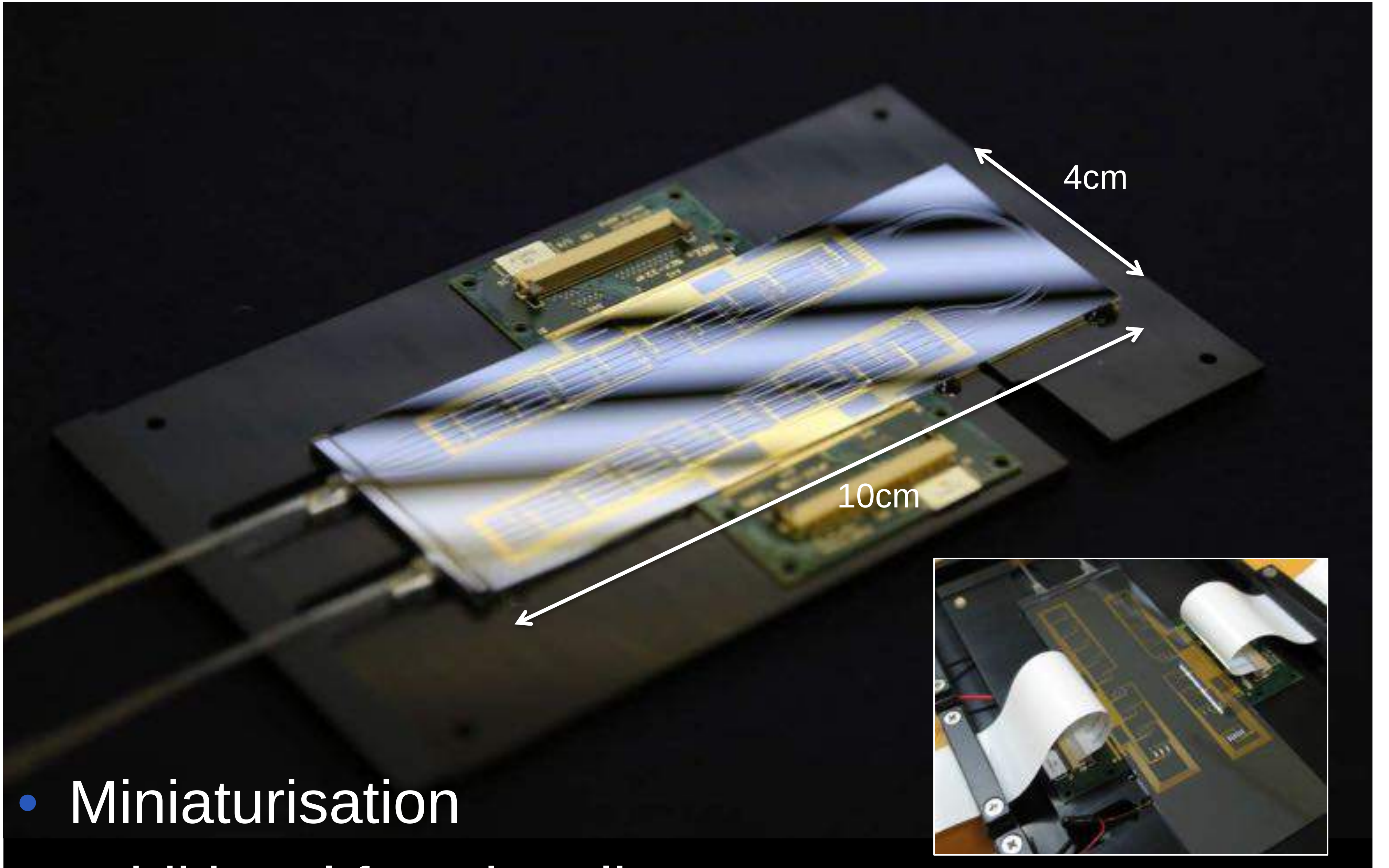
Universal linear optic processor



- Programmable quantum optic circuit
- 6x6 mode reconfigurable unitary
- 15 MZIs with 30 thermal phase heater
- Used to implement 1000's of quantum optics experiments (inc. heralded quantum logic, boson sampling)

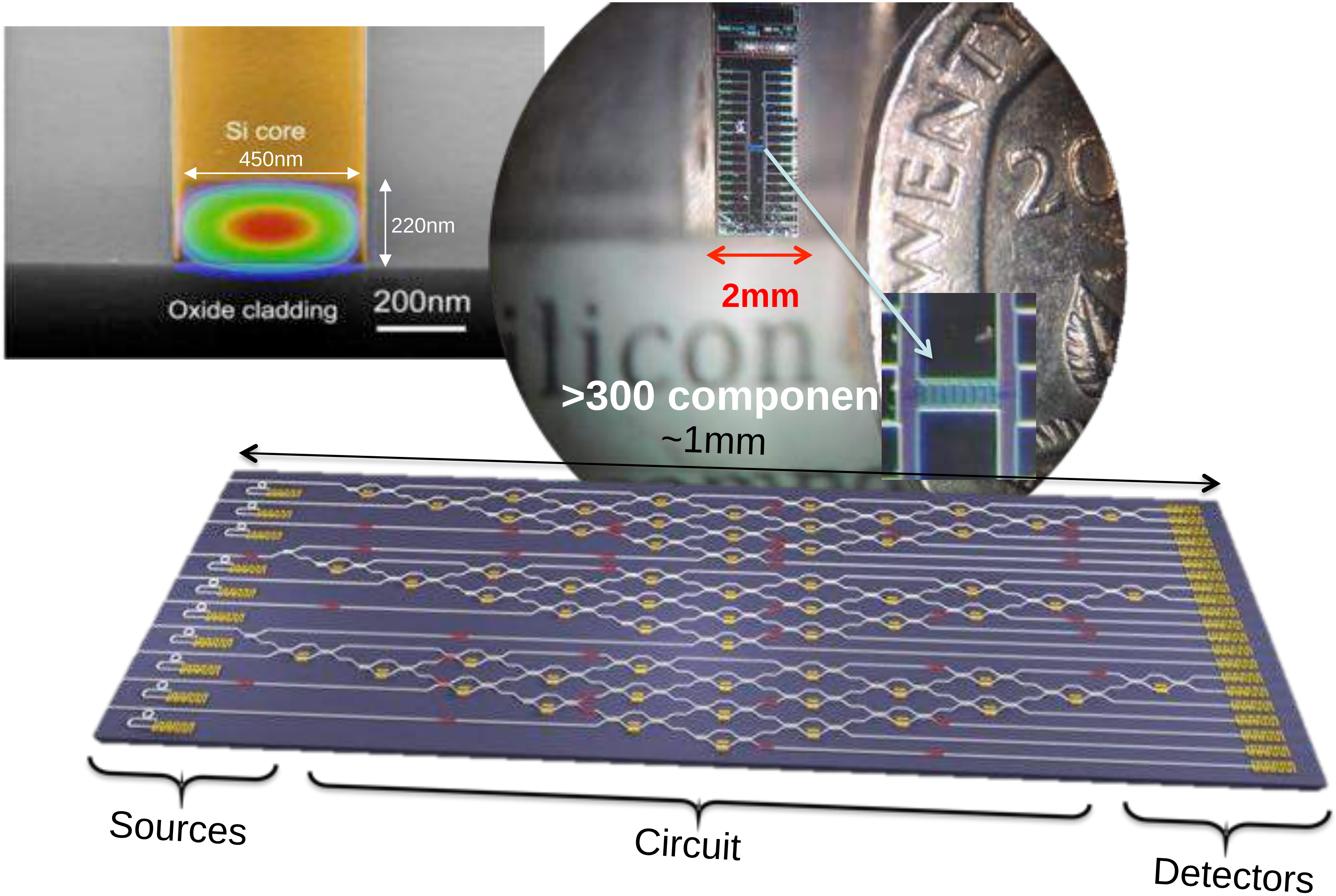
NTT

Carolan et al. Science 349, 6249 (2015)



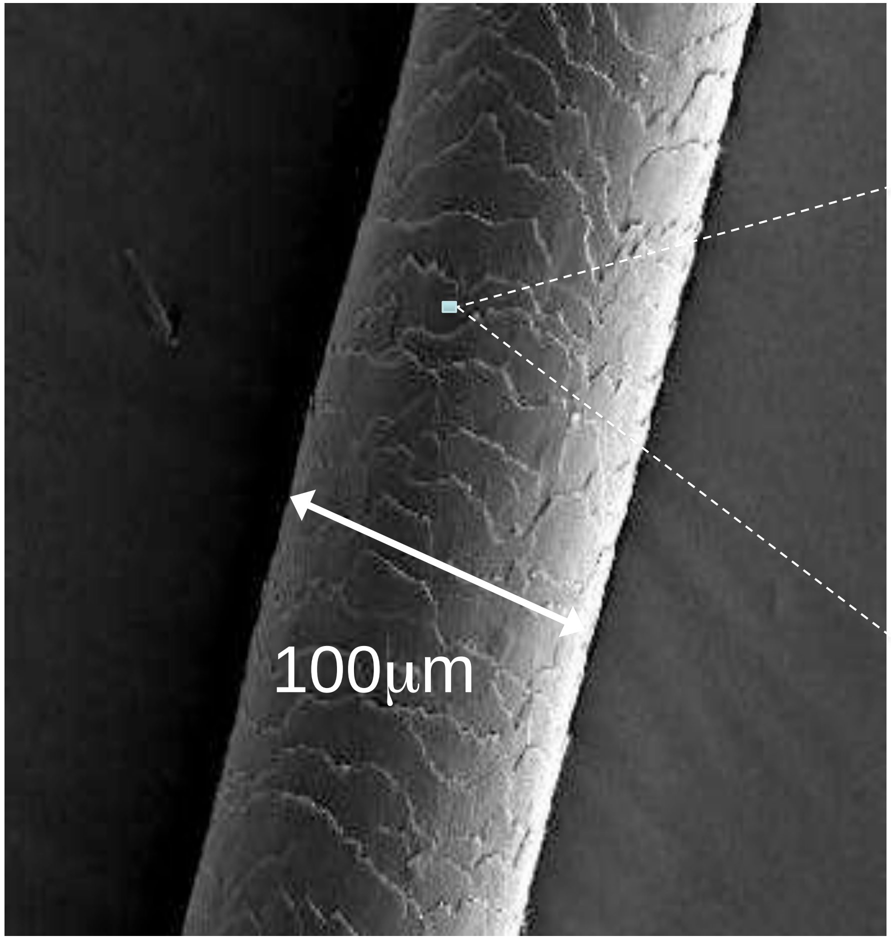
- Miniaturisation
- Additional functionality (sources, detectors)
- Full integration

CMOS / Silicon Quantum Devices



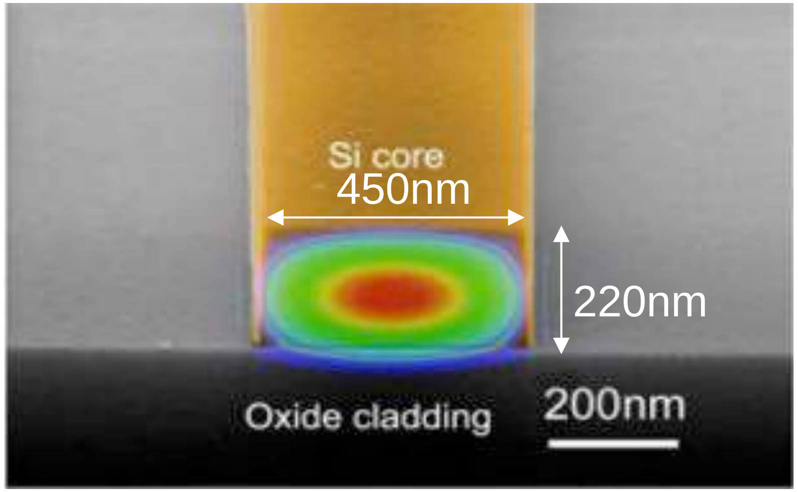
Ultra compact silicon waveguides

Human hair



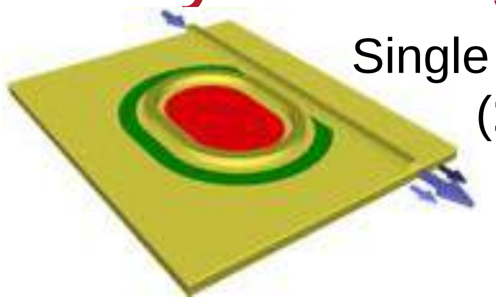
Si waveguide is 200 times smaller

Silicon waveguide



Ultra-high confinement of light

Increasing the complexity of integrated quantum photonics

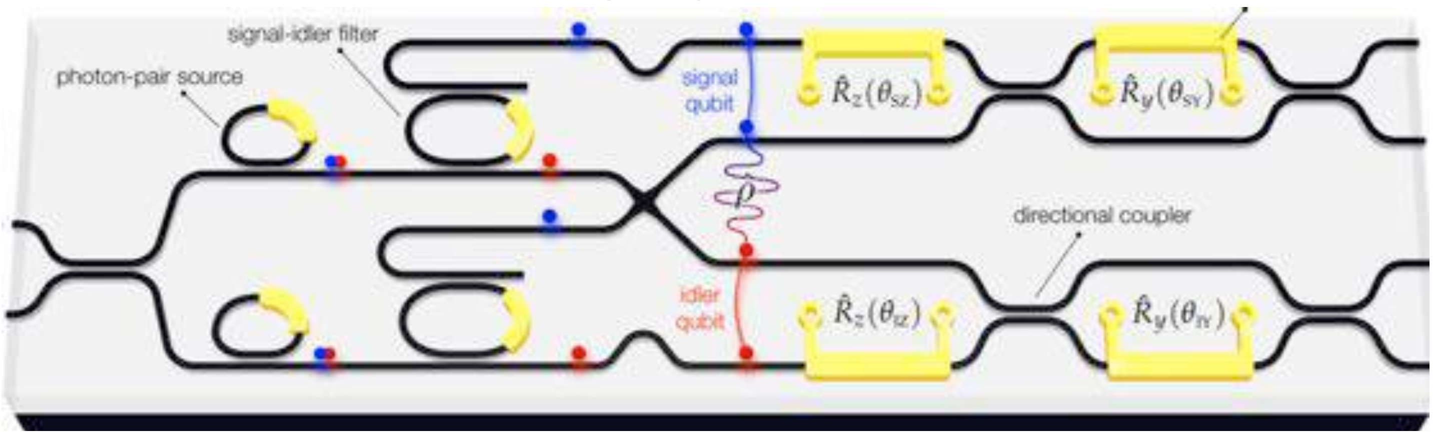


Single photon source
(**1 component**)

Engin et al Opt. Express **21**, 27826 (2013)

+ multiple sources + reconfigurability (**5 components**)

Silverstone et al Nature Photonics **8**, 104 (2014)

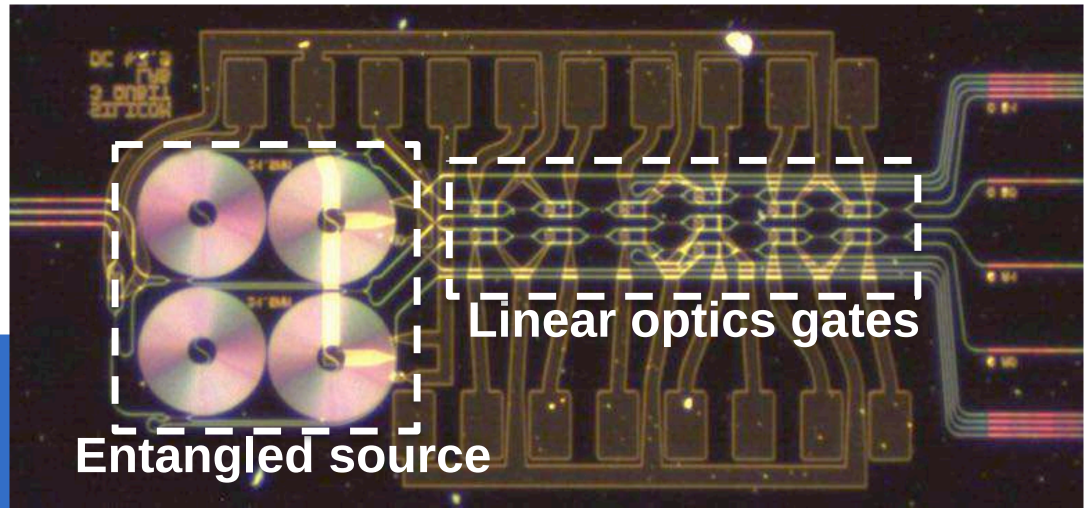


+ ring sources
+ WDM filtering
(**13 components**)

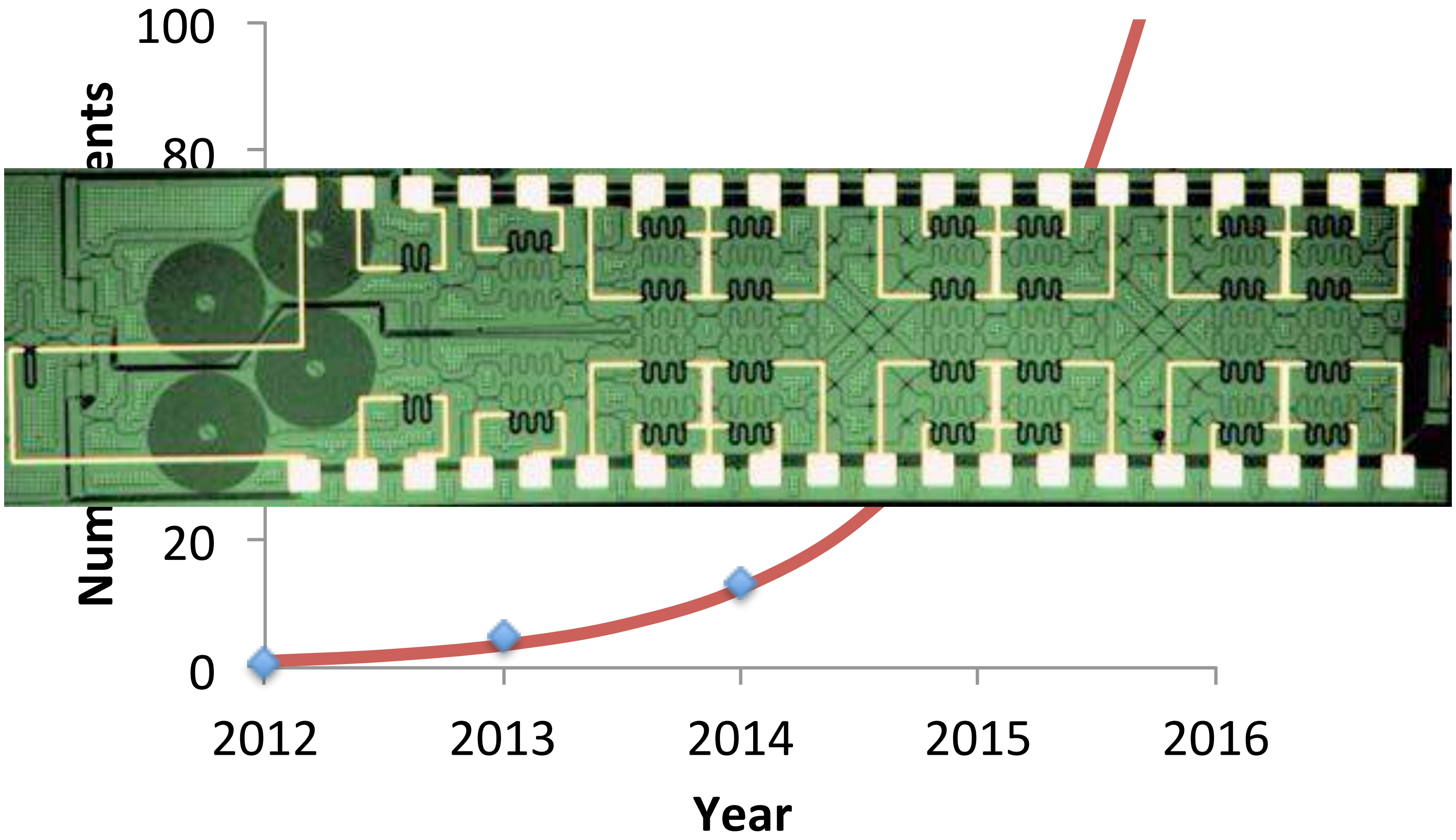
Silverstone et al Nat Comms **6**, 7948 (2015)

+ 4 source + logic gate
(**41 components**)

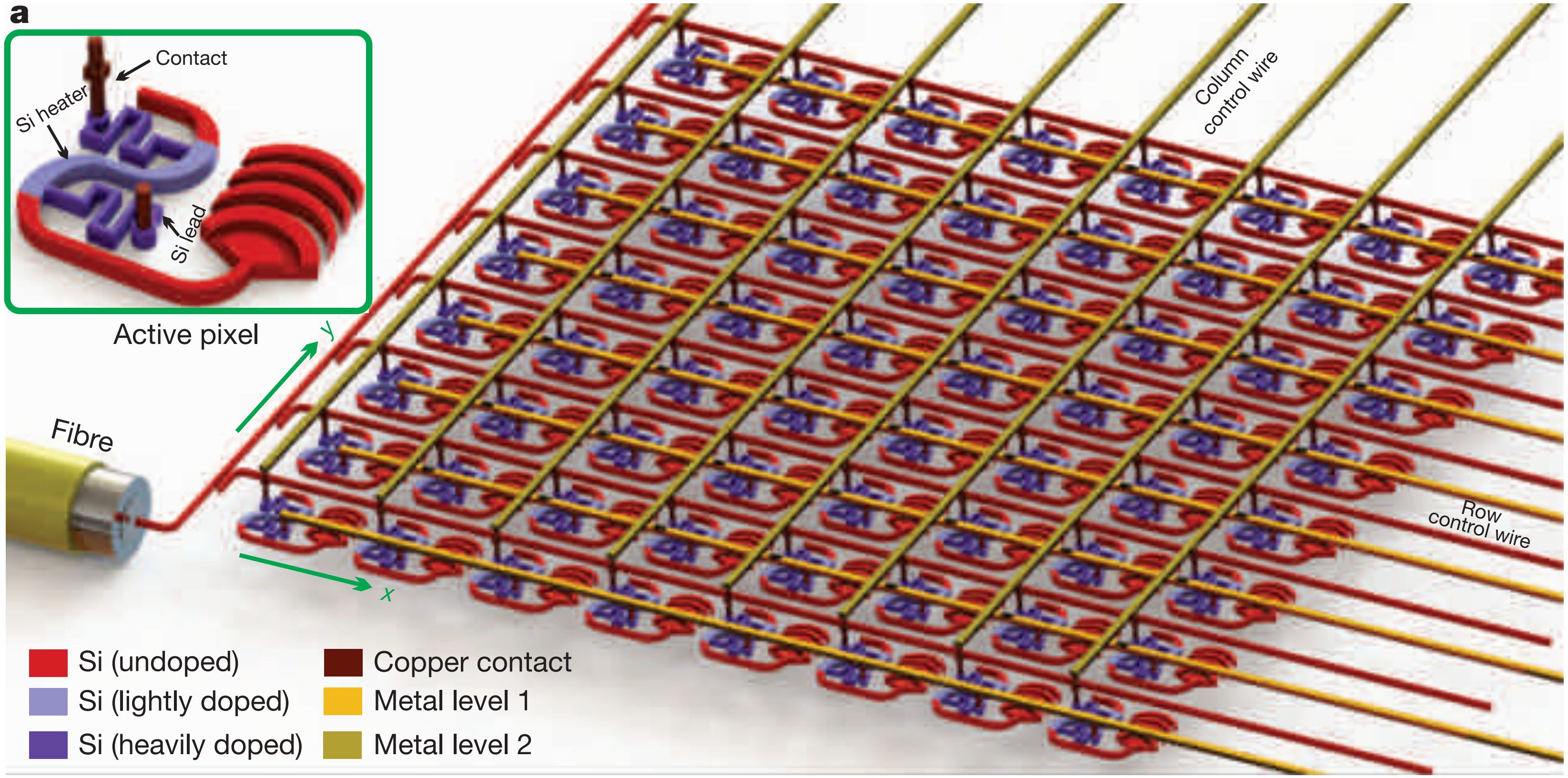
Santagati et al
CLEO (2015)



Quantum photonics Moore's law???



Scaling up



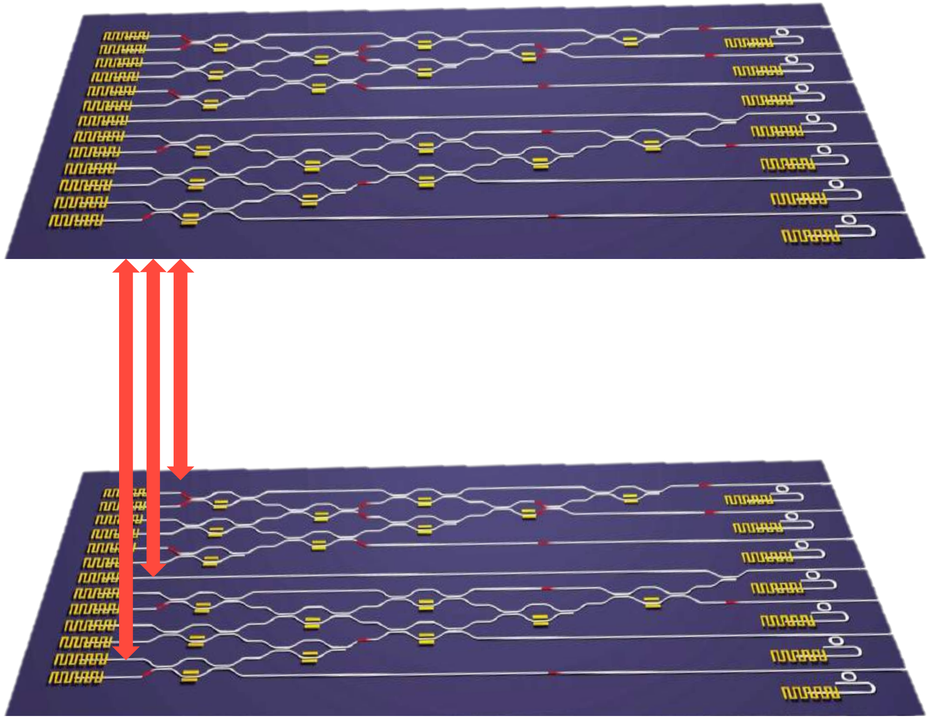
>12,000 components on a single chip

Scalability!!!

J. Sun, E. Timurdogan, A. Yaacobi, E. S. Hosseini, and M. R. Watts, *Nature*, vol. 493, no. 7431, pp. 195–199 (2013)

Quantum Photonic Interconnect

Beyond single chip

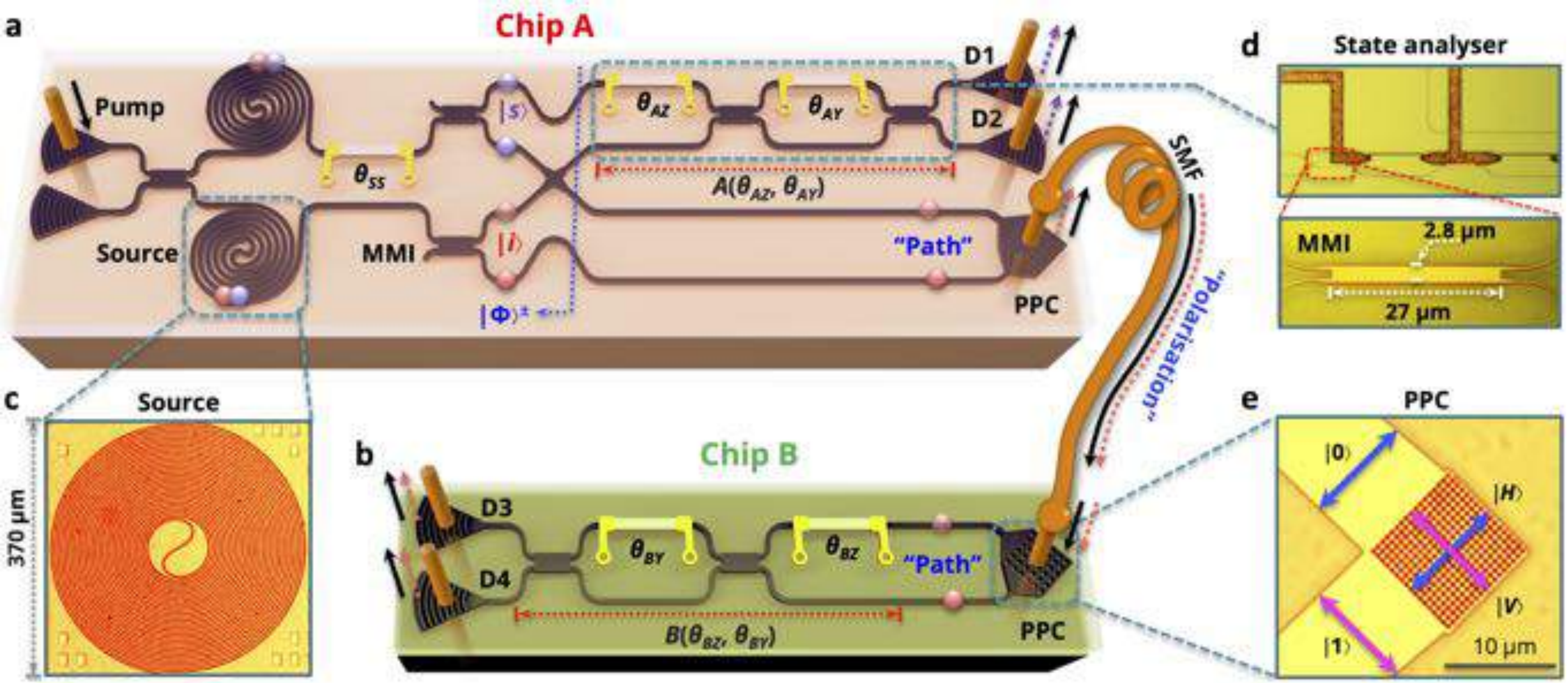


Global interconnect

- Quantum communications
- Entanglement distribution
- Blind quantum computing

- Remote quantum sensing
- Distributed quantum computing
- Non-locality tests

Quantum photonic interconnect

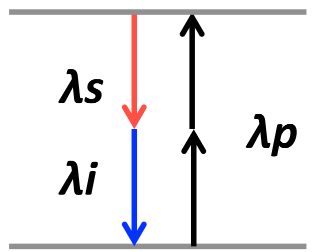


- On-chip generation of path-entanglement
- Path to polarisation interconversion
- Chip-to-chip distribution of entanglement

Wang, et. al, arXiv:1508.03214 (2015)

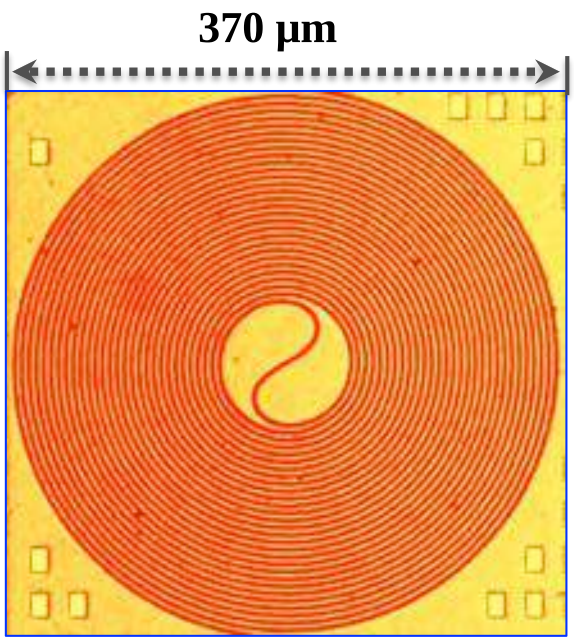
Entanglement generation

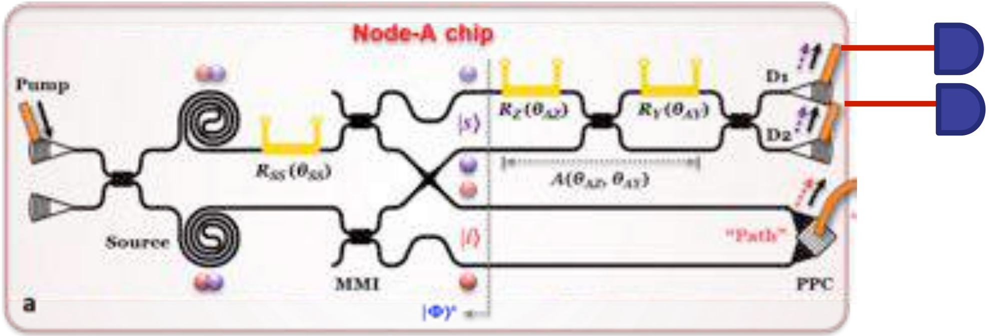
SFWM

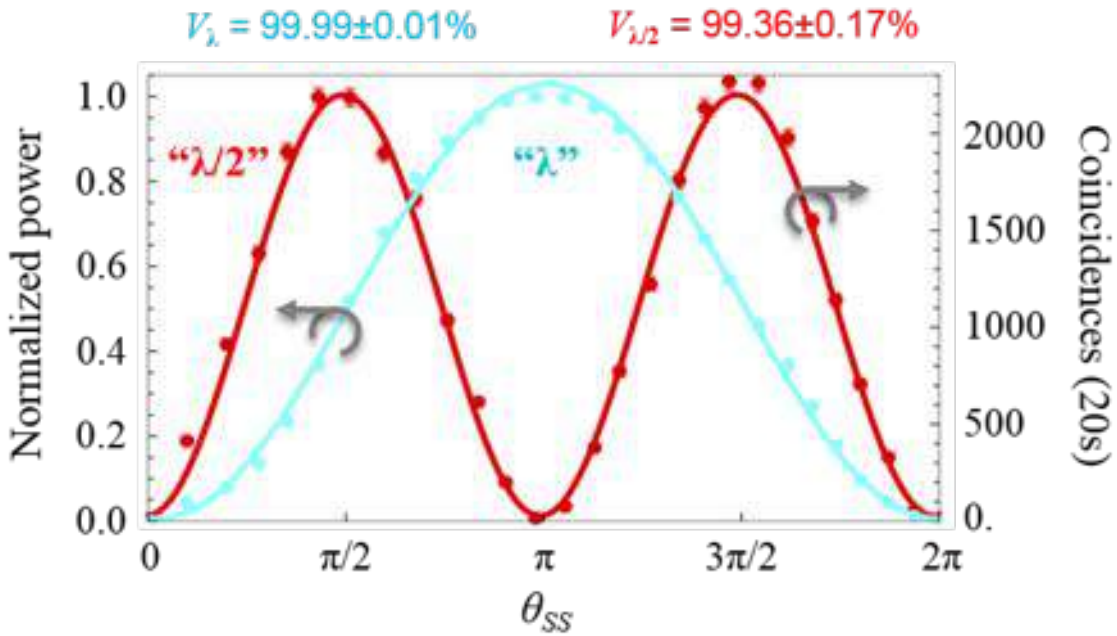


Clemmen, S. et al. Opt. Express 17, 16558–16570 (2009).

Silverstone, J. W. et al. Nat. Photon. 8, 104–108 (2014).



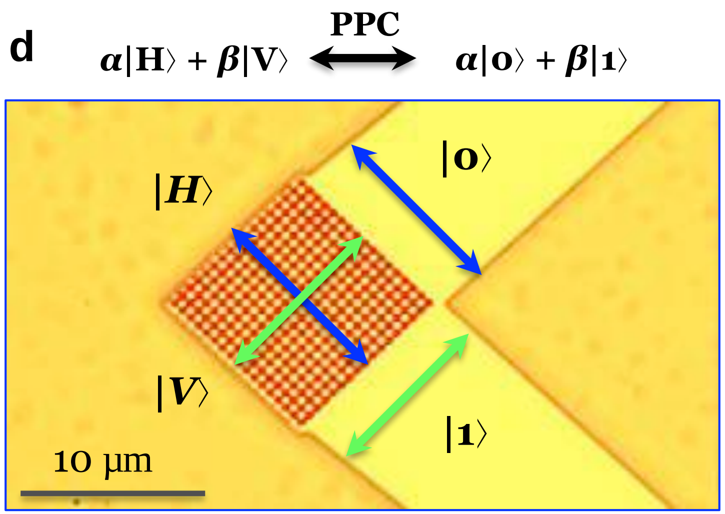


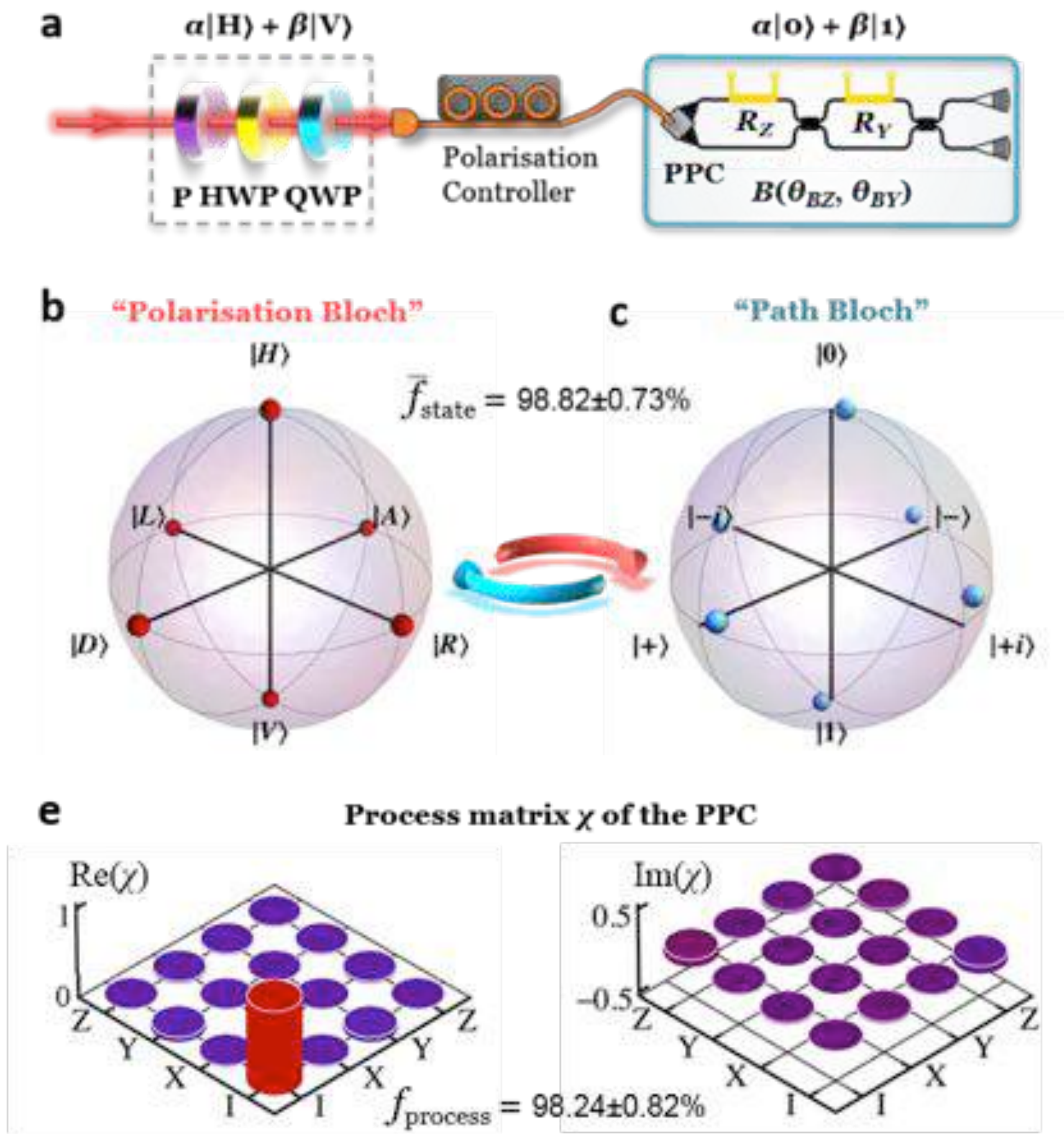


NOON state: $[|1_s 1_i\rangle|0_s 0_i\rangle - e^{i2\theta ss}|0_s 0_i\rangle|1_s 1_i\rangle]/\sqrt{2}$

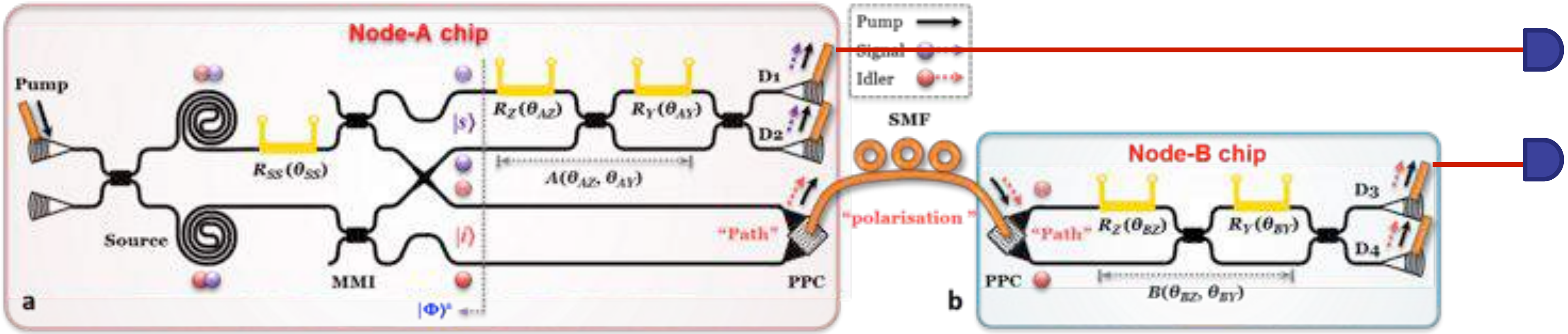
Bell state: $|\Phi\rangle^{\pm} = (|0\rangle_s|0\rangle_i \pm |1\rangle_s|1\rangle_i)/\sqrt{2}$

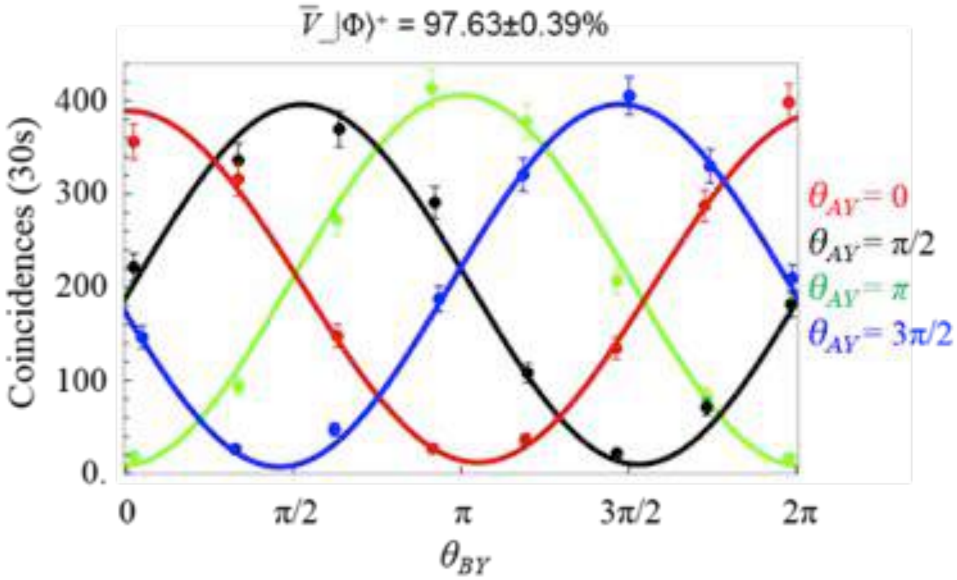
Path-Polarization Conversion (PPC)





Chip-to-chip entanglement distribution

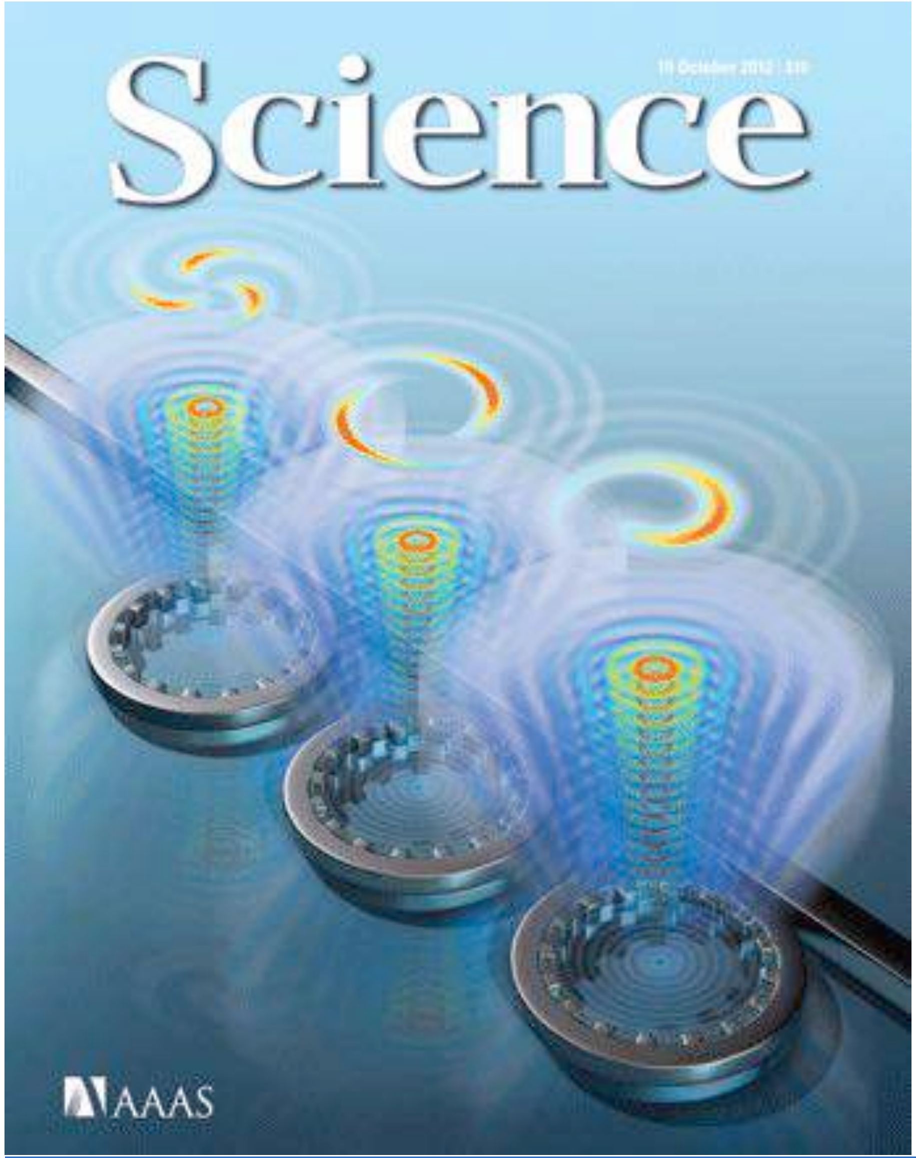


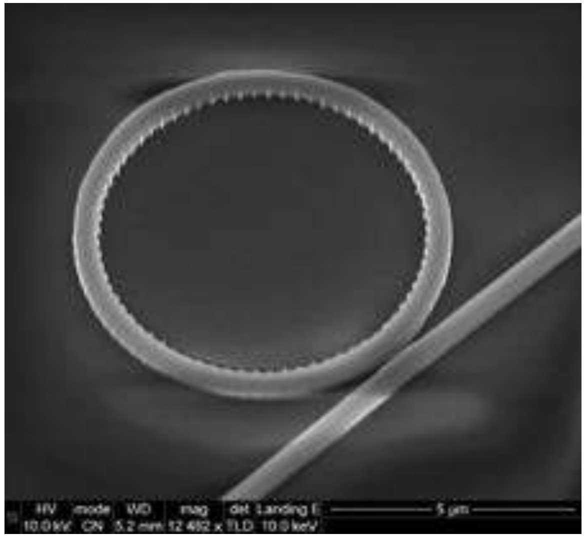


Bell-type violation
S=2.638+-0.039
(violates inequality by 77% and by 16 s.d)

Wang, et. al, arXiv:1508.03214 (2015)

Integrated Compact Optical Vortex Beam Emitters



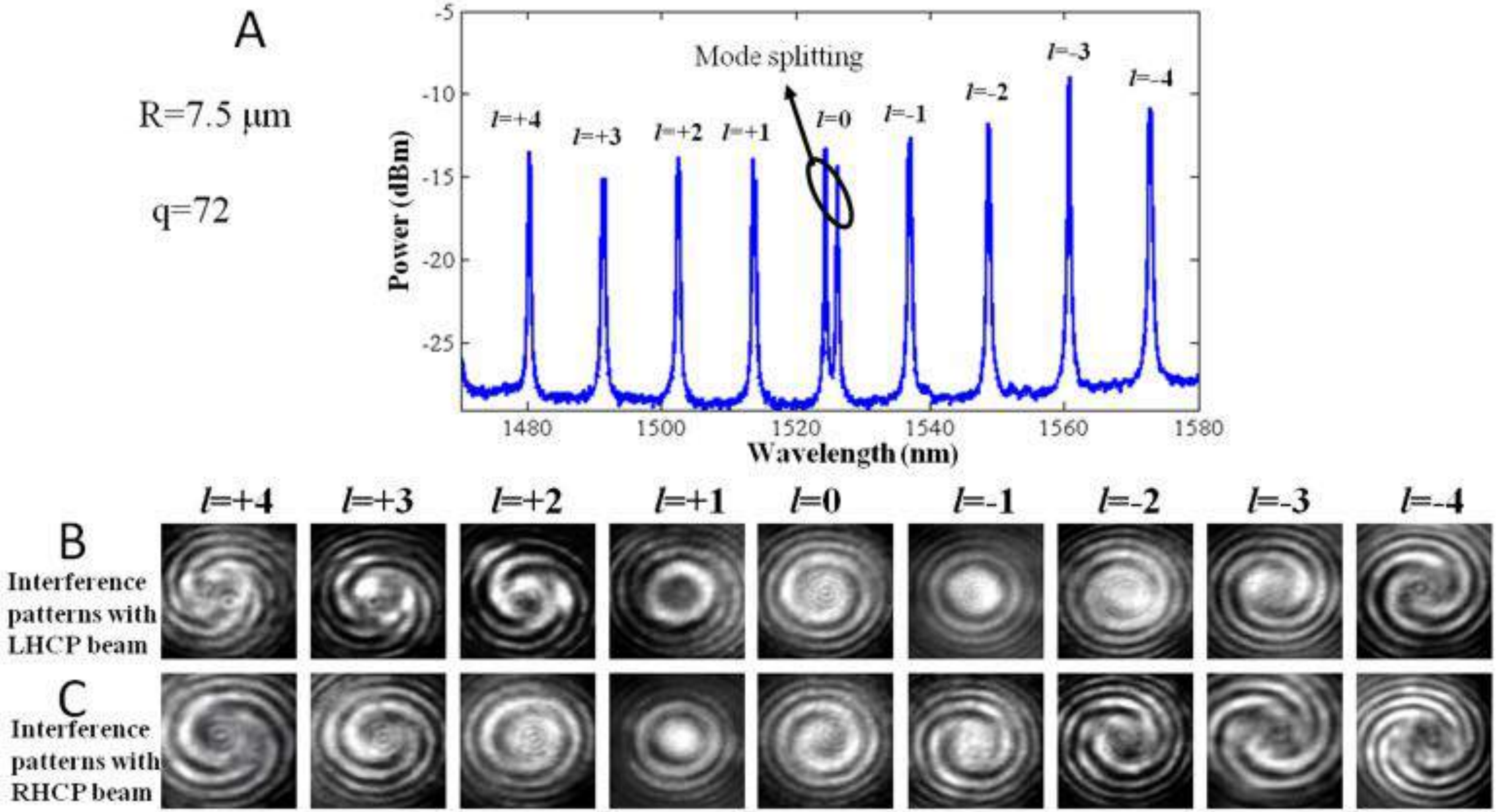


2nd order Bragg grating coupled to the rotating mode of the ring resonator

- Orbital angular momentum generation
- Quantum optics
- Chip-to-chip communications

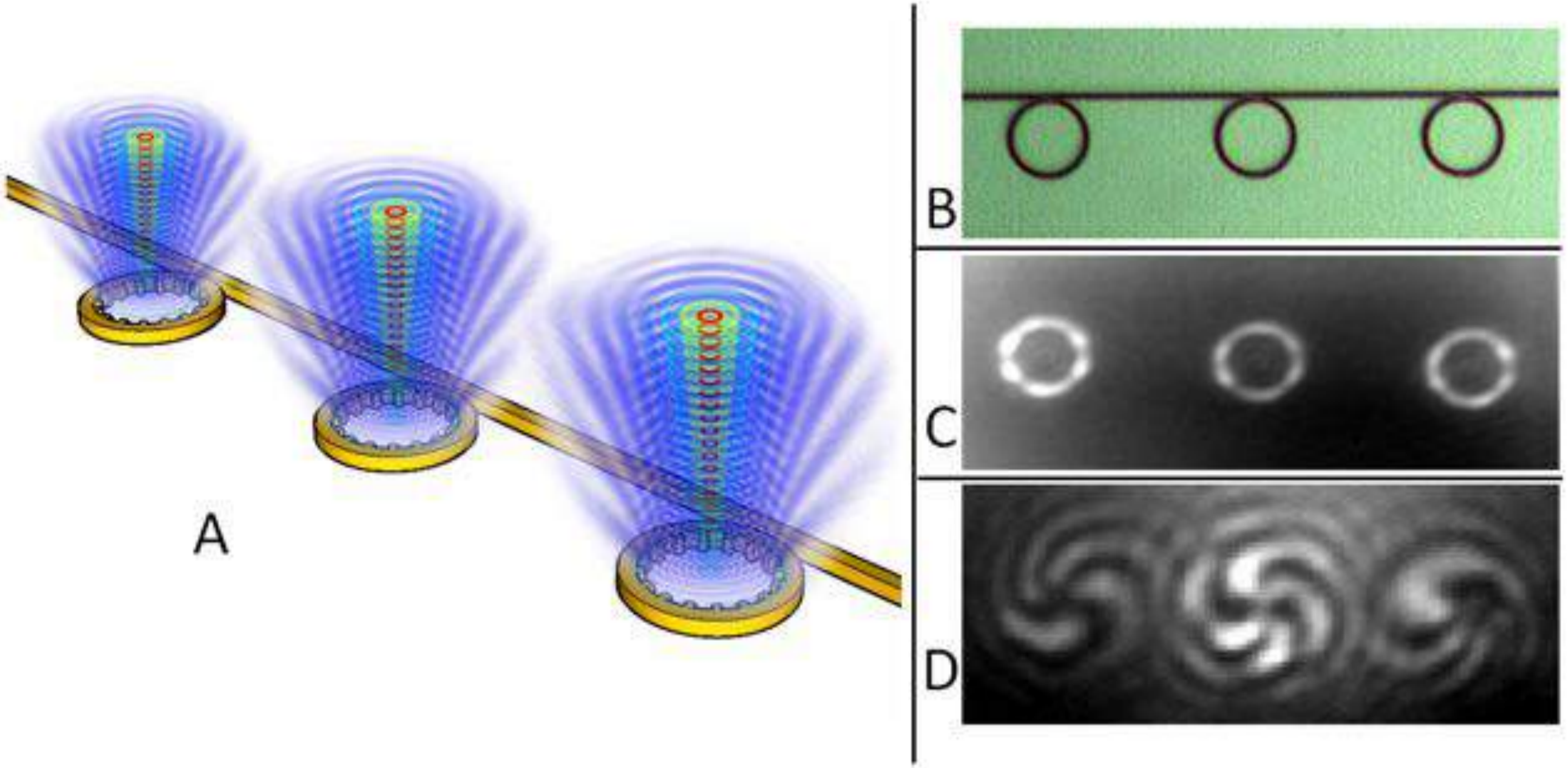
X. Cai, J. Wang, M. J. Strain, B. Johnson-Morris, J. Zhu, M. Sorel, J. L. O'Brien, M. G. Thompson, and S. Yu, *Science*, vol. 338, no. 6105 (2012)

Experimental Results



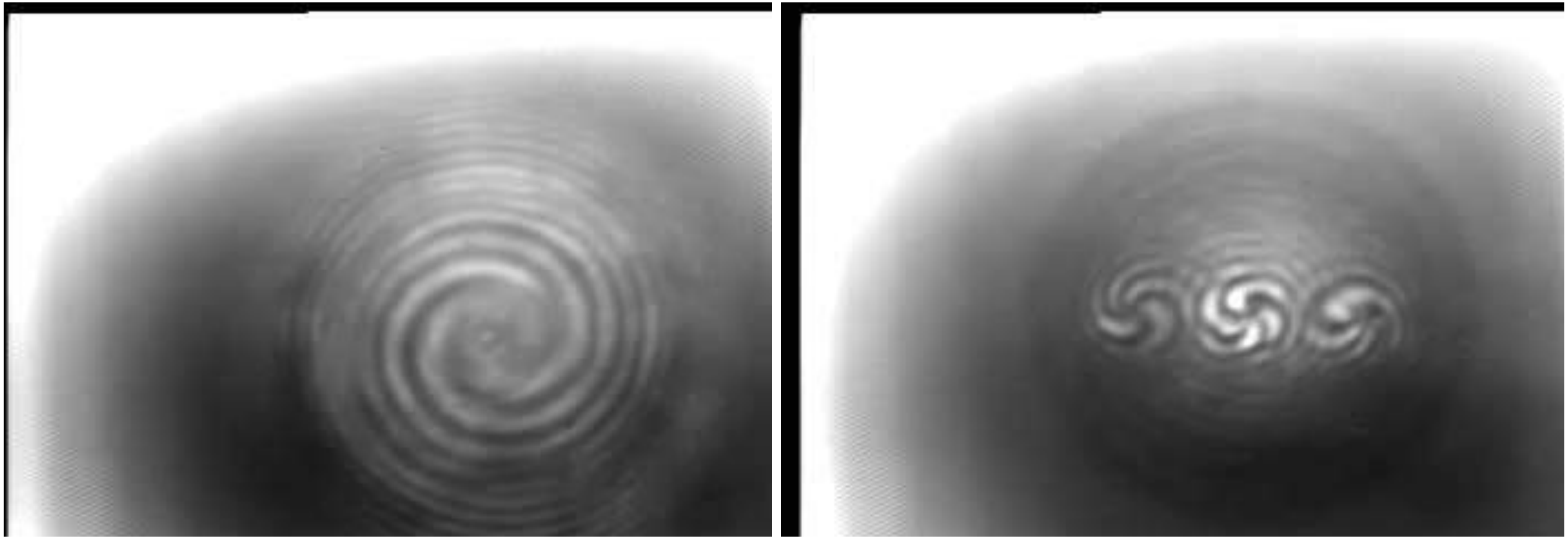
X. Cai, J. Wang, M. J. Strain, B. Johnson-Morris, J. Zhu, M. Sorel, J. L. O'Brien, M. G. Thompson, and S. Yu, *Science*, vol. 338, no. 6105 (2012)

Integrated emitter array

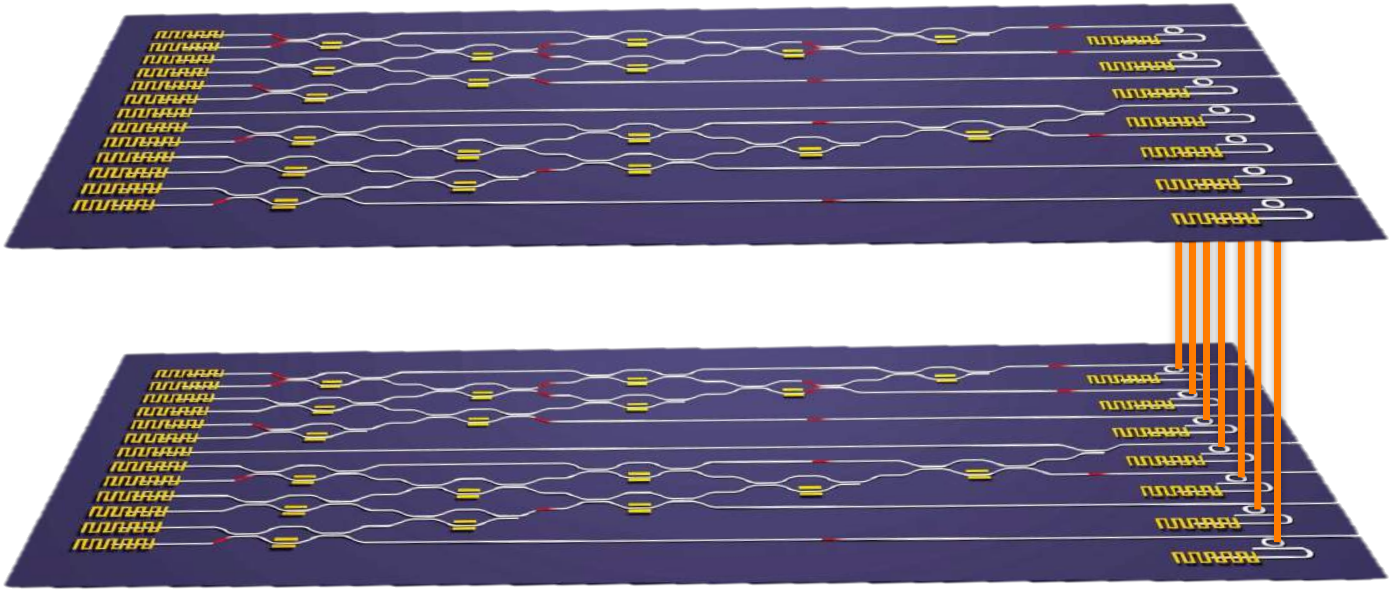


- Integrated vortex emitter array with identical emitters realised

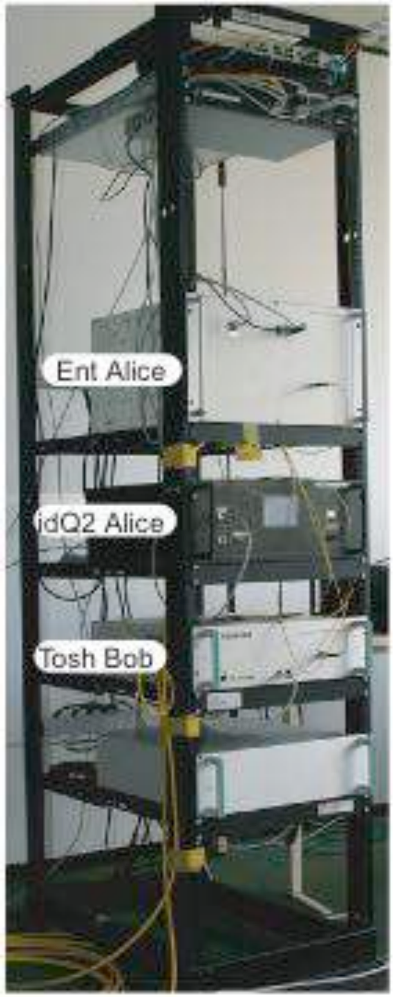
Movies



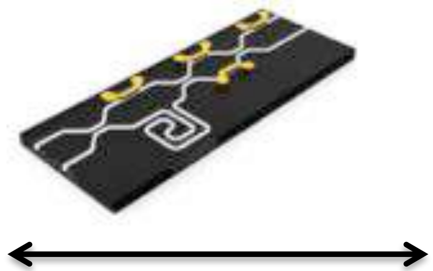
Chip-to-chip interconnects



Chip-based Quantum Key Distribution



Current approach



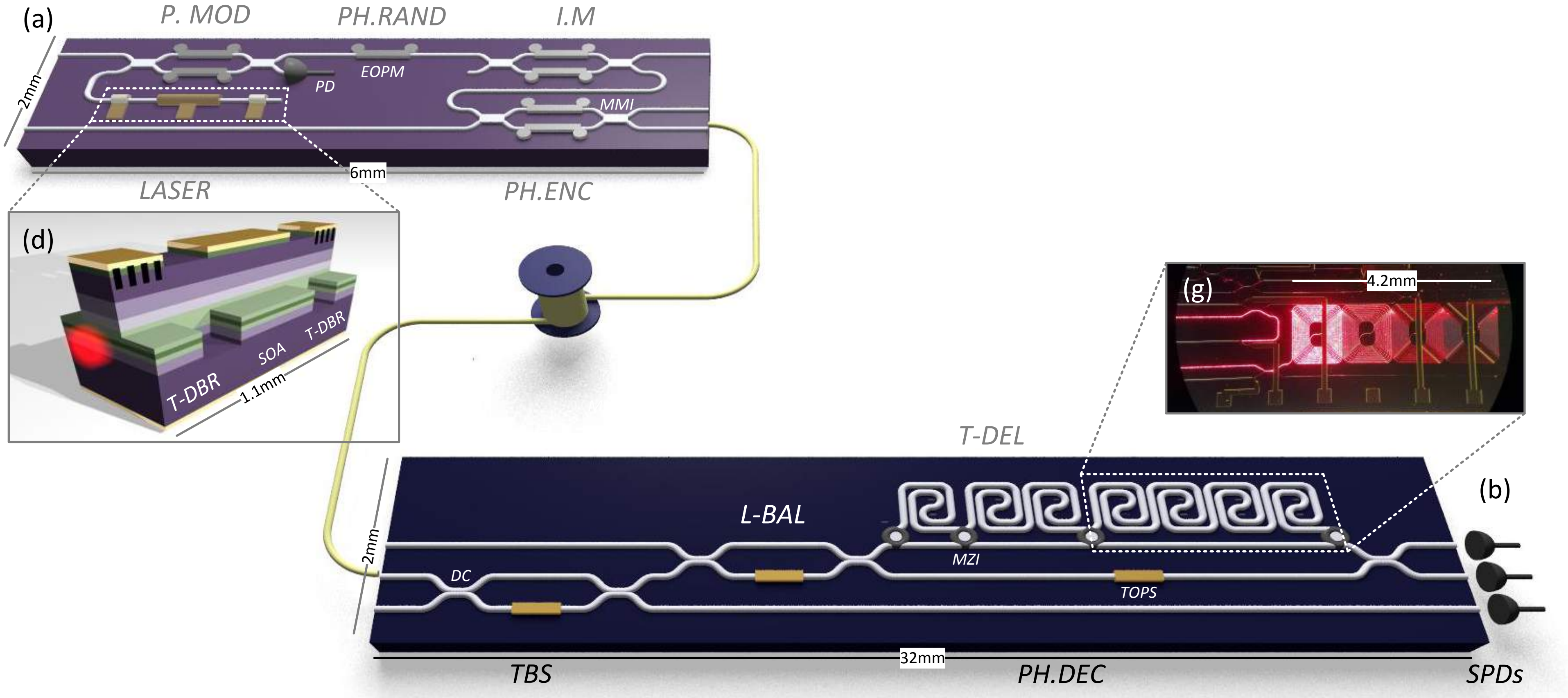
1mm

Chip-based devices for:

- Low cost
- Compact
- Energy efficient
- Mass-manufacture
- Compatibility with microelectronics

Chip-to-chip QKD system

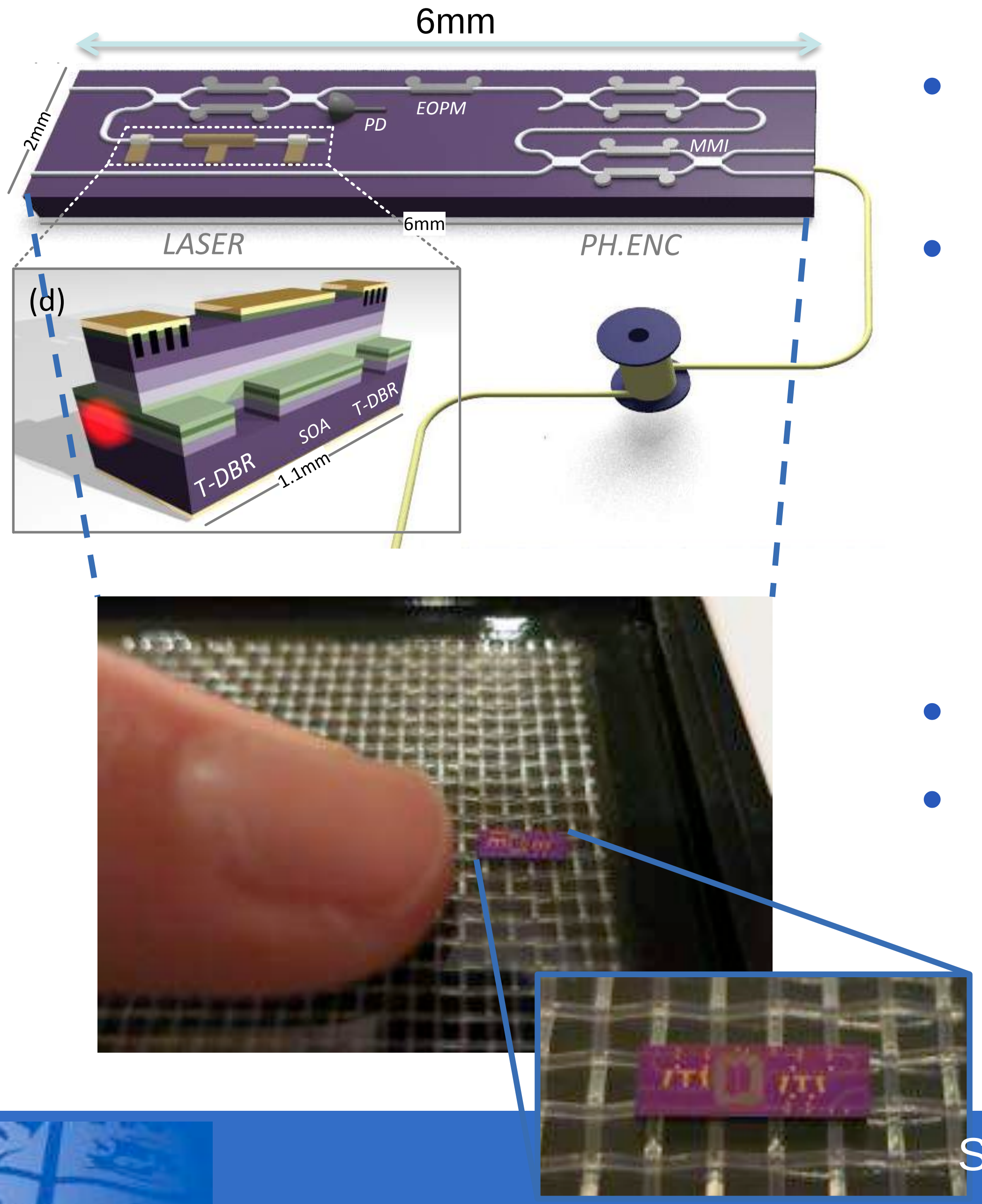
InP-based transmitter chip



SiON-based receiver chip

Sibson, et. al, arXiv:1509.00768 (2015)

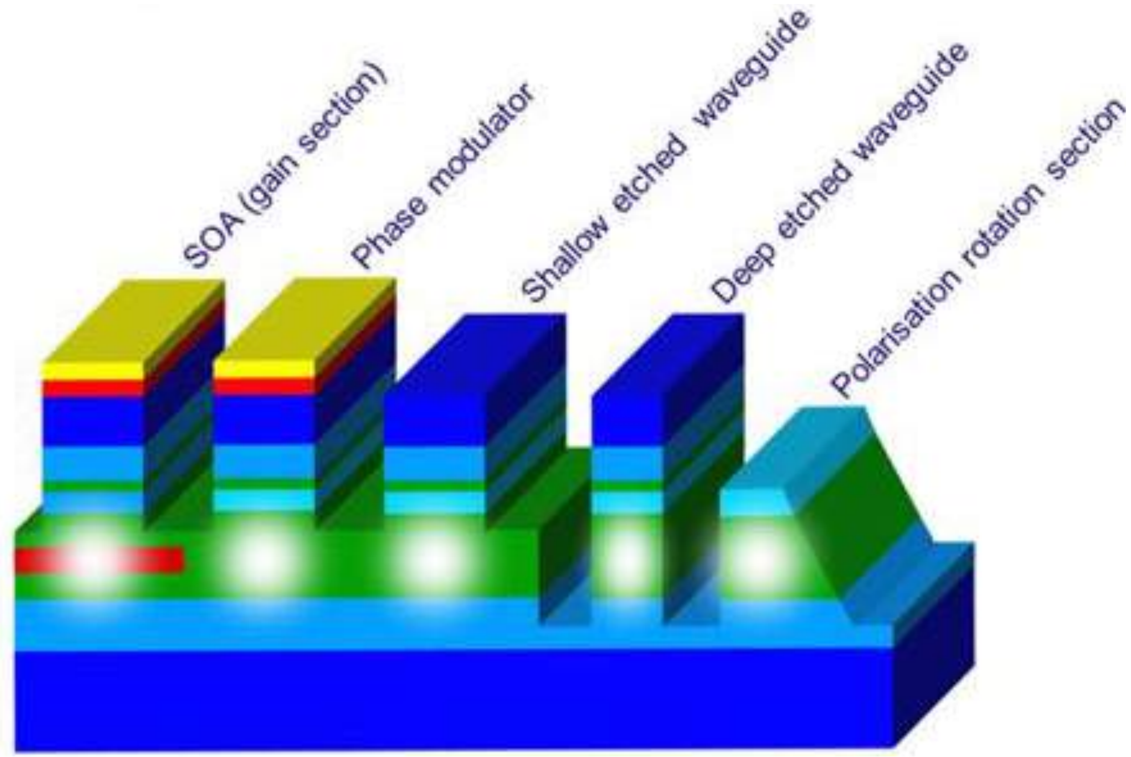
InP QKD transmitter (Alice)

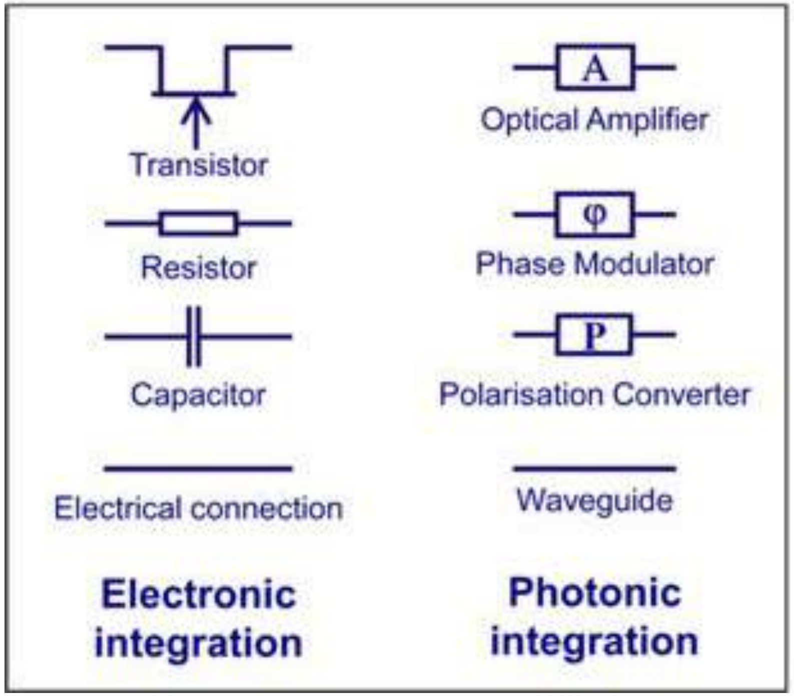


- Contains 17 discrete photonic elements
- Includes:
  - Tunable laser source
  - Pulse modulator
  - Phase modulator
  - Intensity modulator
  - Photo-diodes
- Size: 2mm x 6mm
- Produces time-bin encoded quantum states

Sibson, et. al, arXiv:1509.00768 (2015)

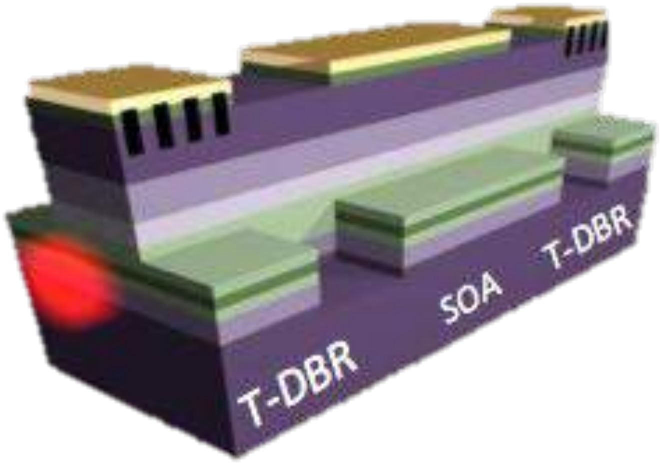
InP Technology Platform



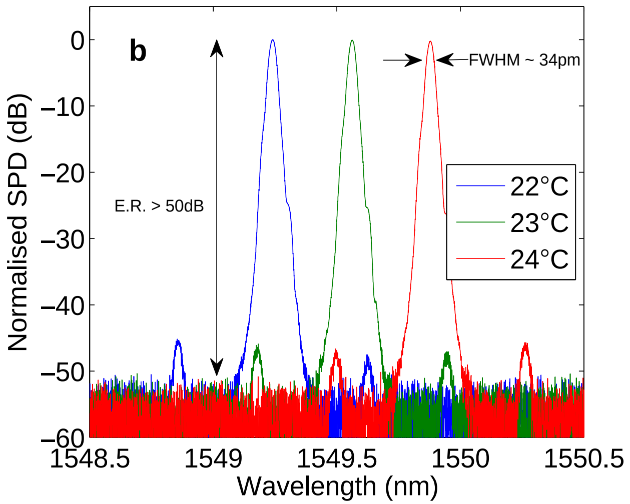


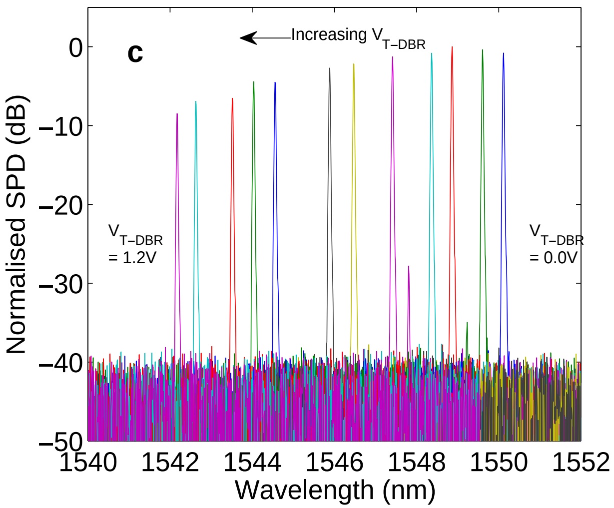
- Advanced photonic integration platform
- Active and passive integration:
  - Low loss waveguides, Amplifiers, Detectors, Lasers, Modulators, Switches, Filters,

Integrated tunable laser



- Tunable laser
  - 3 section device
  - 2xDBR + SOA
- 12mA lasing threshold current

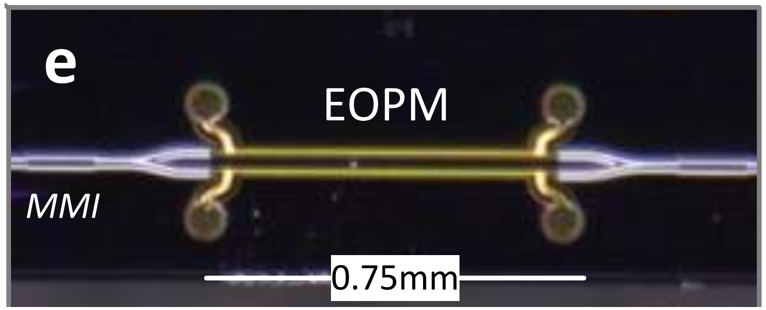




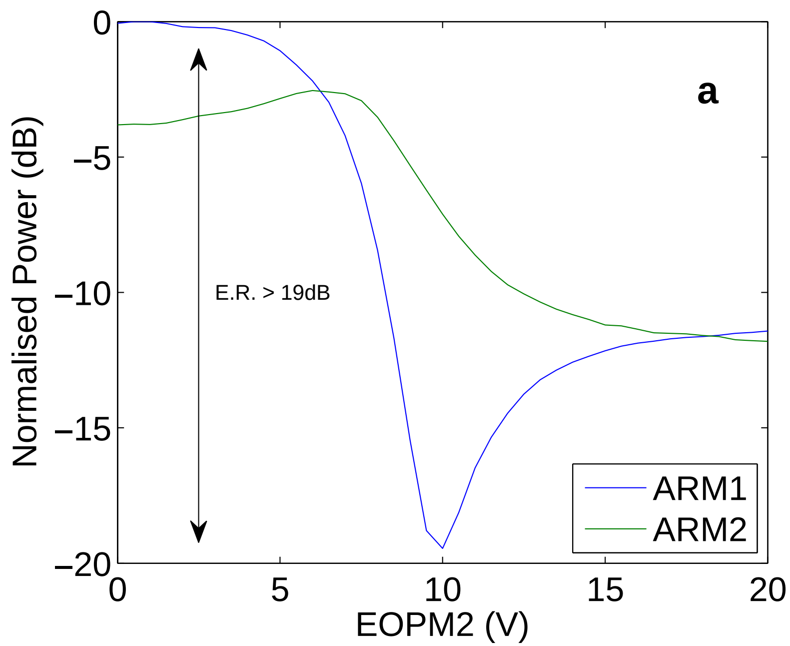
Spectral performance:

- ~1550nm
- 34pm linewidth
- 50dB ER
- 10nm tuning range

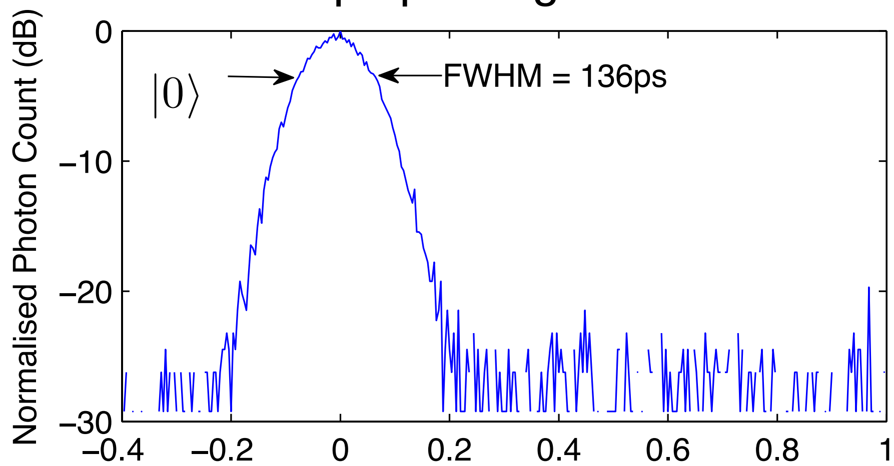
Phase and amplitude modulators



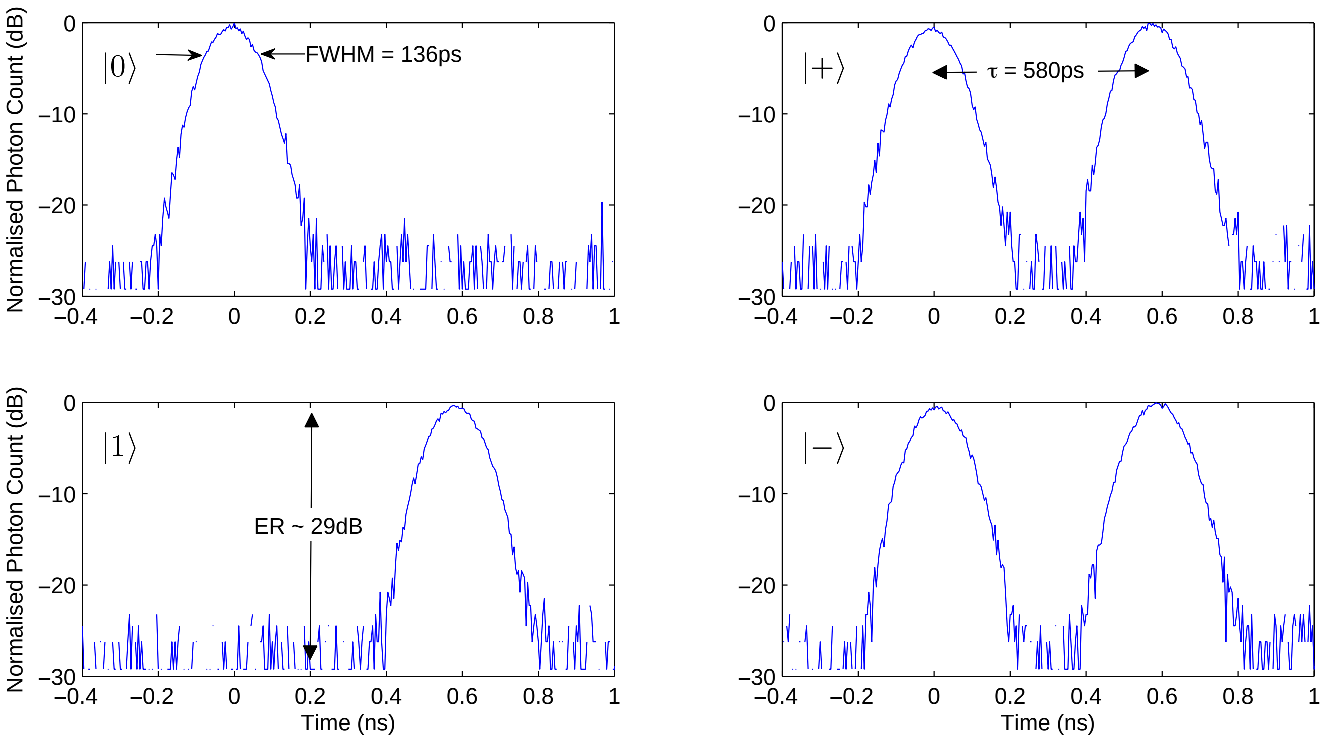
- Electro-optic phase modulators, based on the Quantum Confined Stark Effect.
- >10GHz modulation possible



136ps pulse generation

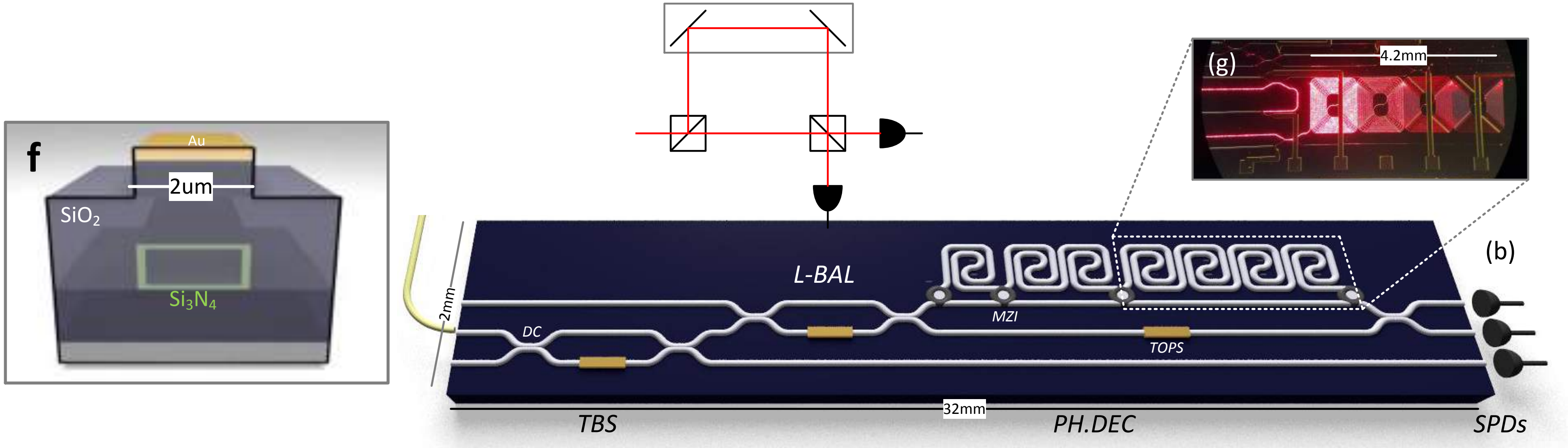


Time-bin encoded BB84



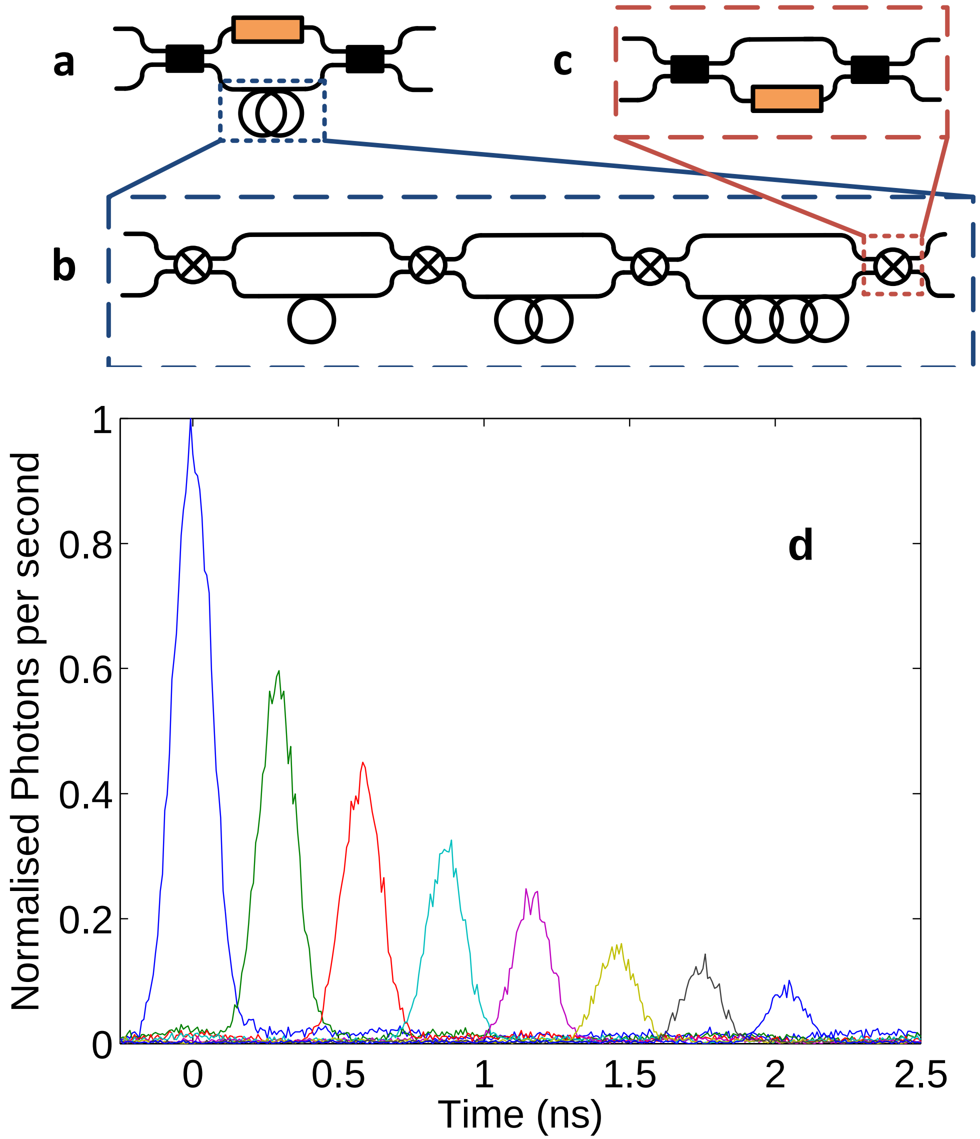
- Four BB84 time-bin encoded states
- ~600ps separation
- High extinction ratio

SiON QKD receiver device



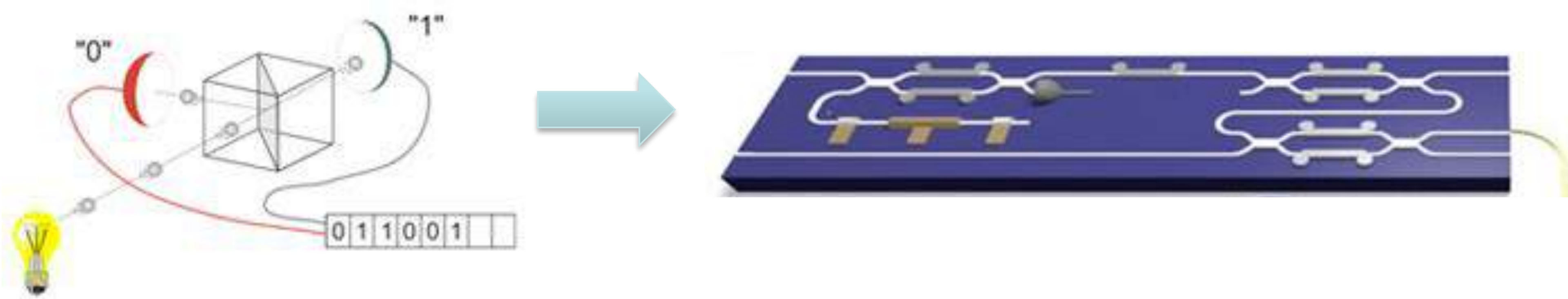
- Contains 23 individual photonic elements
- Includes:
  - Asymmetric MZI
  - Tunable delay line
  - Balancer MZI
  - Tap-off MZI (for COW protocol)
- Reconfigurable

Tunable delay line



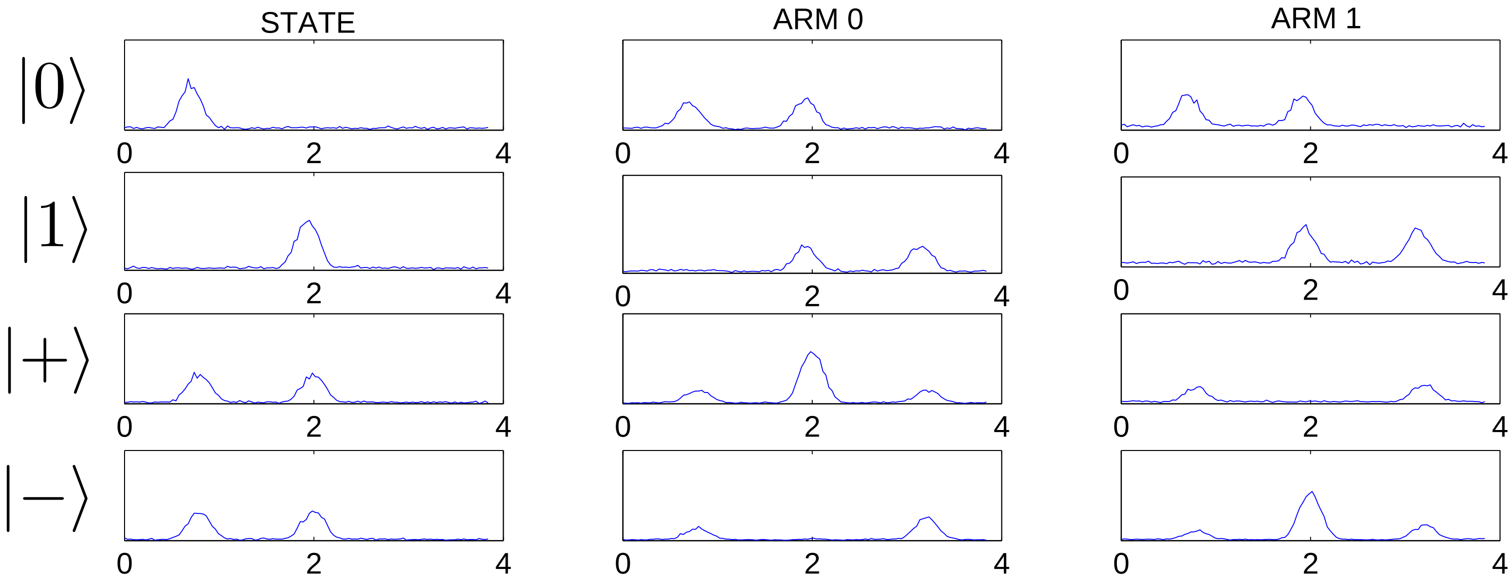
- 8 programmable time bins
- 0 to 2.1ns in 300ps steps
- Loss ~ 5dB/ns

On-chip quantum random number generation



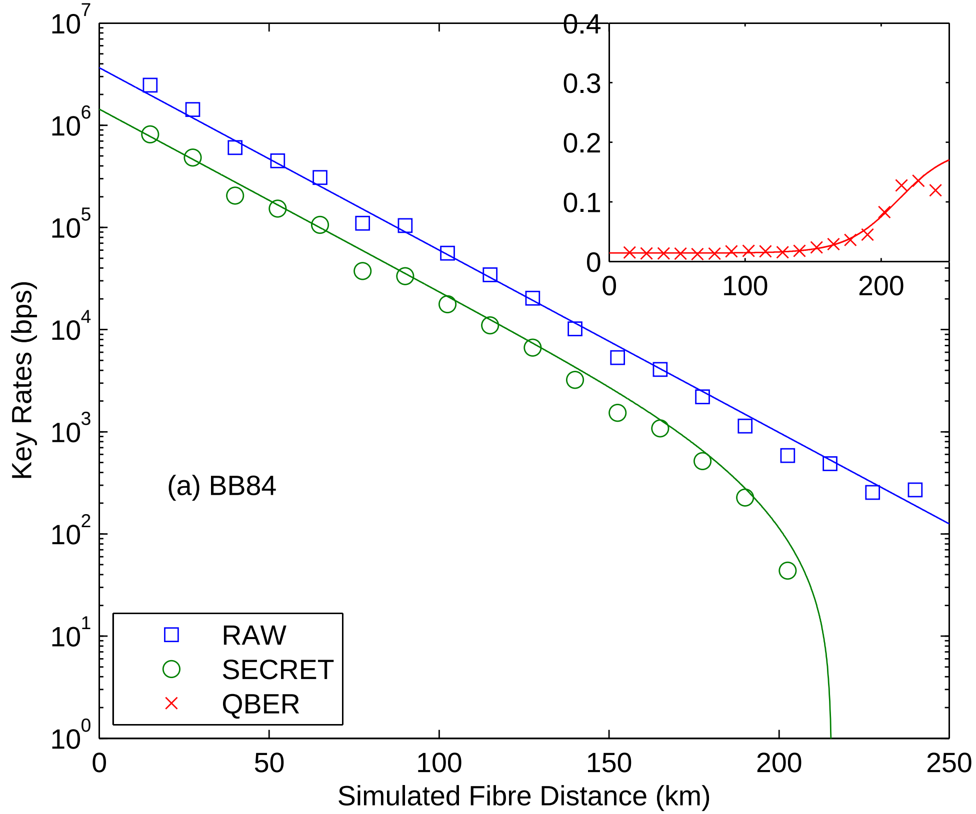
- Alice chip reconfigured to generate 'offline' quantum random numbers
- Single photon detectors at the outputs detect either a 0 or 1
- Bernoulli factory algorithm used to provide a balanced coin
- Random numbers used to set the basis, bit states, decoy intensities and phase randomisation for each qubit sent

Time-bin decoded BB84



- The four BB84 states and the receiver outcome probabilities.
- Information encoded in both time of arrival and phase between time bins – causing interference at the output

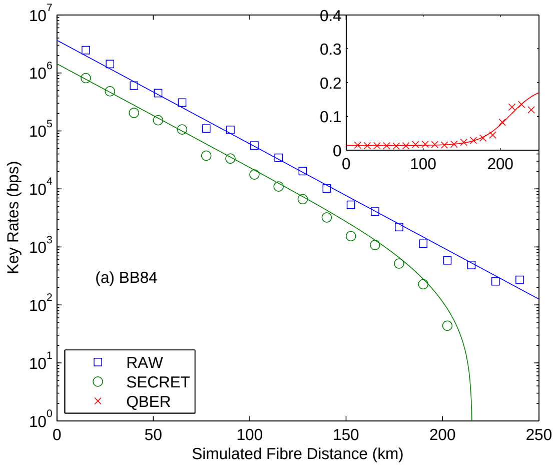
BB84 result



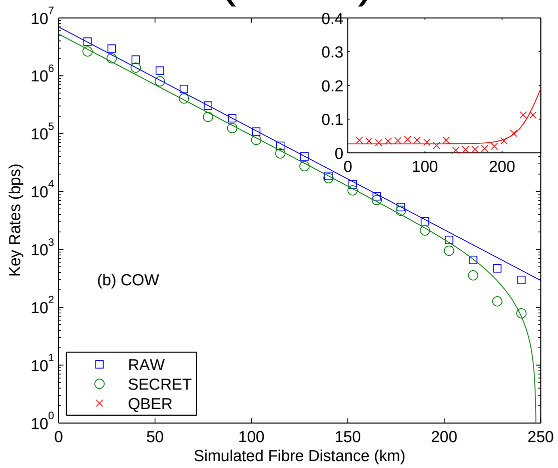
- 150ps duration pulses with 600ps separation
- Comparable to commercial systems
- @20km
  - 560MHz transmission rate
  - 1.6Mbps raw key rate
  - 1.4% QBER

Summary of all protocols

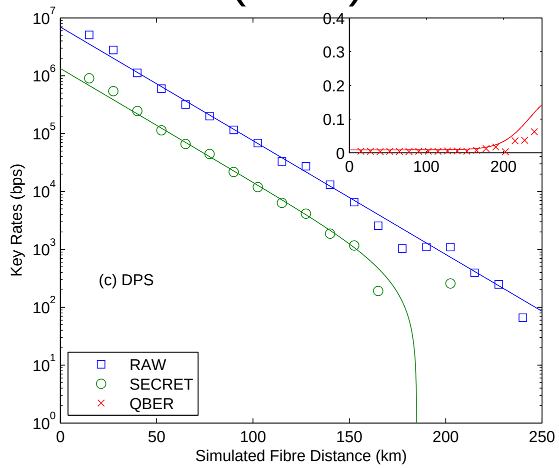
BB84



Coherent one way (COW)



Differential Phase Shift (DPS)



Protocol	μ (per pulse)	State Rate (GHz)	QBER Time (%)	QBER Phase (%)	Raw Rate (Mbps)	Secret Rate (Mbps)
BB84	0.45	0.56	1.46	1.40	1.61	0.63
COW	0.45	0.86	1.4	1.4	3.11	2.35
DPS	0.28	1.76	-	1.4	2.82	0.54

@20km distance

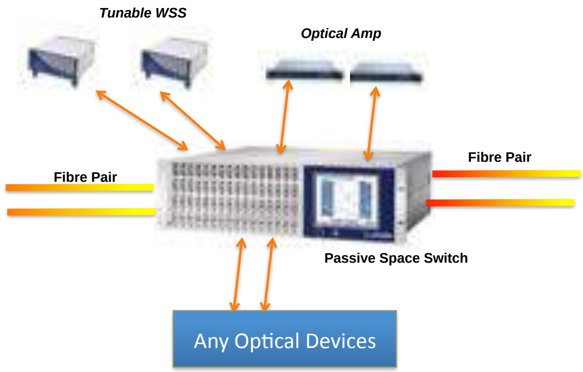
- Clock rate up to 1.7GHz
- QBER as low as 1.4%
- Secrete key rates up to 2.35 Mb/s

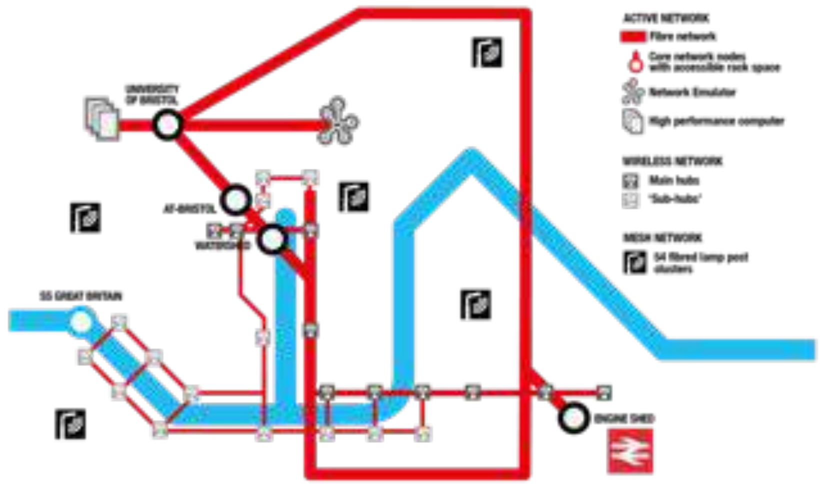
Sibson, et. al, arXiv:1509.00768 (2015)

Future directions

- Fully packaged and deployable protoypes

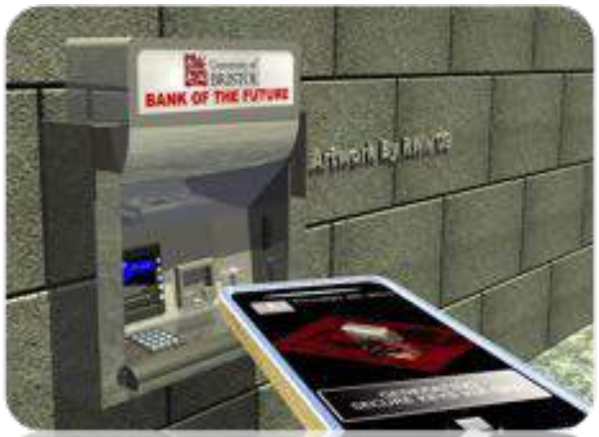
- Working demonstrators within the Bristol city-wide QKD network





Targeted Applications

- Mobile devices
- Computer networks
- City wide communication networks



Conclusion

QUANTUM
COMMUNICATIONS
HUB

Chip-based technologies for Quantum Communications

- Compact, stable, robust
- Reconfigurable
- Multi-protocol
- Scalable
- Compatible with current photonic and/or microelectronic processing

arXiv:1509.00768 - Chip-based Quantum Key Distribution
arXiv:1508.03214 - Quantum Photonic Interconnect