The Application of Hybrid Photonic Integration to Quantum Key Distribution

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Cambridge Research Laboratory
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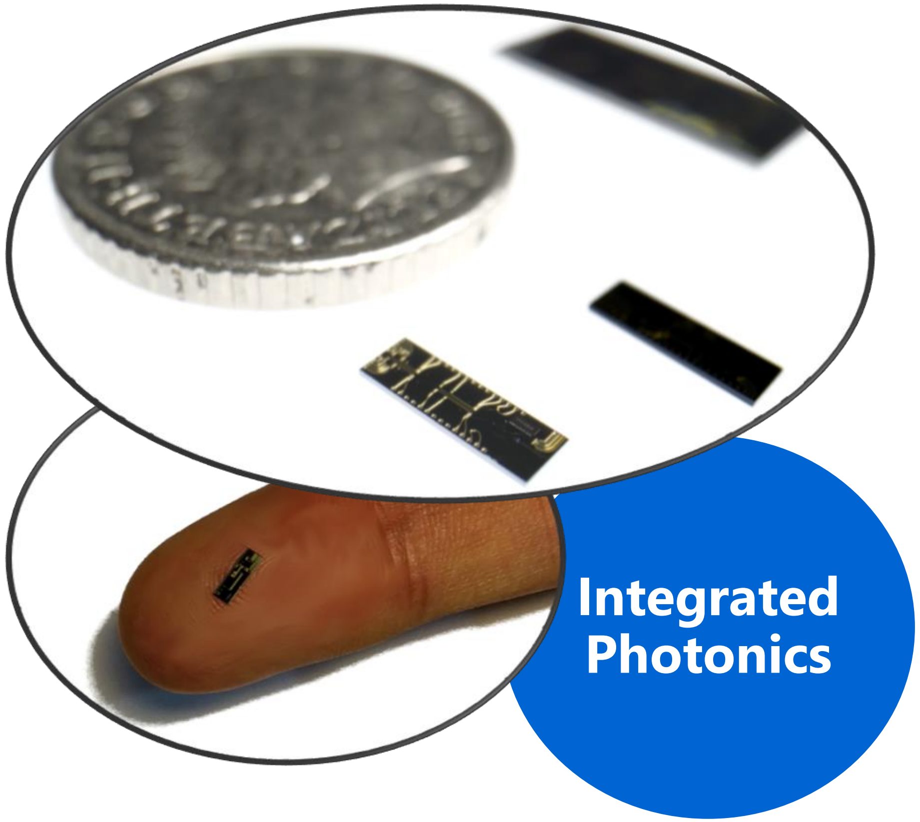
Quantum Key Distribution (QKD) and Integrated Photonics



Potential Advantages:
- **Size**
- **Cost**
- **Repeatability**
- **Stability**
- **Performance**

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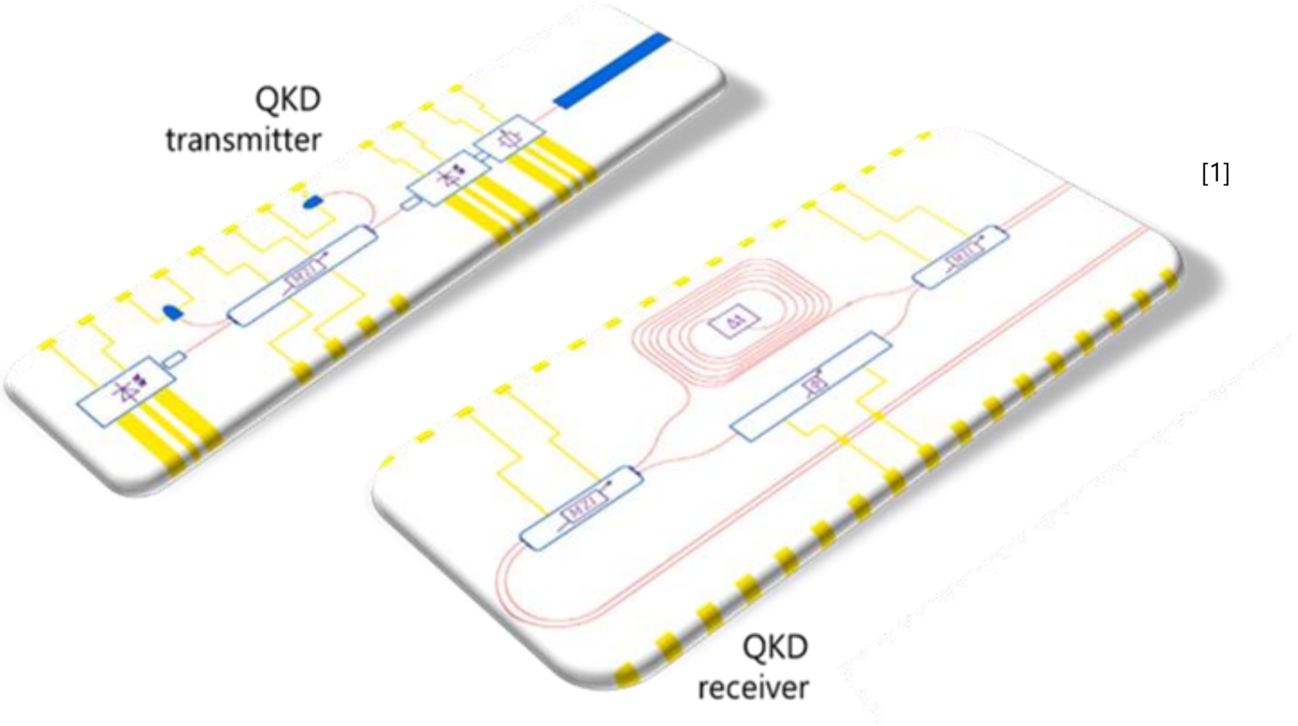


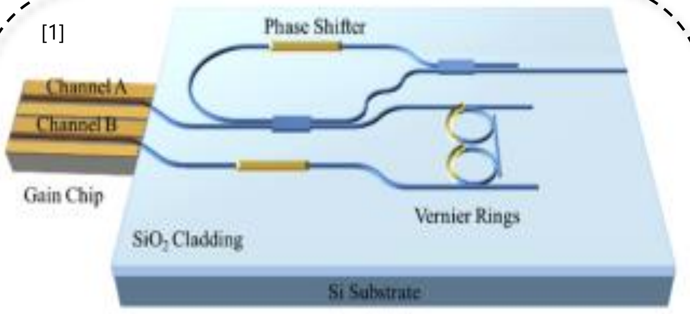
[1]

[1] Paraïso, T.K., Roger, T., Marangon, D.G. et al. A photonic integrated quantum secure communication system. Nat. Photon. 15, 850–856 (2021)

Hybrid Integration Technologies

Edge-coupling

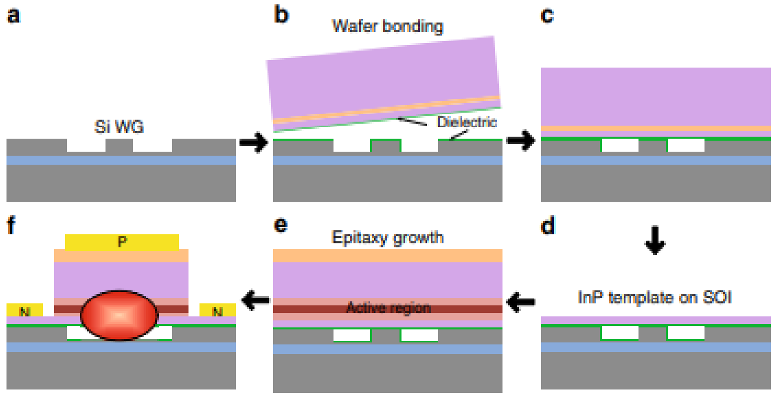
[1]



[2]

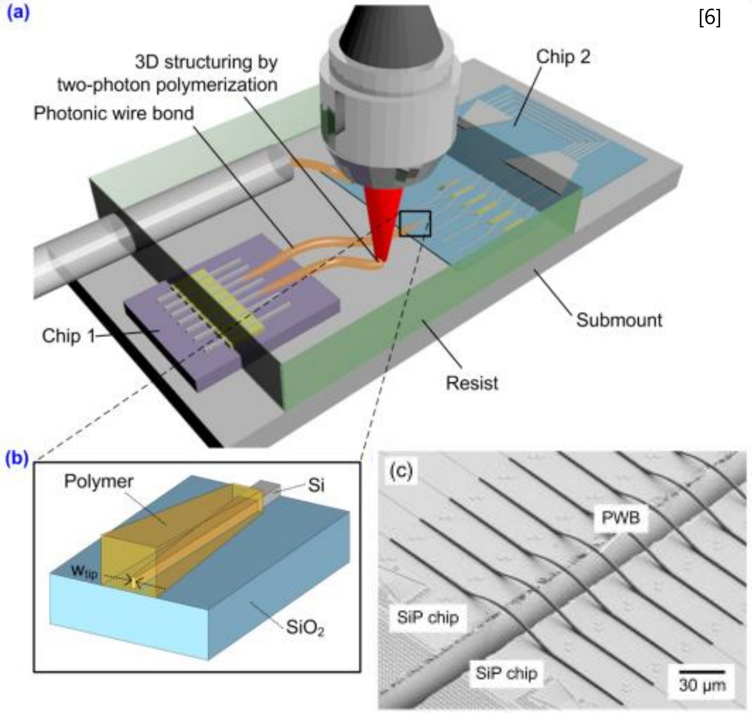
Hetero-epitaxial growth

[3]



Photonic wire bonding

[6]



Flip-Chip

[5]

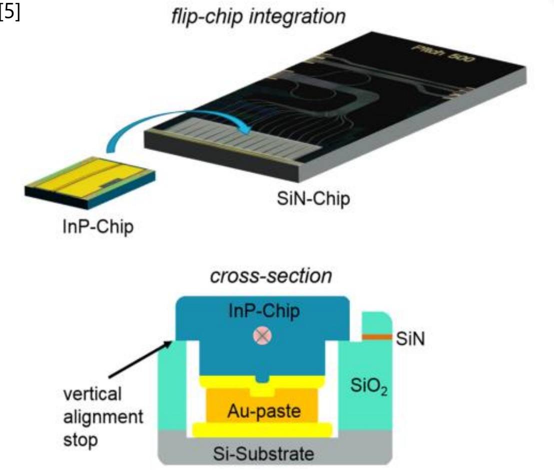
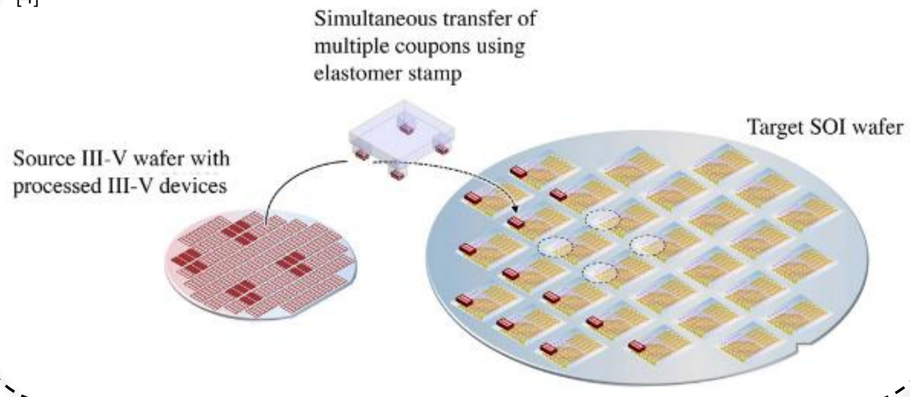


Fig. 1. Hybrid flip-chip integration of InP chip into etched recess on SiN TriPleX chip (top) and cross-section through InP chip bonded to SiN chip (bottom).

Micro-transfer printing

[4]



[1] Zhao et al. (2021) Hybrid dual-gain tunable integrated InP-Si3N4 external cavity laser

[2] Lionix press release (2019) High power, tunable, narrow linewidth dual gain hybrid laser

[3] Hu et al. (2019) III/V-on-Si MQW lasers by using a novel photonic integration method of regrowth on a bonding template

[4] Haq et al. (2020) Micro-Transfer-Printed III-V-on-Silicon C-Band Semiconductor Optical Amplifiers

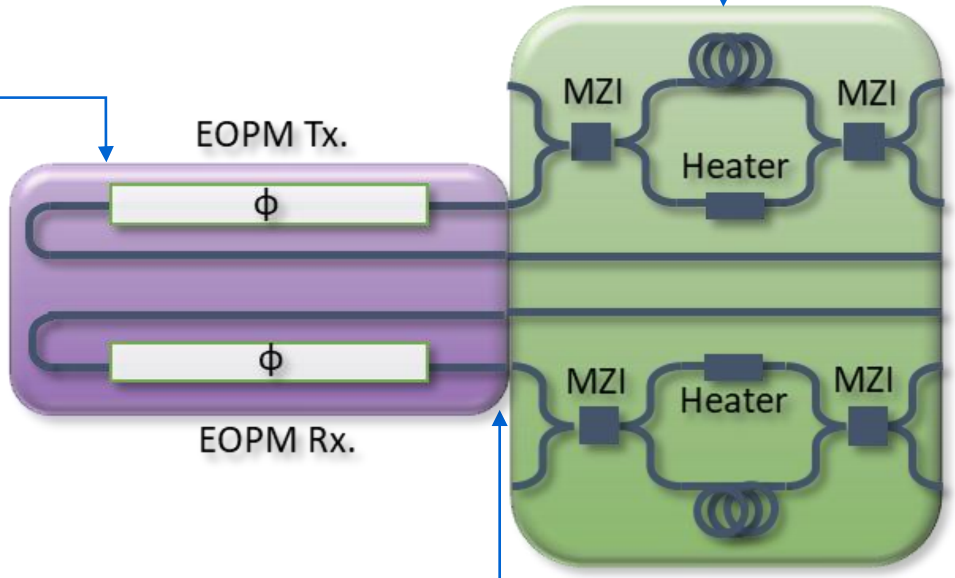
[5] Theurer et al. (2020) Flip-Chip Integration of InP to SiN Photonic Integrated Circuits

[6] Lindenmann (2012) Photonic wire bonding: a novel concept for chip-scale interconnects

Our solution: A Hybrid InP/SiN QKD Transceiver PIC

InP – 2 x Electro-optic phase modulators

- High bandwidth
- Low V_π
- Constant loss



SiN – 2 x Asymmetric Mach Zehnder Interferometers

- Ultra-low propagation loss (0.1 dB/cm)
- Precise manufacturing
- Integrated thermo-optic phase shifters

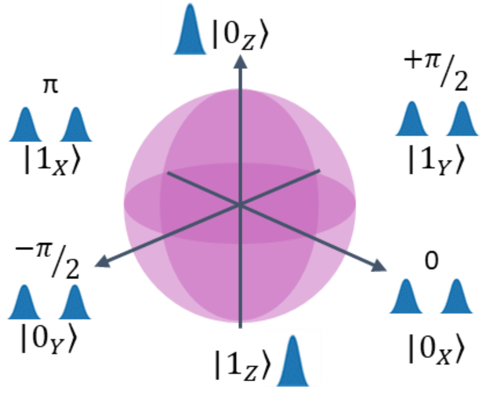
0.9 dB interface loss

➢ 7.5 dB total circuit loss

Operates as both quantum encoder and decoder at 1 GHz

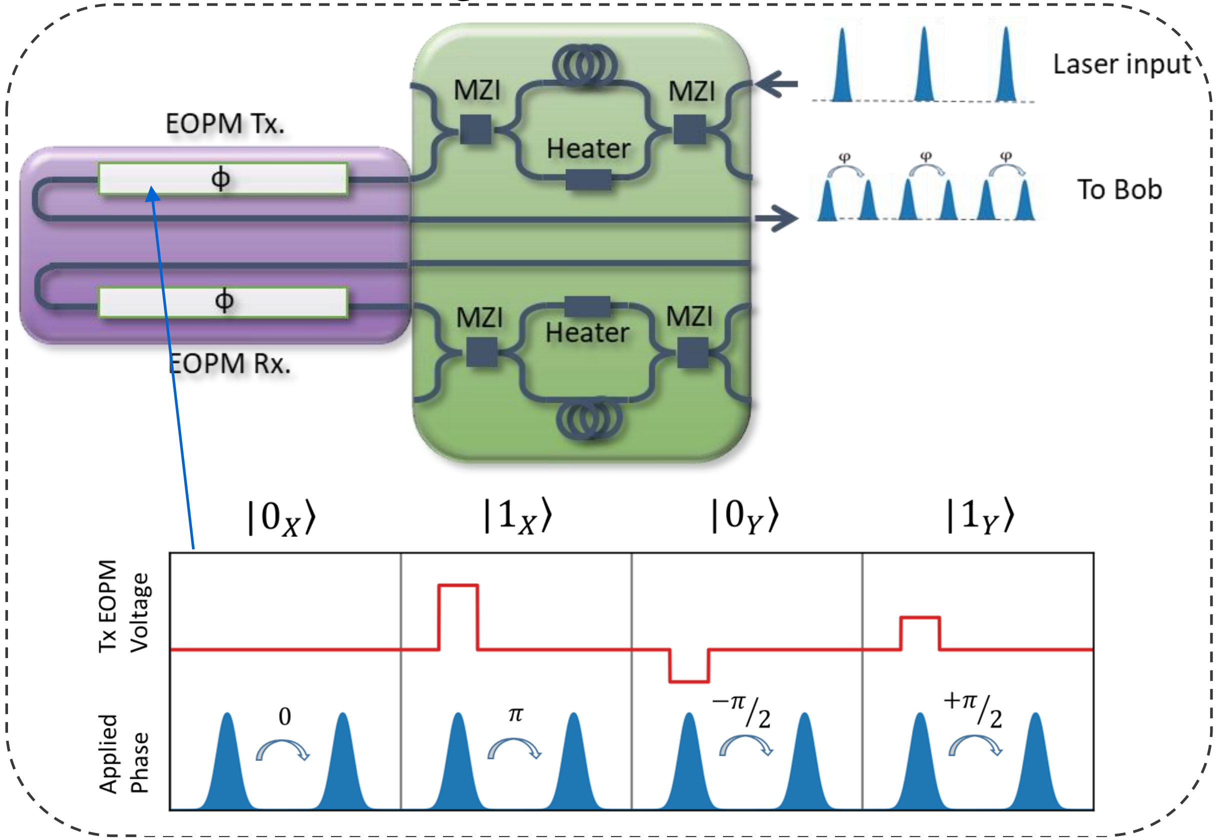
Our solution: A Hybrid InP/SiN QKD Transceiver PIC

BB84 Time-bin encoding

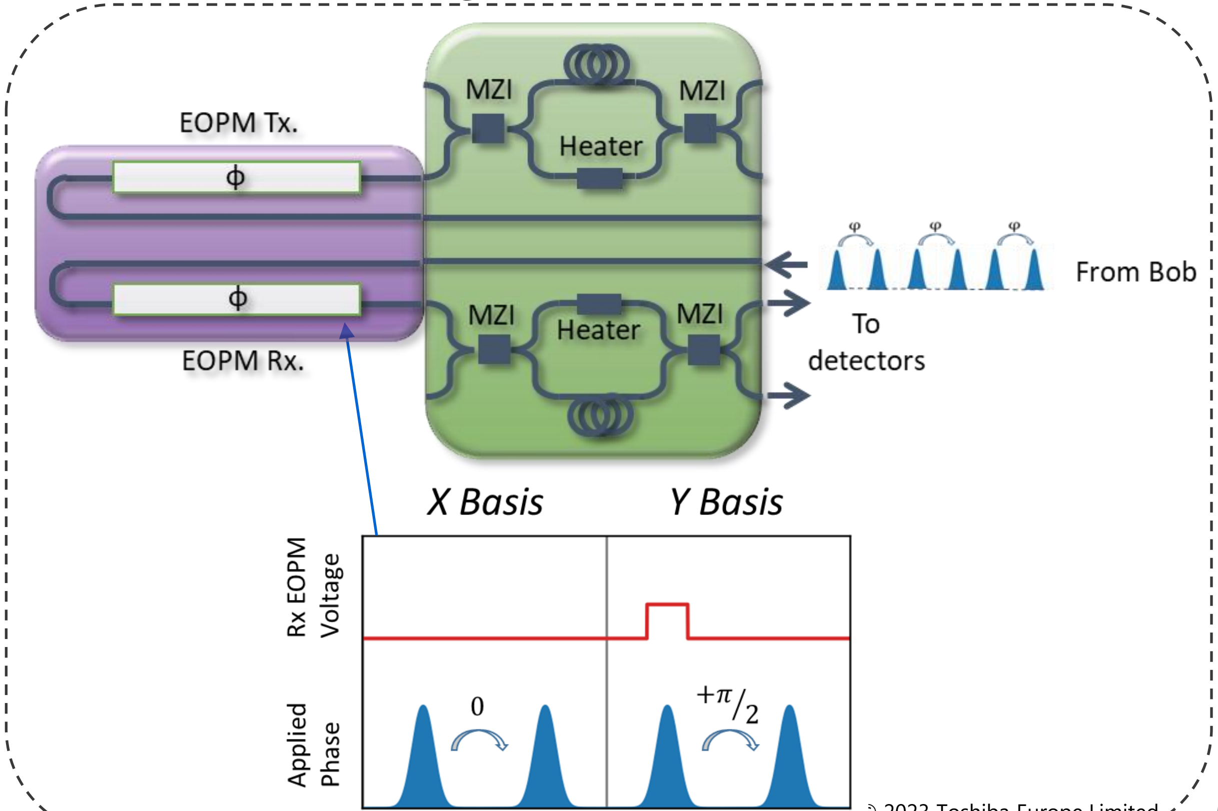


X-Y Bases – Equatorial phase states only

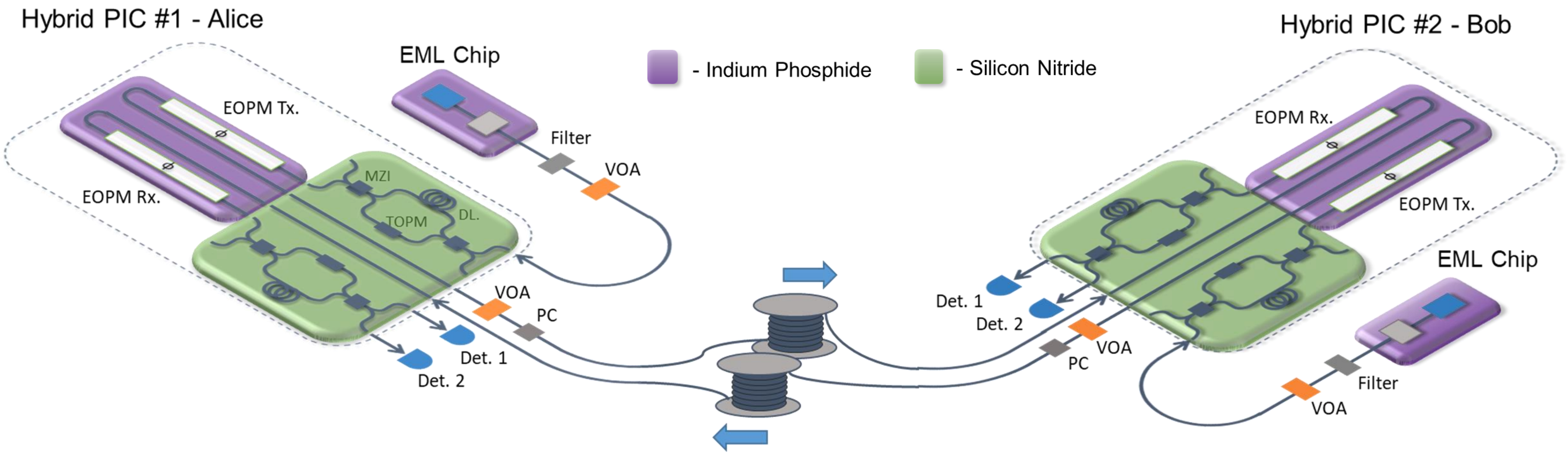
As Quantum Encoder



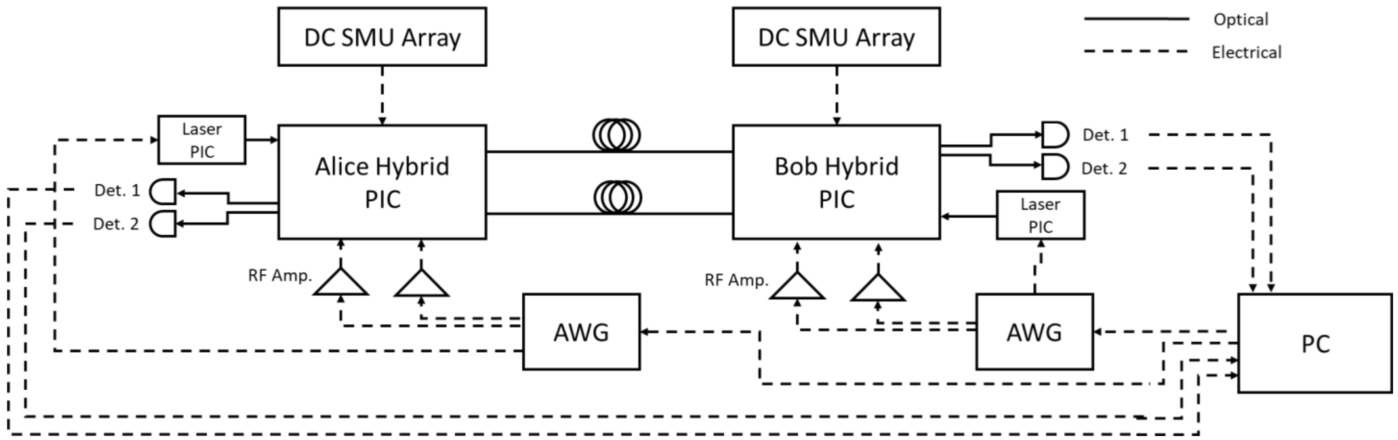
As Quantum Decoder



Experimental setup



Control schematic:

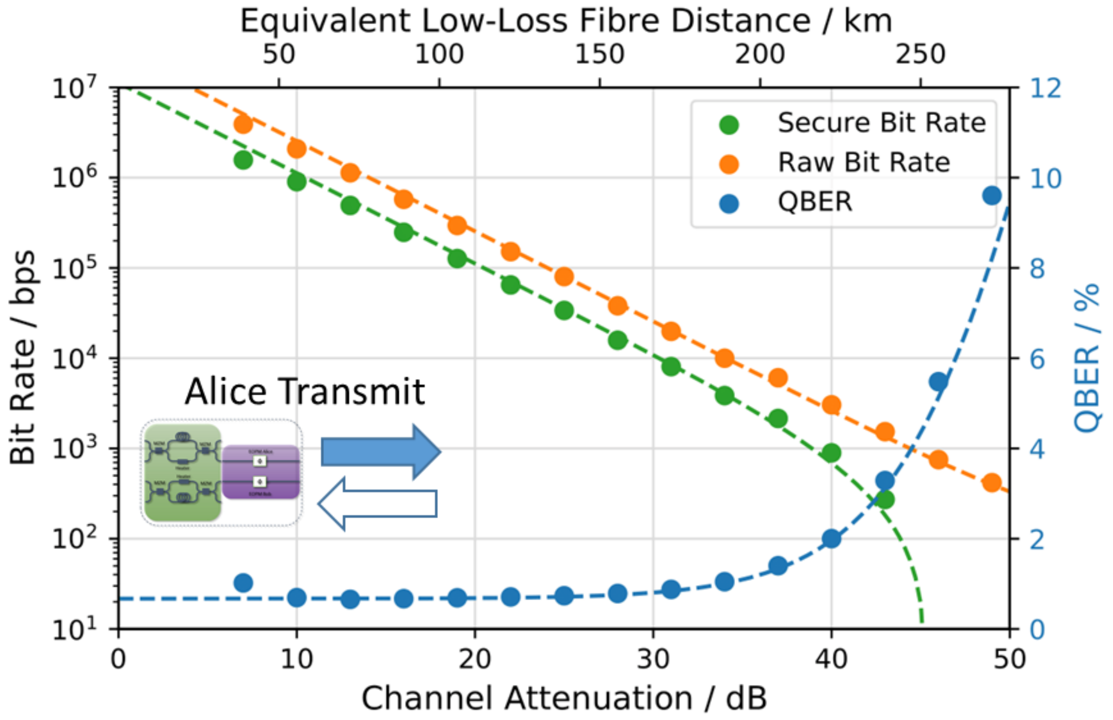


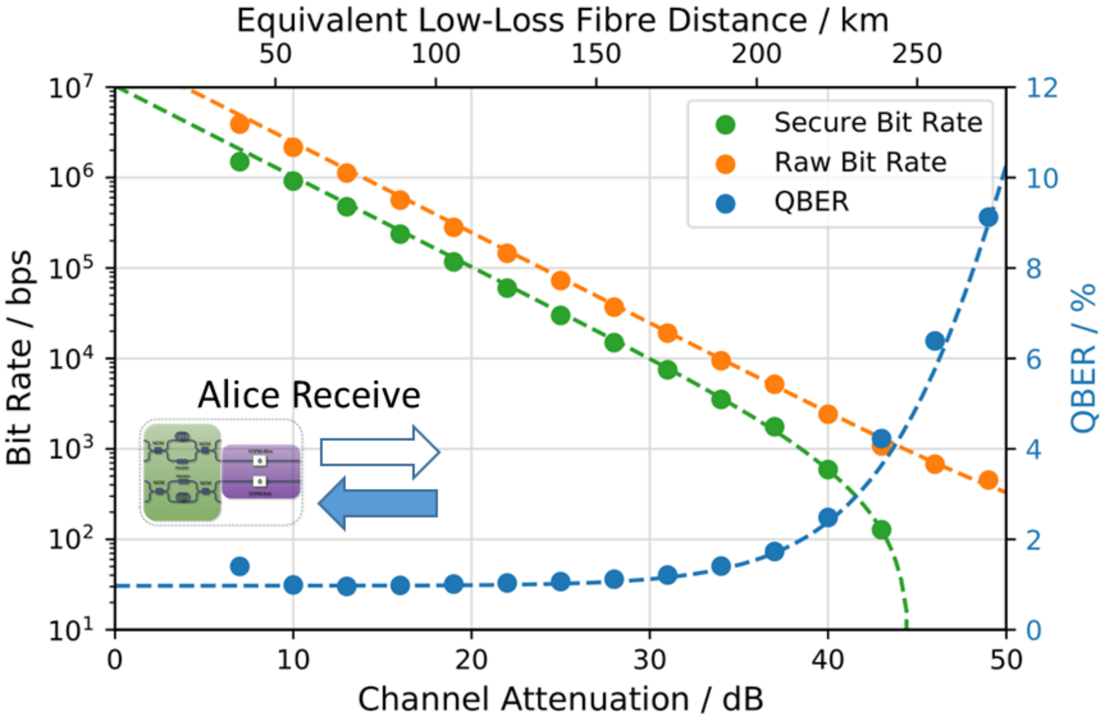
- SNSPD photon detection (~85 % SPDE)
- 10’000 ns pseudo-random pattern
- Secure key rates estimated in post-processing

QKD Performance

- ➢ 0.66 % min. quantum bit error rate

<u>7dB channel → 1.57 Mbps secure key rate</u>





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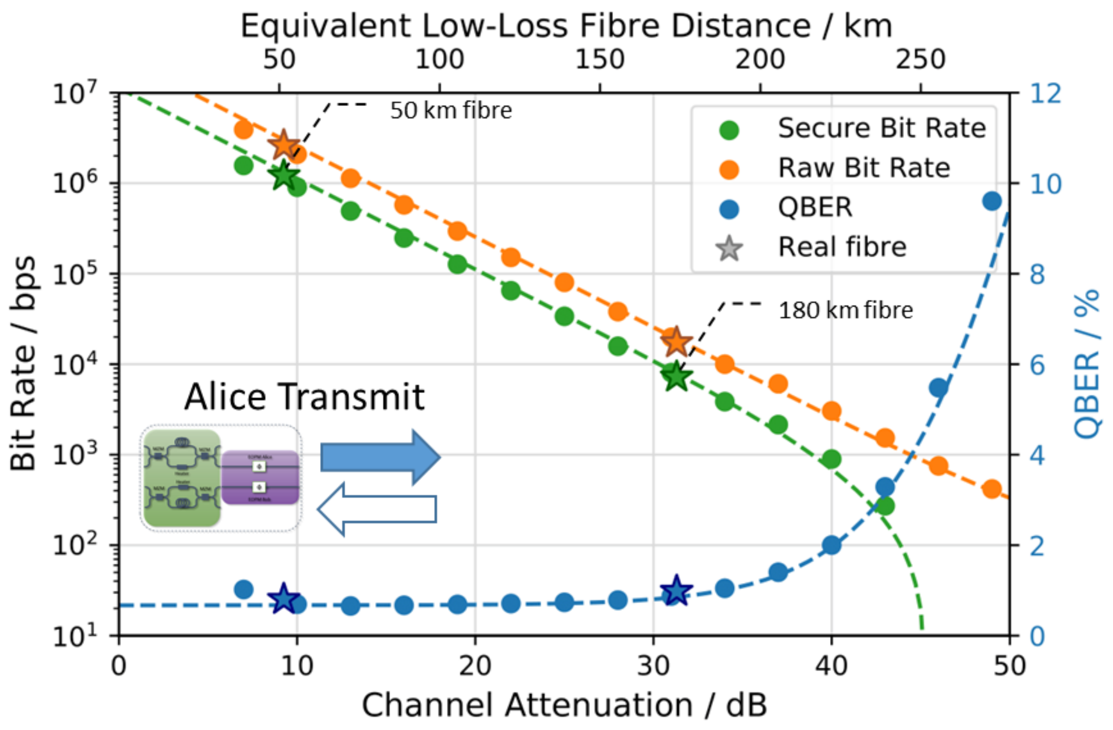
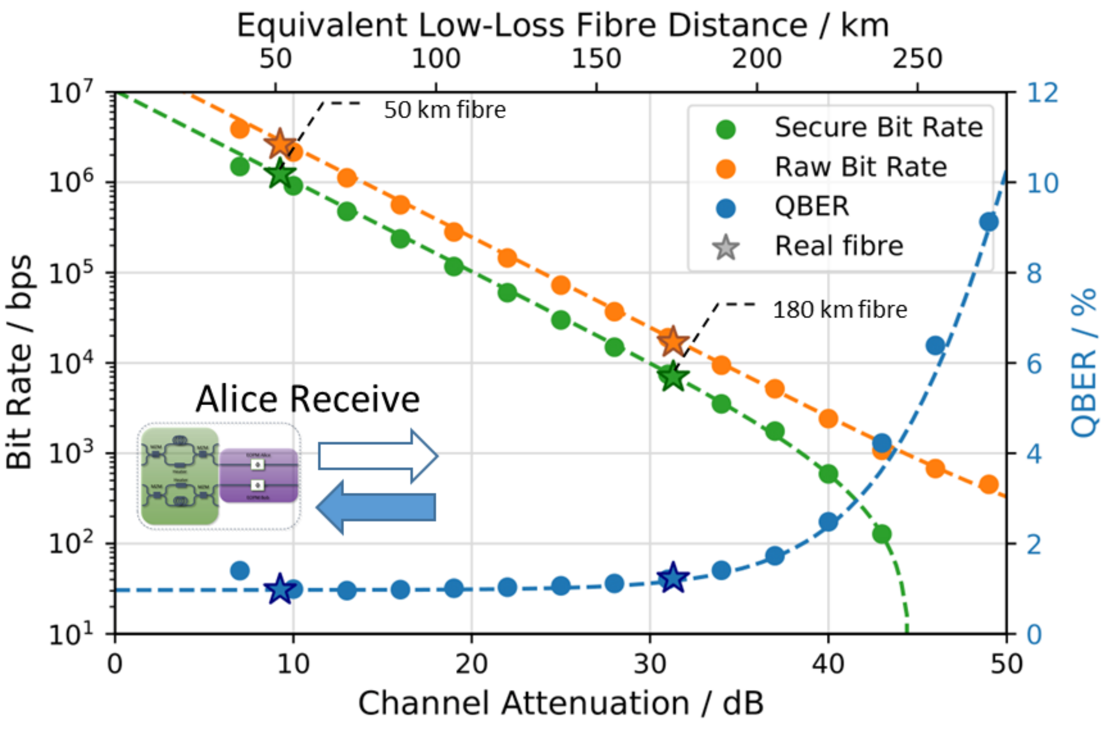
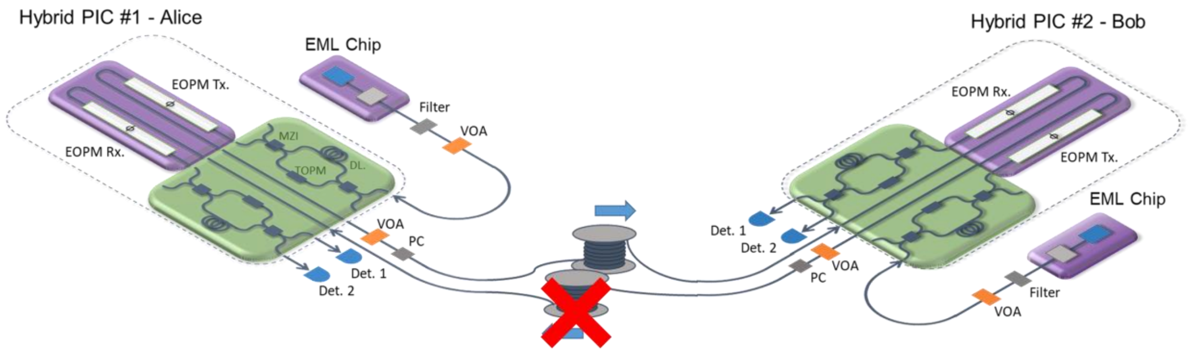
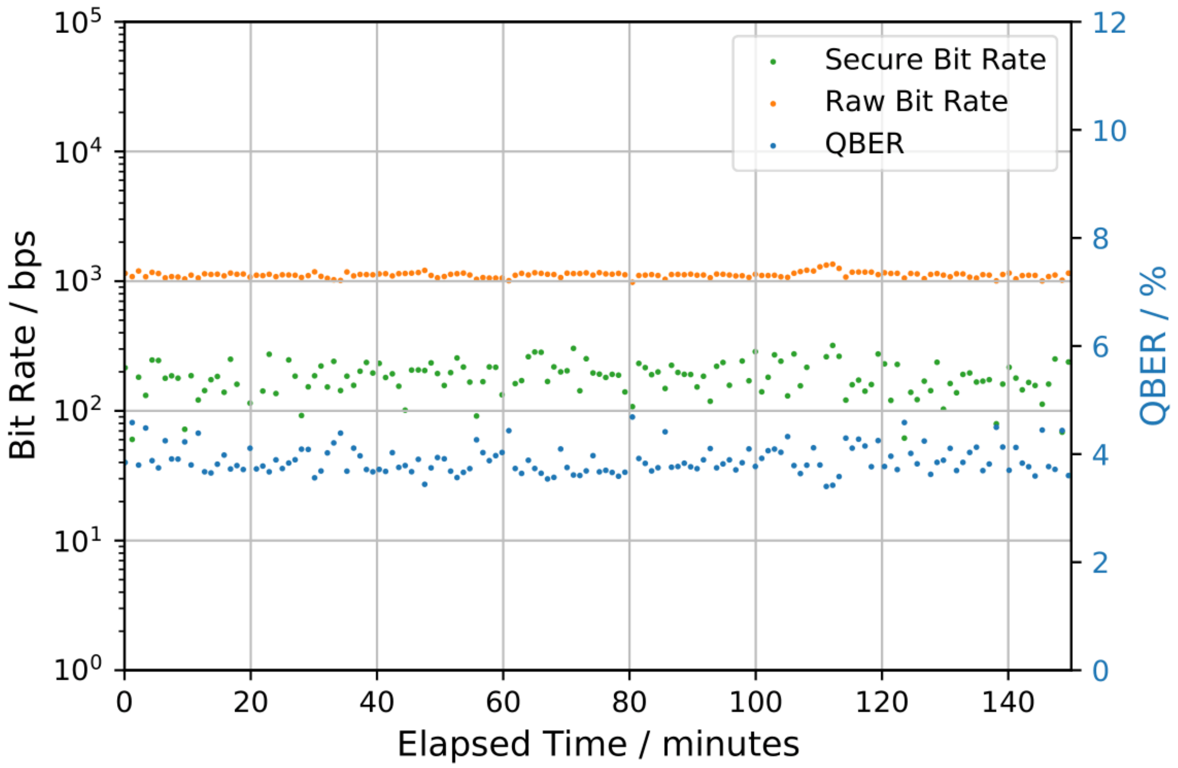




Long-Distance Unidirectional Operation

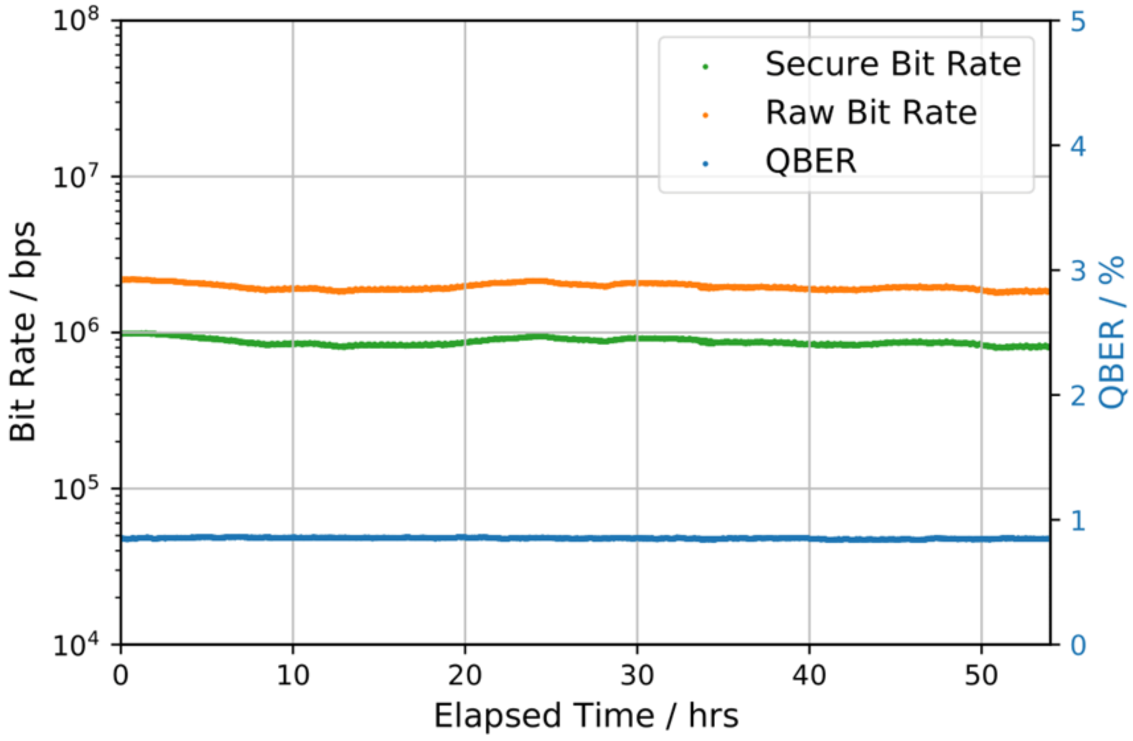


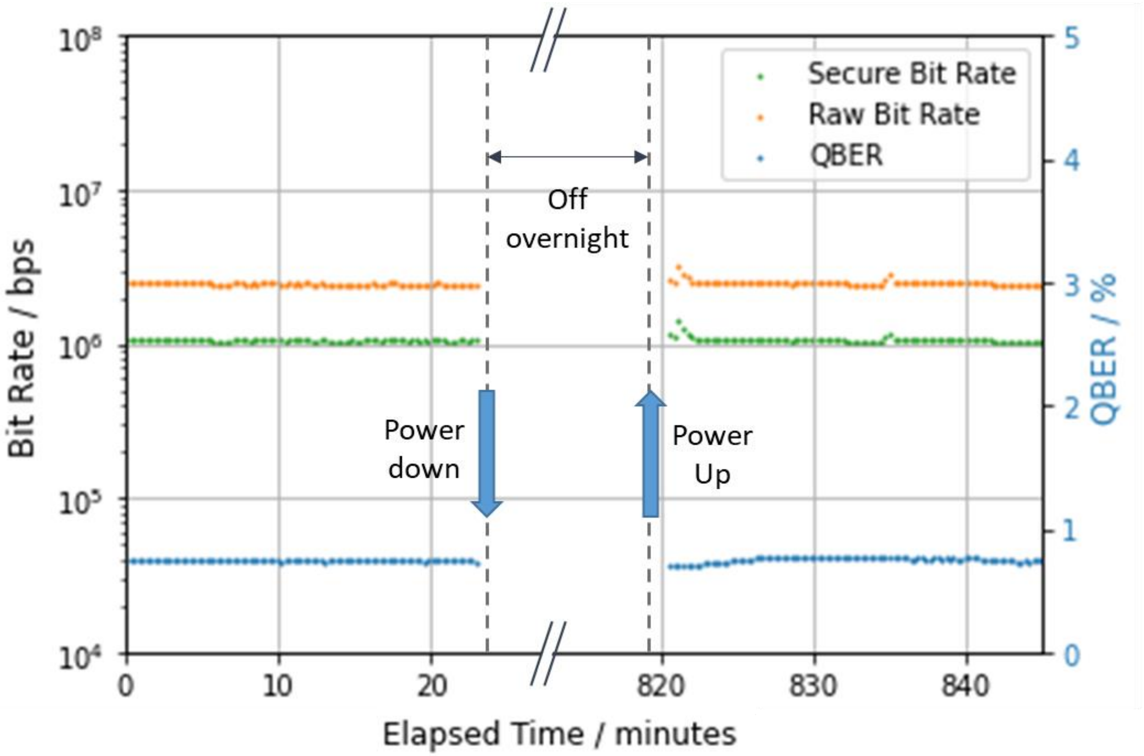


- 250 km (44 dB loss) real fibre range
  - 186 bps (asymptotic[2])
  - 67 bps (finite key[3])

[2] Ma, X., Qi, B., Zhao, Y. & Lo, H.-K. Practical decoy state for quantum key distribution. Phys. Rev. A 72, 012326 (2005)
[3] Lucamarini, M. et al. Efficient decoy-state quantum key distribution with quantified security. Opt. Express 21, 24550–24565 (2013)

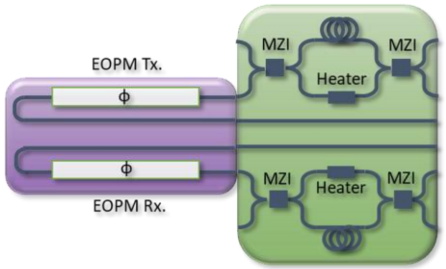
Stability



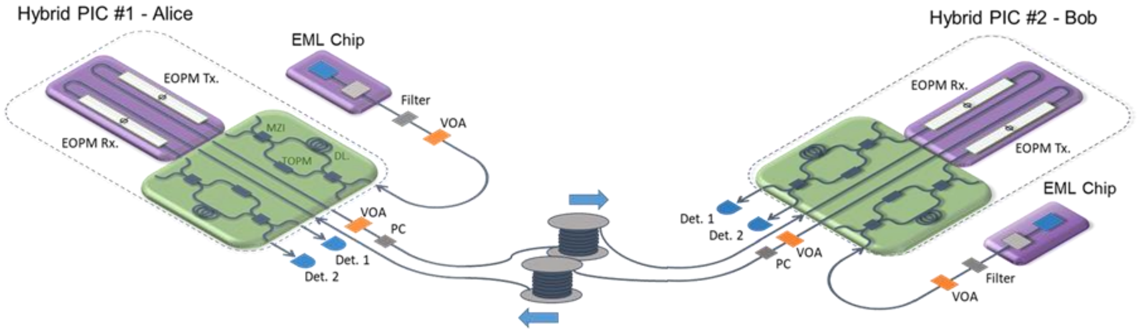


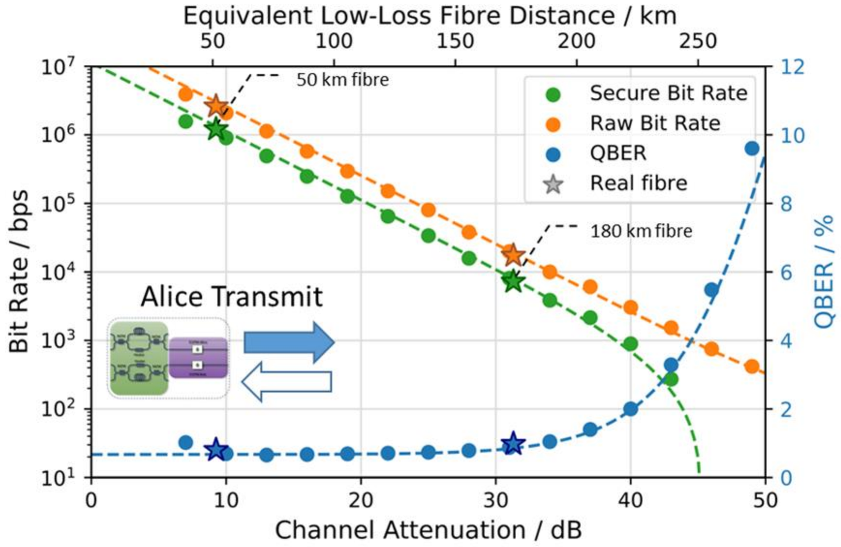
- System stability over 50 hours runtime (10 dB attenuation)
- Stable through power cycling

Conclusions



- We have developed an edge-coupled hybrid InP/SiN QKD transceiver PIC
  - Bidirectional QKD operation with an actively modulated receiver
    - Exhibiting competitive secure key rates, stability, reproducibility, low operating voltages and state-of-the-art fibre distances.





Thank You

A Hybrid Integrated Quantum Key Distribution Transceiver Chip

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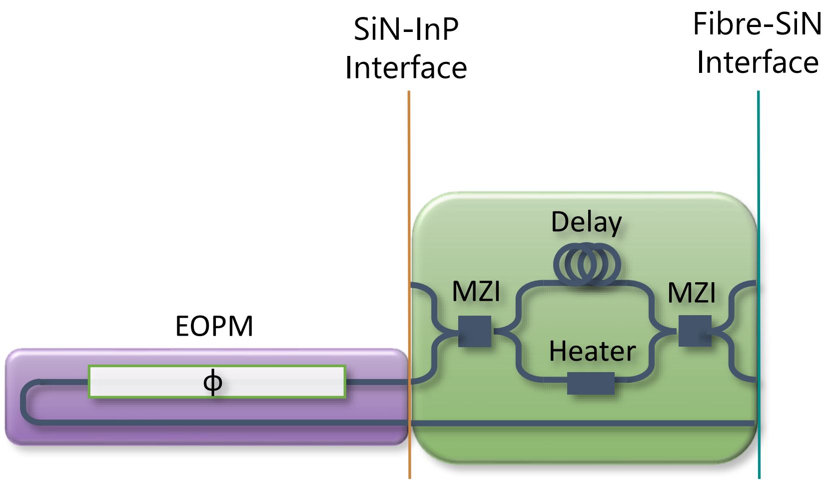
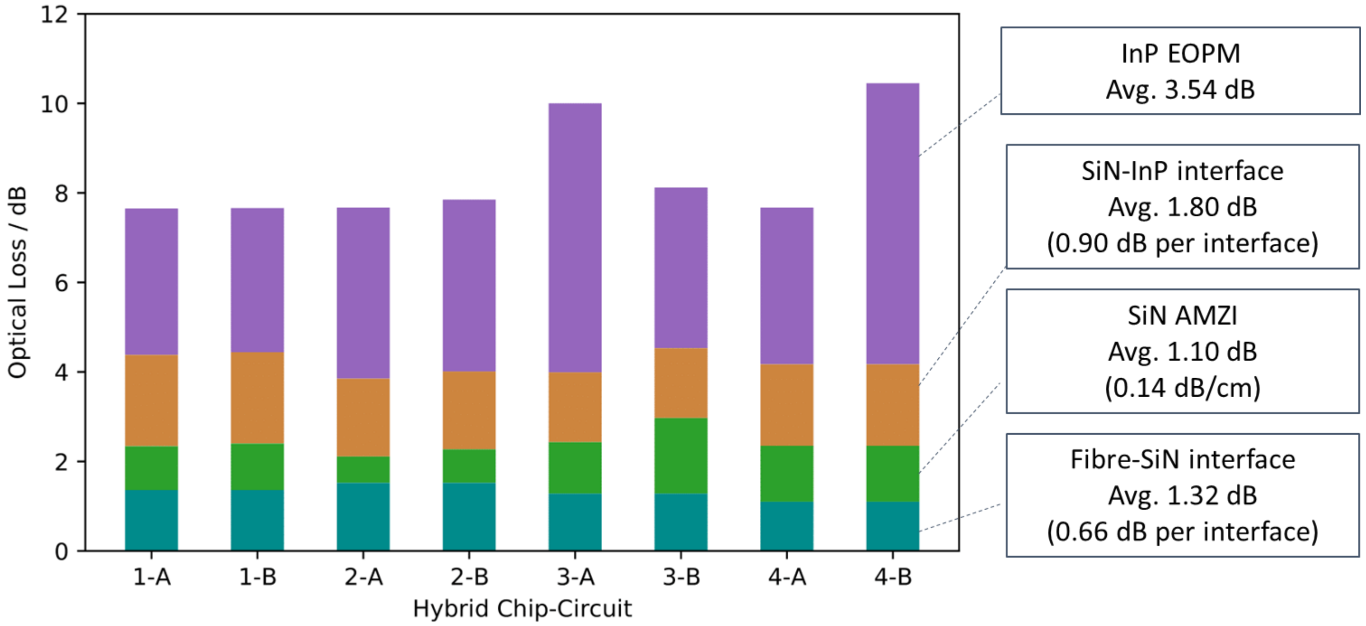
arXiv:2308.02238, to appear in NPJ Quantum Information

Additional Slides

Appendix Slide 1: Optical Loss

- Reduction of optical loss is critical to any quantum receiver circuit
- We characterise eight identical hybrid circuits to investigate the achievable loss
- Redundant waveguide structures in the chip allow us isolate the different sources of loss.

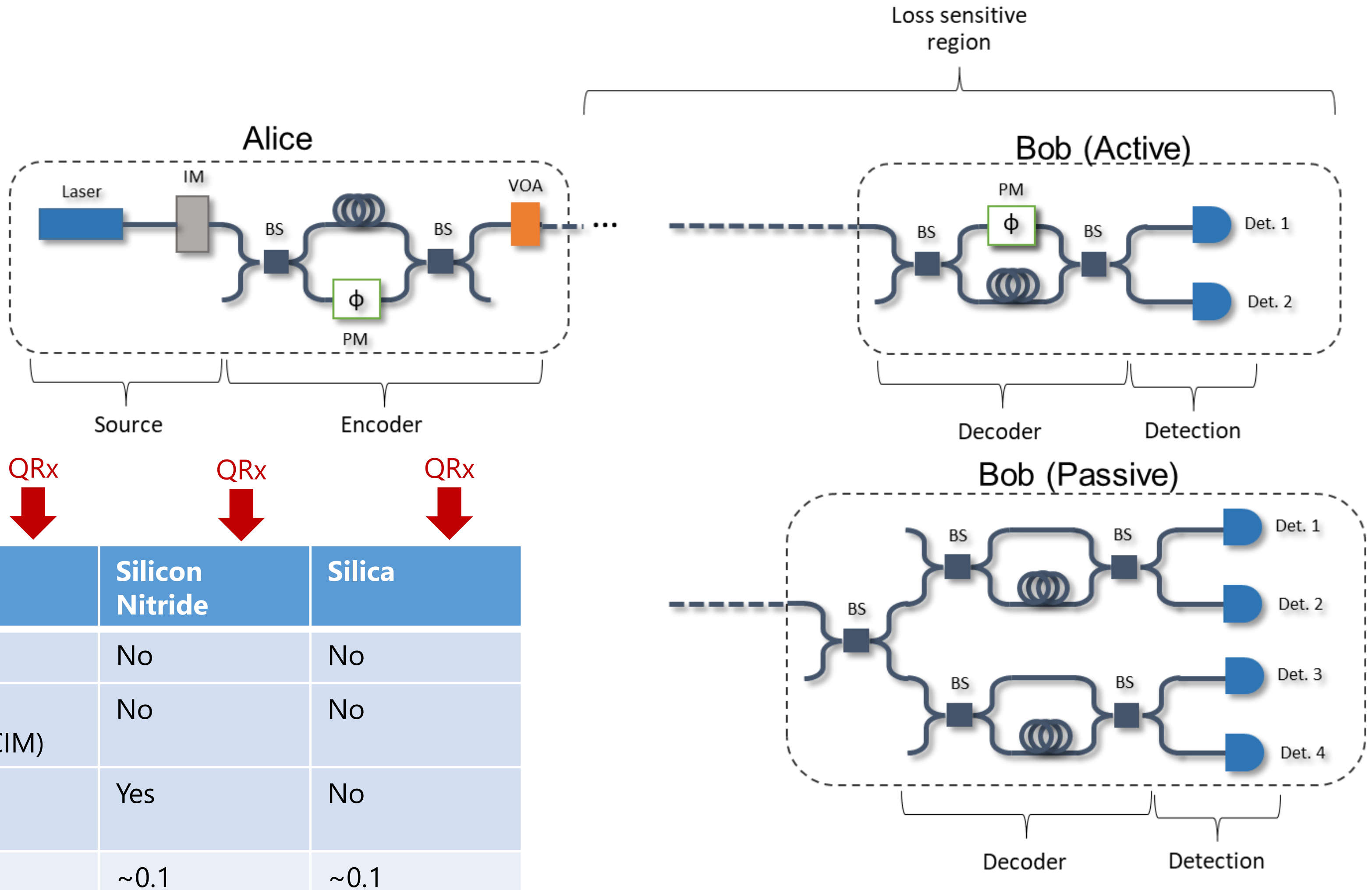




- We measure six out of eight circuits to have optical loss <8 dB, with four best performers at ~ 7.5 B

Appendix Slide 2: Material Platforms

Example QKD System (Time-bin Encoding, Discrete Variable)



QTx QTx QRx QRx QRx

	Indium Phosphide	Silicon	Silicon Nitride	Silica
Native lasers?	Yes	No	No	No
Fast modulators?	Yes (EOPM)	Yes (CDM/CIM)	No	No
Thermo-optic phase shifters?	Yes	Yes	Yes	No
Waveguide loss (dB / cm)	~3	~0.5	~0.1	~0.1
CMOS compatible?	No	Yes	Yes	No

Appendix Slide 3: Existing On-Chip QKD Demonstrations

	QTx/ QRx On-chip	QTx Platform	Protocol	Encoding	Laser source	QTx State Modulation	QRx Platform	QRx Basis Modulation	Receiver Loss	Clock rate
Honjo et al. *Optics Letters* **29,** 23 (2004)	QRx only	Fibre	DPS	Phase	-	-	Silica	Passive	2.6 dB	1 GHz
Tanaka et al. IEEE J. Quantum Electron. **48**, 4 (2012)	QRx only	Fibre	BB84	Time-bin	-	-	Silica	Passive	4 dB	1.25 GHz
Ma et al. *Optica* **3**, 11 (2016)	QTx only	Si	BB84	Polarisation	External	Carrier depletion (CDM)	Fibre	-	-	10 MHz
Sibson et al. *Nat Commun* **8**, 13984 (2017)	QTx + QRx	InP	BB84, DPS, COW	Time-bin, Phase	On-chip	Travelling wave EOPM	SiOxNy	Passive	9 dB	560 MHz [BB84] 1.76 GHz [DPS]
Sibson et al. *Optica* **4**, 2 (2017) (b)	QTx + QRx	Si	BB84, COW	Time-bin Polarisation	External	CDM	Si	Passive	Not stated	1 GHz 0.86 GHz
Ding et al. *npj Quantum Inf* **3**, 25 (2017)	QTx + QRx	Si	High-Dim. QKD	Path entanglement	External	TOPM	Si	TOPM	8 dB	5 kHz / 10 kHz
Bunandar et al. *Phys Rev X* **8**, 021009 (2018)	QTx only	Si	3-state BB84	Polarisation	External	CDM	Fibre	-	-	625 MHz
Paraiso et al. *npj Quantum Inf* **5**, 42 (2019)	QTx + QRx	InP	BB84, DPS	Time-bin, Phase	On-chip	Phase-seeding	SiN	Passive	Not stated	1 GHz
Zhang et al. *Nat. Photonics* **13**, 839 (2019)	QTx + QRx	Si	CV-QKD	Gaussian-modulated	External	CDM	Si	CDM	5 dB	1-10 MHz
Geng et al. *Opt Express* **27**, 29045 (2019)	QTx + QRx	Si	BB84	Time-bin	External	CDM	Si	Passive	15 dB	100 MHz
Cao et al. *Phys Rev Applied* **14**, 011001 (2020)	QTx + QRx	Si	MDI-QKD	Polarisation	External	CDM	Si	Passive	Not stated	0.5 MHz
Semenenko et al. *Optica* **7**, No. 3 (2020)	QTx only	InP	MDI-QKD	Time-bin	On-chip	Travelling wave EOPM	Fibre	-	-	250 MHz
Wei et al. *Phys Rev X* **10**, 031030 (2020)	QTx only	Si	MDI-QKD	Polarisation	External	CDM	Fibre	-	-	1.25 GHz
Avesani et al. *npj Quantum Inf* **7**, 93 (2021)	QTx only	Si	3-state BB84, free space	Polarisation	External	CDM	Fibre	-	-	50 MHz
Paraiso et al. *Nat. Photonics* **15**, 11 (2021)	QTx + QRx	InP	BB84	Time-bin	On-chip	Phase-seeding	SiN	External Phase Modulator	Not stated	1 GHz
Beutel et al. *npj Quantum Inf* **7**, 1 (2021)	QRx only	Fibre	3-state BB84	Time-bin	-	-	SiN	Passive	Not stated	2.6 GHz
Zhu et al. *Phys Rev Applied* **17**, 6 (2022)	QTx only	Si	BB84	Polarisation	External	CDM	Fibre	-	-	1 GHz
Beutel et .al *Optica* **9**, 10 (2022)	QRx only	Fibre	3-state BB84, 4 WDM channels	Time-bin	-	-	SiN	Passive	< 8 dB (deduced)	3.35 GHz
Sax et al. *arXiv* preprint (2022)	QTx + QRx	Si	3-state BB84	Time-bin	External	Carrier Insertion (CIM)	Silica	Passive	3 dB	2.5 GHz
Li et al. *Nat. Photonics* (2023)	QTx only	Si	BB84	Polarisation	External	Carrier depletion (CDM)	Fibre	-	-	2.5 GHz
This work (2023)	QTx + QRx	SiN / InP Hybrid	BB84	Time-bin	External	EOPM	SiN / InP Hybrid	EOPM	7.5 dB	1 GHz

Appendix Slide 4: Extended Stability Data