Quantum Key Distribution powered by silicon photonics and III-V photonics

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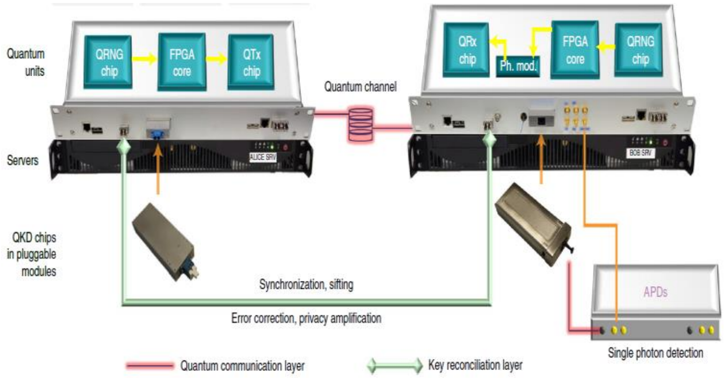
National Optoelectronics Innovation Center

Outline:

- Compact size QKD : state of art
- Cost issues with current QKD systems
- QKD powered by silicon photonics + III-V photonics
- Chance for standardization of MSA QKD module

Compact size QKD: state of art

The Cerberis XG QKD System



Company	Quantum Ctek	IDQuantique	Toshiba
#ofU	1U	1U	1U
W x L x H	440mm x 421mm x 44.5mm	425mm x 565mm x 40mm	unknown
Integrated Photonic chip used?	No	Unknown	Partially photonic chip used with external Lithium niobate modulator and external single photon detector
Performance	Max channel loss tolerant 24dB	2kbps @ 12dB channel loss	28kbps @ 50km(about 12dB)
Protocol	Decoy state BB84	COW or BB84 ?	T12 (a variation of BB84)

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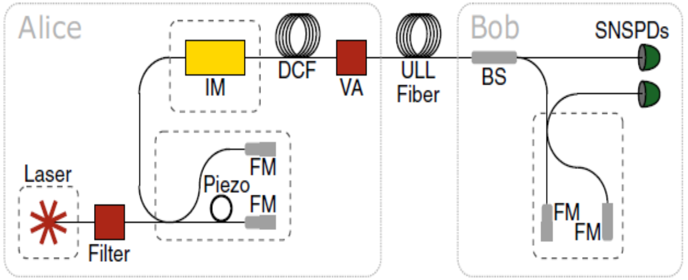
Two families of prepare-and-measurement QKD

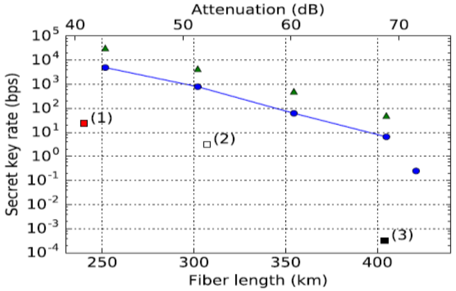
Discrete Variable QKD

- Maximum Baud rate at 1.25Ghz for product
- Maximum Baud rate at 10Ghz record
- Based on single photon detection
- Degree of freedom: polarization, time bin + phase, frequency
- Dark fiber preferred, good at high loss channel
- Co- existence with data communication possible, low tolerance.
- Relatively simple post-processing
- Record from Uni.Geneva : 6.5bps@69.3dB

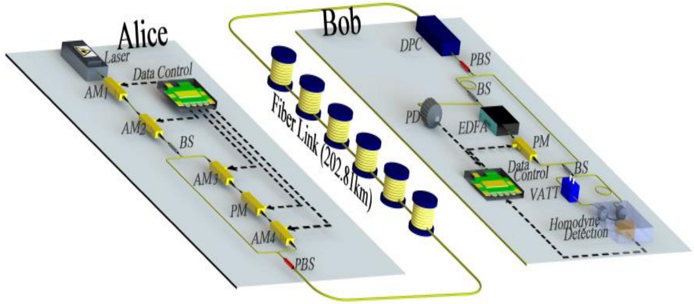
Continuous Variable QKD

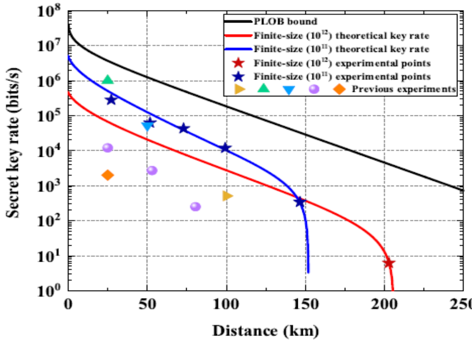
- Maximum Baud rate no more than 5Mhz for product
- Maximum Baud rate around 1Ghz record
- Based on coherent detection
- Degree of freedom: In-phase and quadrature of EM field
- Dark fiber is not a must, good at low loss channel
- Co- existence with data communication possible, high tolerance
- Complex post-processing
- Record from BUPT&PKU: 6.2bps@32.45 dB





Phys. Rev. Lett. 121, 190502 (2018)





Phys. Rev. Lett. 125, 010502 (2020)

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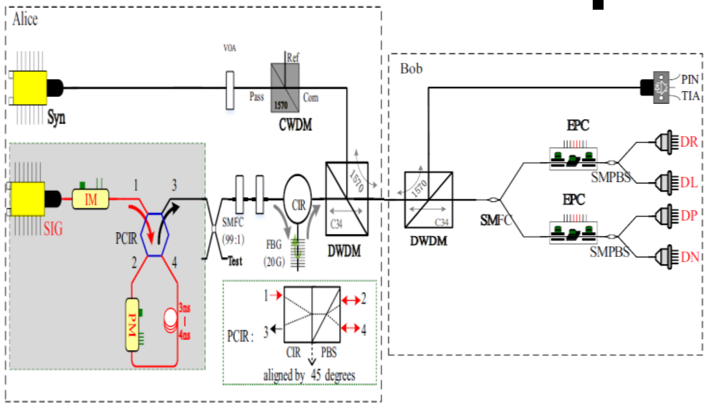
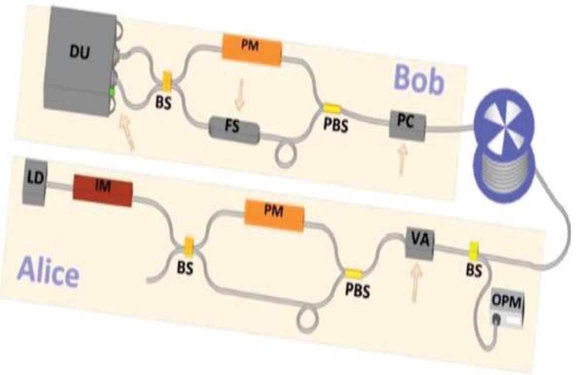
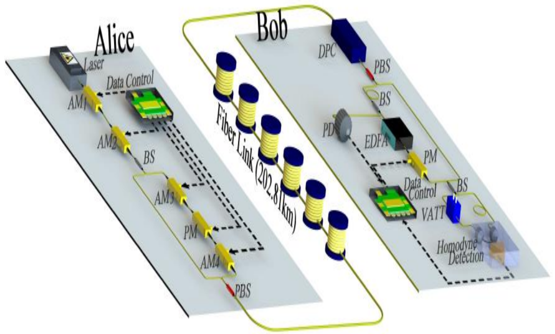
Cost issue with discrete optics based QKD



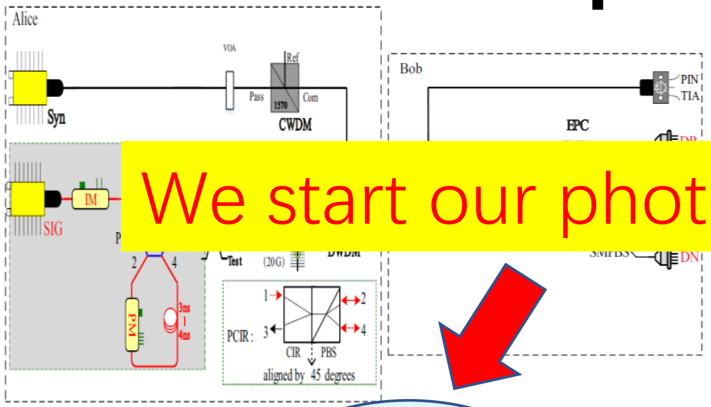


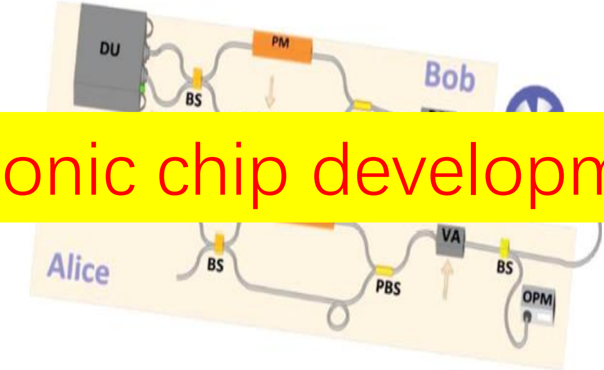


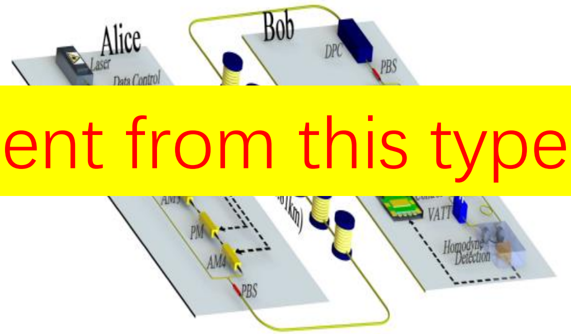
QKD Type	DV-QKD Polarization	DV-QKD Time-Phase	CV-QKD-TLO GG02
Typical Groups	**Quantum Cteck, Univ.Padova**	**Toshiba (their old system)**	**BUPT，CNRS**
Laser	DFB Laser	DFB Laser	Narrow linewidth Laser
Encoding/Modulation	LN Modulatorx2,Sagnac loop	LN modulatorx2， fiber-AMZI	LN modulatorx3~5， fiber-AMZI
Channel Control	Electric Pol.Controller	Electric Pol.Controller	Electric Pol.Controller
Decoding/De-modulation	Electric Pol.Controller	LN modulatorx2， fiber-AMZI	LN modulatorx1， fiber-AMZI
Optical signal detection	Single photon detectorx4	Single photon detectorx2~4	Homodyne detectorx1~2

Very High cost (red) — High cost (yellow) — Moderate cost (green)

Cost issue with discrete optics based QKD







We start our photonic chip development from this type

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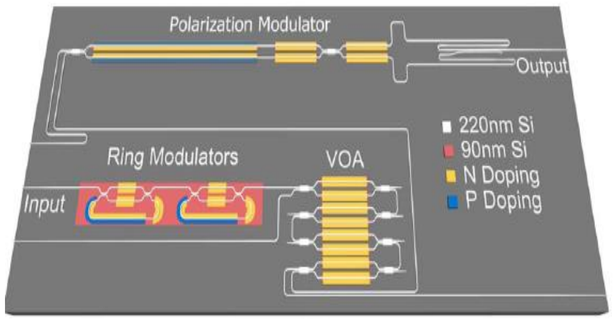
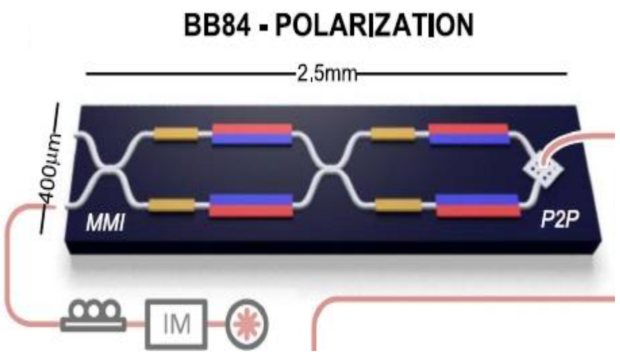
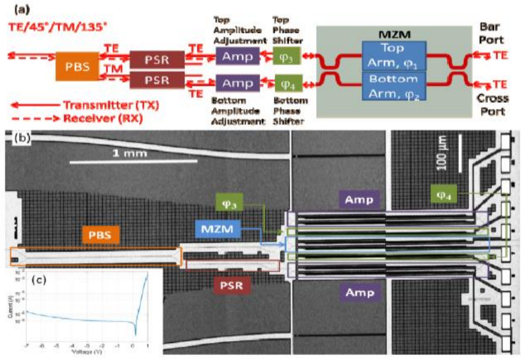
QKD with silicon photonics – Polarization BB84



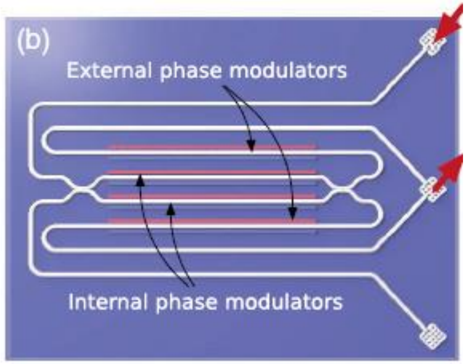
Optica Vol. 3, No. 11, 2016



Optica Vol. 4, No. 2, 2017

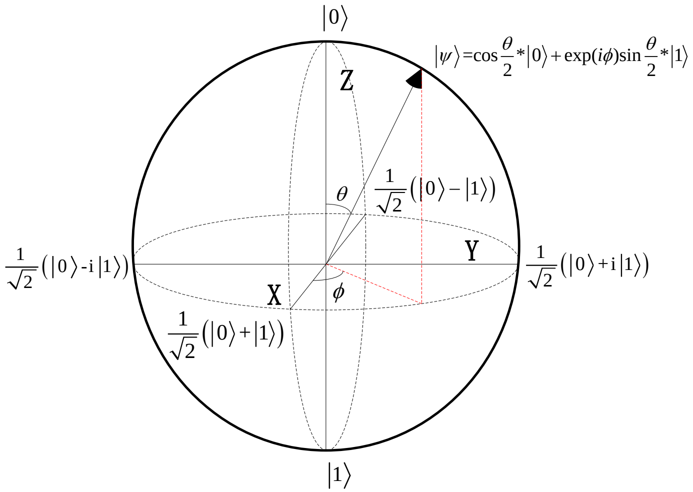


Optics Express, Vol.25, No.11, 2017



PRX 8, 021009 ,2018

- Using the technique "path to polarization conversion".
- On demand generation of any polarization state, such as vertical, horizontal, diagonal, off-diagonal.
- Off chip pulsed Laser.
- 2D grating coupler introduces high loss(5~7db) but doesn't matter with transmitter.
- Need high extinction ratio for on-chip Modulator – reduce state preparation error.
- Fully discrete component based receiver – passive polarization decoding.
- Off chip single photon detector.



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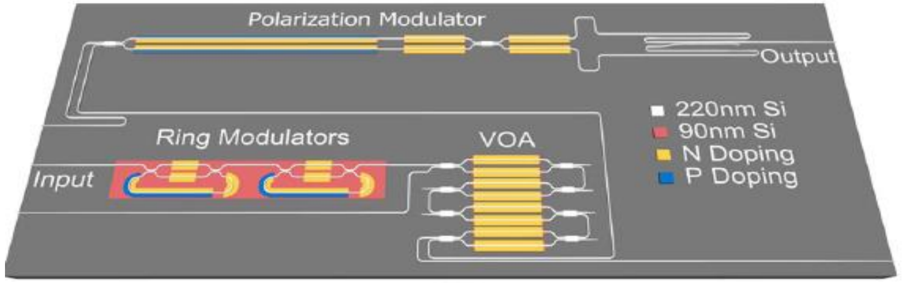
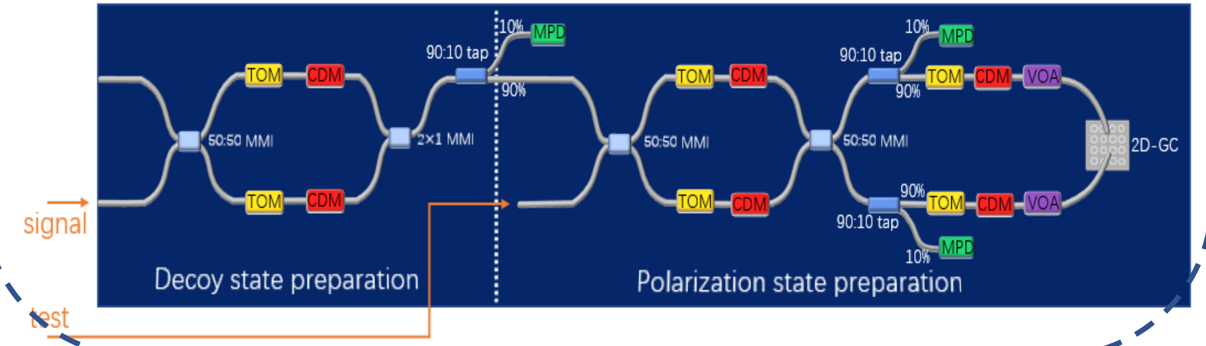
Transmitter of DV-QKD Polarization: which part can be implemented on silicon-photonics?

Pulsed Laser (High ER, phase randomized) → Intensity Modulation for decoy state → Polarization state preparation → VOA, Power Monitoring, Isolator, etc.

The demand



The work from Univ.Toronto Optica Vol. 3, No. 11, 2016



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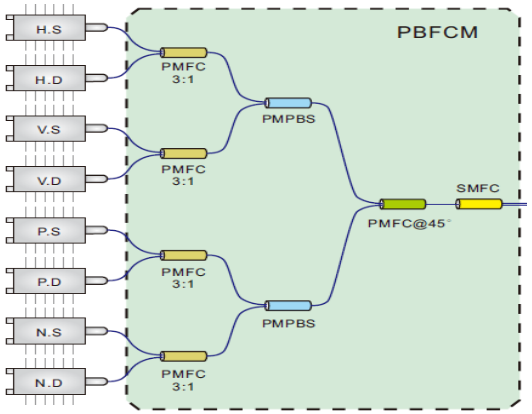
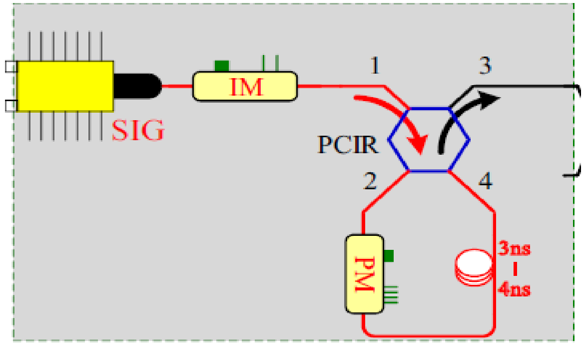
Polarization preparation on silicon-photonics

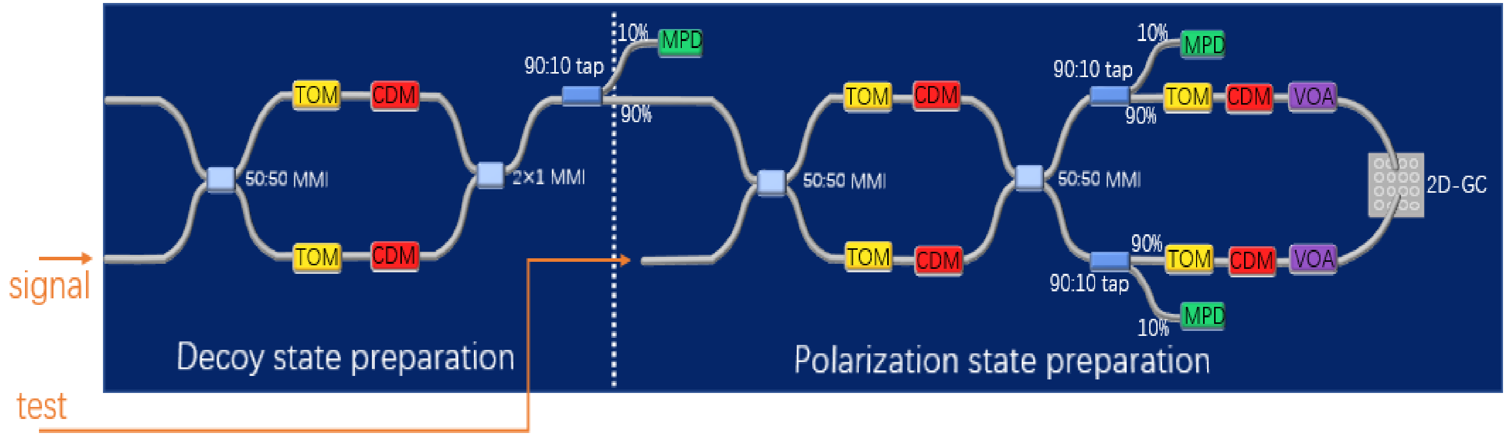


Passive polarization + decoy state sate encoding



Active polarization + decoy state encoding

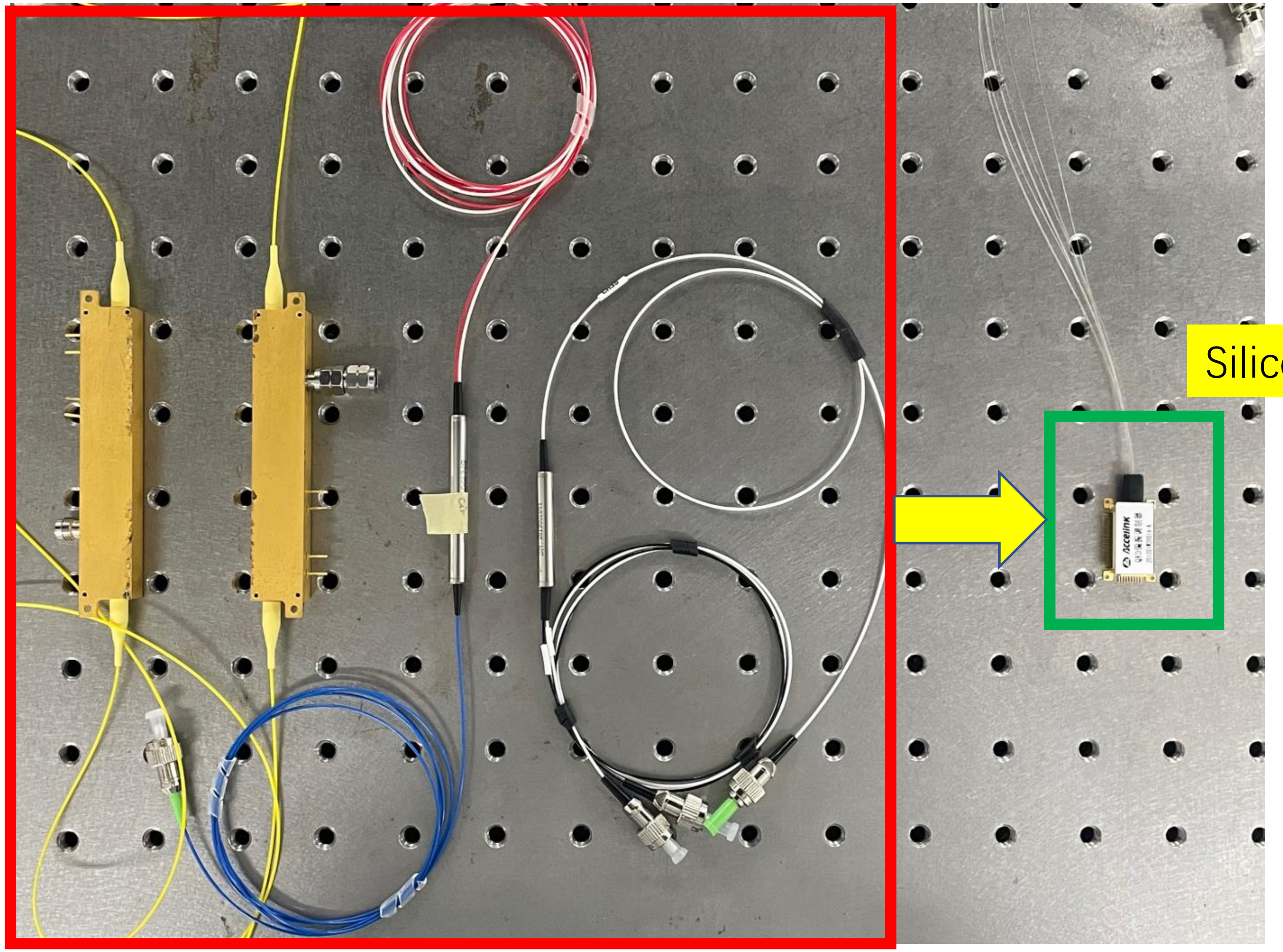
Nature 589, pages214–219 (2021)



Single chip with external single DBF laser

- **Self developed PDK**
- **3dB bandwidth of Carrier Depletion Modulator is 21Ghz**
- **Power consumption of 30mV for Pi-shift on Thermal Optic Modulator**
- **Dynamic ER of intensity modulation close to 20dB@2Ghz**
- **Static ER of intensity modulation close to 30dB**
- **Polarization Extinction Ration 25dB**
- **Can generate polarization state : 0°/90°/45°/-45°/Left circular/Right circular**

Polarization preparation on silicon-photonics - packaged



Silicon based intensity + polarization encoder

Size of the chip: **4.5mm x 2.5mm**

Size of the packaged device:
24.2mm x 15.3mm x 4.9mm

The components needed for polarization preparation with LN modulator and passive components

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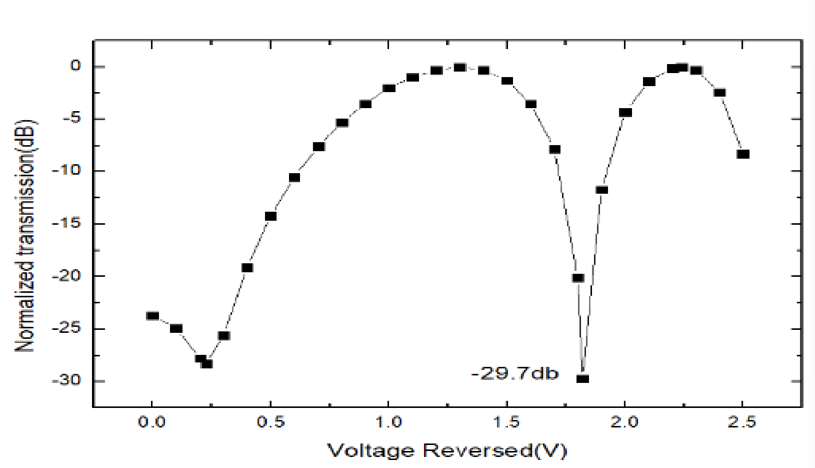
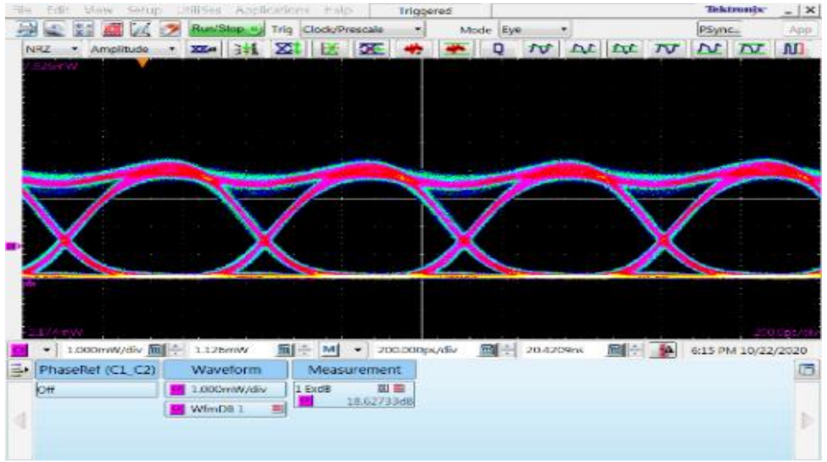
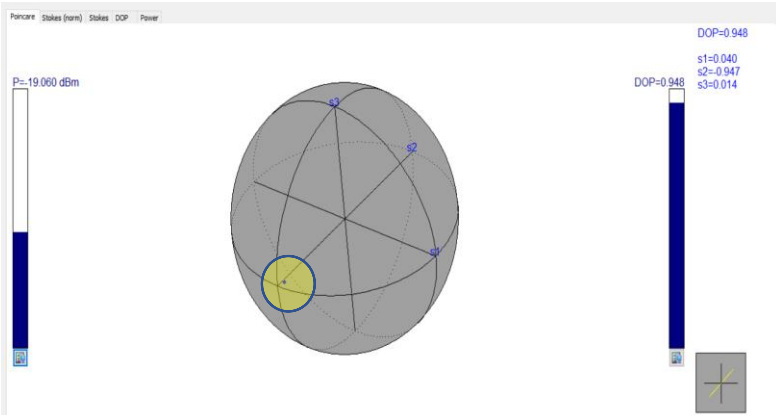
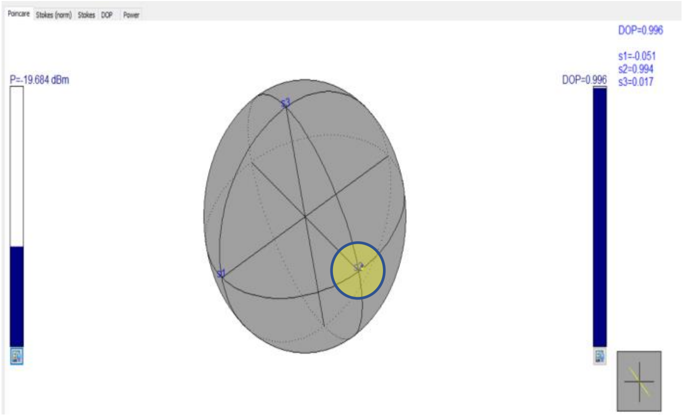
Test results of intensity and polarization modulation

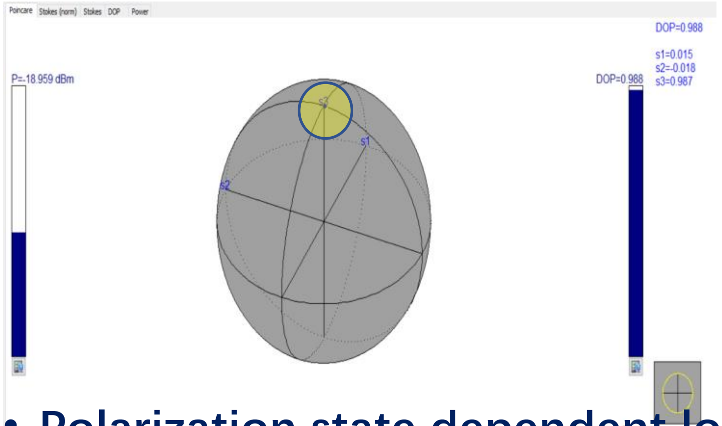


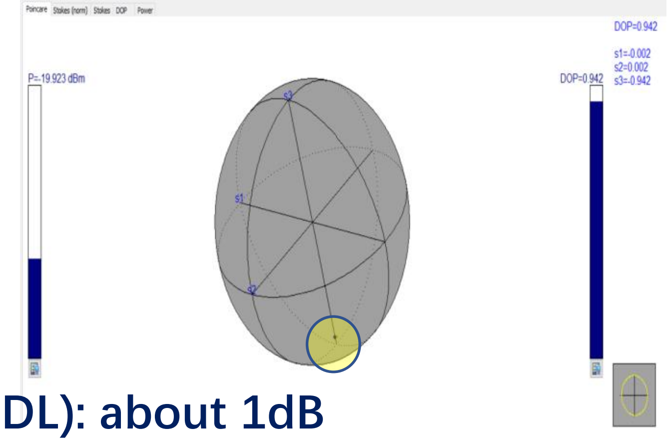


- Dynamic ER : 20dB@2Ghz
- Static ER :30dB





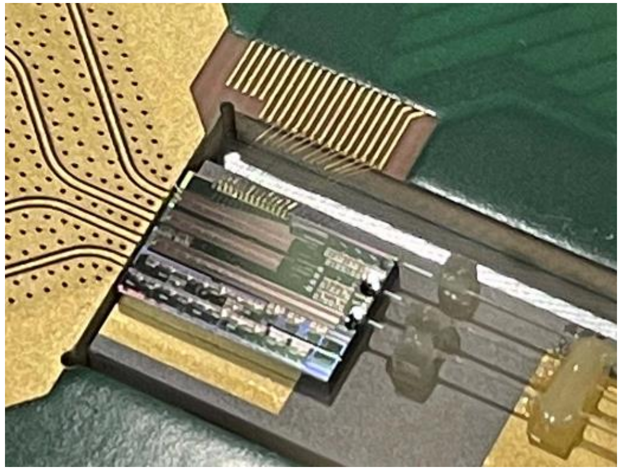




- Polarization state dependent loss(PDL): about 1dB
- Can be post-selected via QKD protocol: PHYSICAL REVIEW A 98, 042324 (2018)

Receiver of DV-QKD Polarization: which part can be implemented on silicon-photonics?

Pol.Controller → Polarization Decoding → Single photon detector x 2~4



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- Self developed PDK
- 3dB bandwidth of Carrier Depletion Modulator is 15Ghz
- Power consumption of 30mV for Pi-shift on Thermal Optic Modulator
- Polarization decoding extinction ratio 22dB
- Active basis choice
- Passive basis choice version under development

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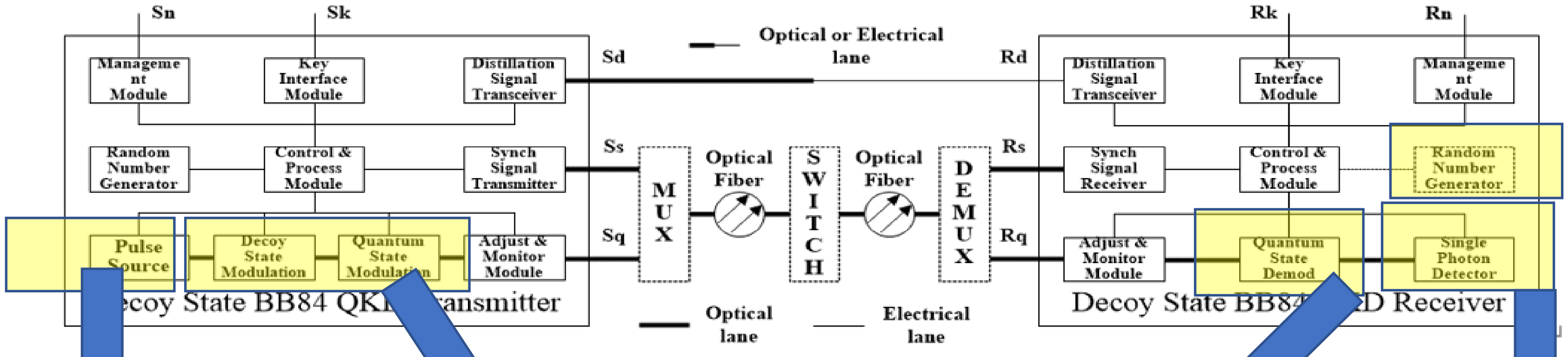
DV-QKD system with Si + III-V solutions



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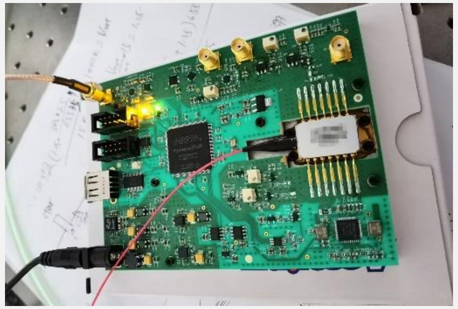
III-V

1550nm pulsed laser



- Max 1.25Ghz
- Pulse width 50ps FWHM
- ER 40db
- Power RMS<3%

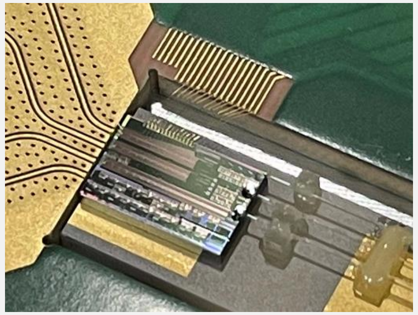
Si

Silicon based encoder

- Intensity + Polarization Modulation

Si

Silicon based decoder



- Active polarization decoding

III-V

Infrared SPD

- 22mm x 13mm x 10mm
- InP/InGaAs APD
- Built-in TEC, -30℃
- 200Mhz
- 20% detection efficicy
- DCR<5e-6, app<5%

III-V

Si

Silicon based ICR

- Integrated MMI and BPD
- Built-in TIA up to 700Mhz
- Shot noise clearance > 10dB

What about CV-QKD with Silicon photonics ?

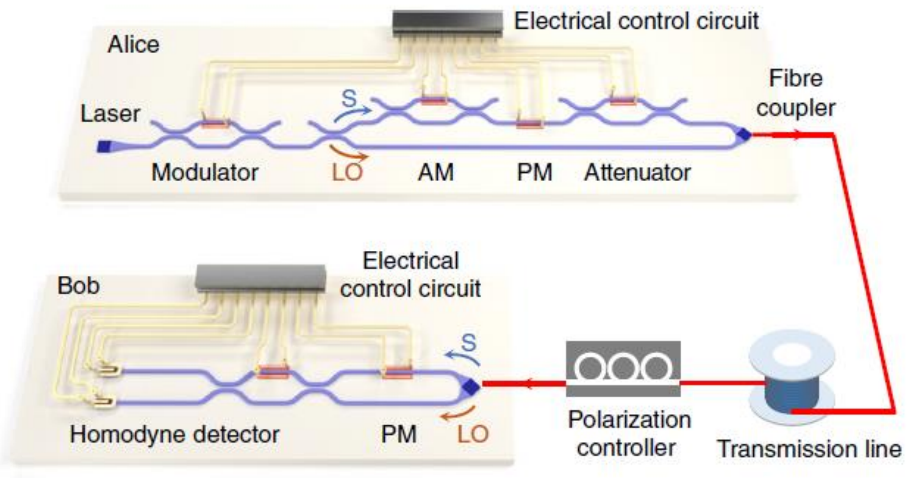
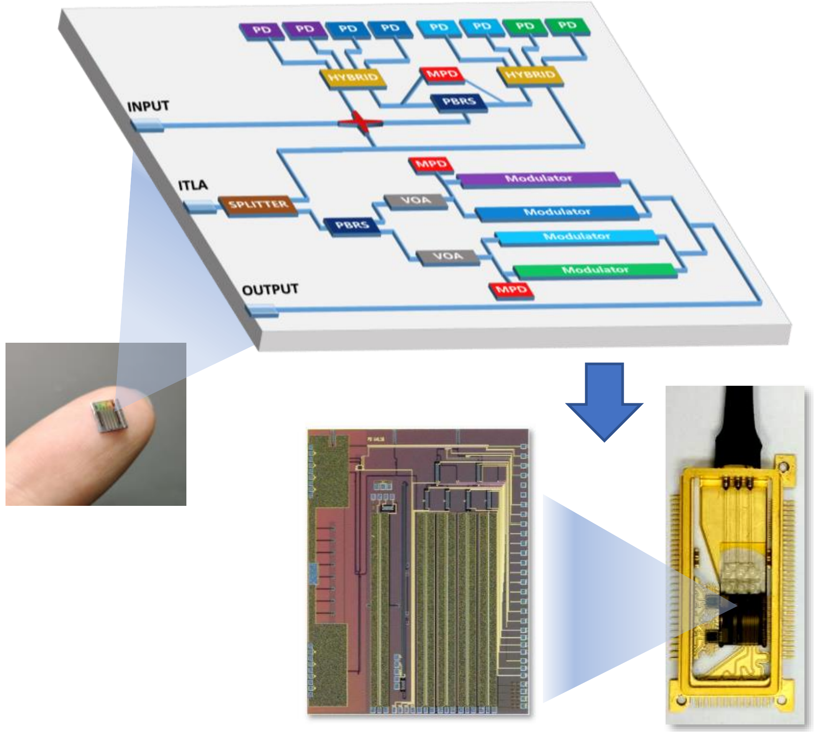


Fig. 1 | Schematic of the CV-QKD system. The system built on silicon photonic chips contains two parties, Alice and Bob, which are used as the transmitter and receiver. Alice's side consists of several AMs, PMs, attenuators and grating couplers, which can modulate the signal (S) and multiplex the signal with the LO in two orthogonal polarization states. Bob demultiplexes and detects the signal with the receiver chip.

Nature Photonics, **13**, pages839–842 (2019)
CV-QKD-TLO on silicon chip
No-use of delay line by side-band modulation
Channel loss tolerant up to 16dB



Size of device 30.7mm x 15.3mm x 3.5mm

Our approach:
Re-use of our commercially successful coherent transceiver silicon chip. CV-QKD-LLO test in progress.

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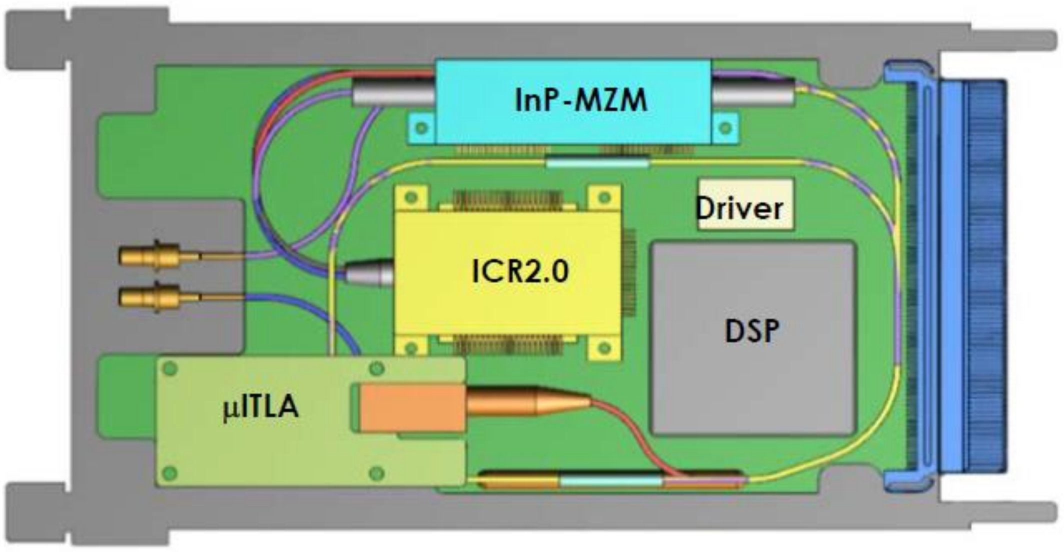
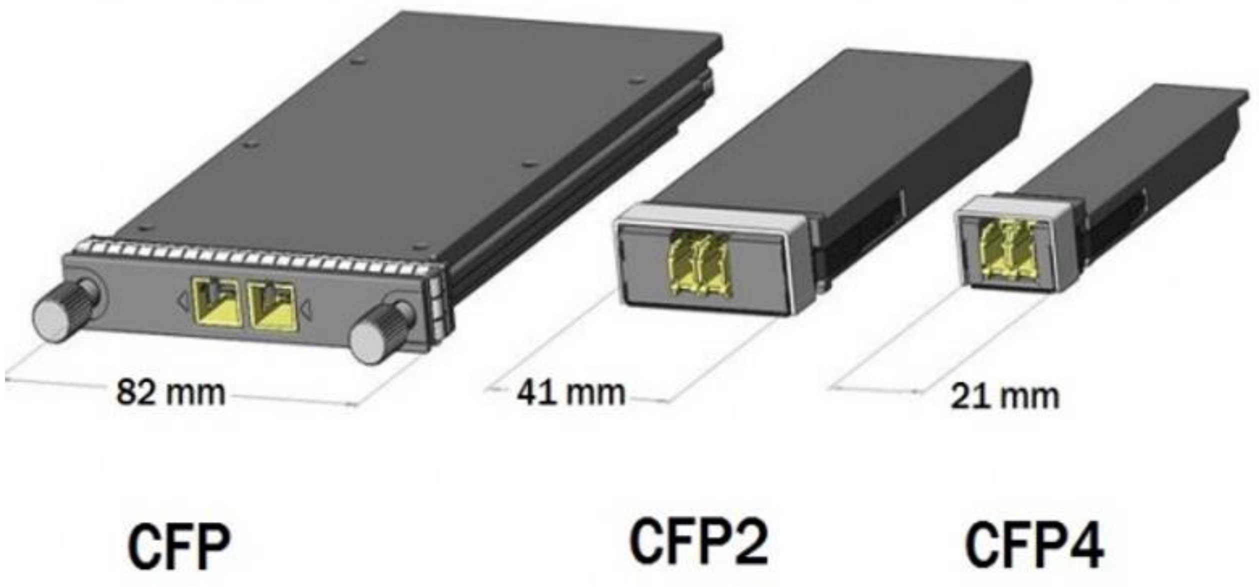
The route towards standardization of QKD module





Reference of coherent transceiver module
82mm x 145mm x 14mm
Source NTT Electronics, OFC 2013

82 x 145 x 14 mm^3   41.5 x 107.5 x 12.4 mm^3   21.5 x 88 x 9.5 mm^3

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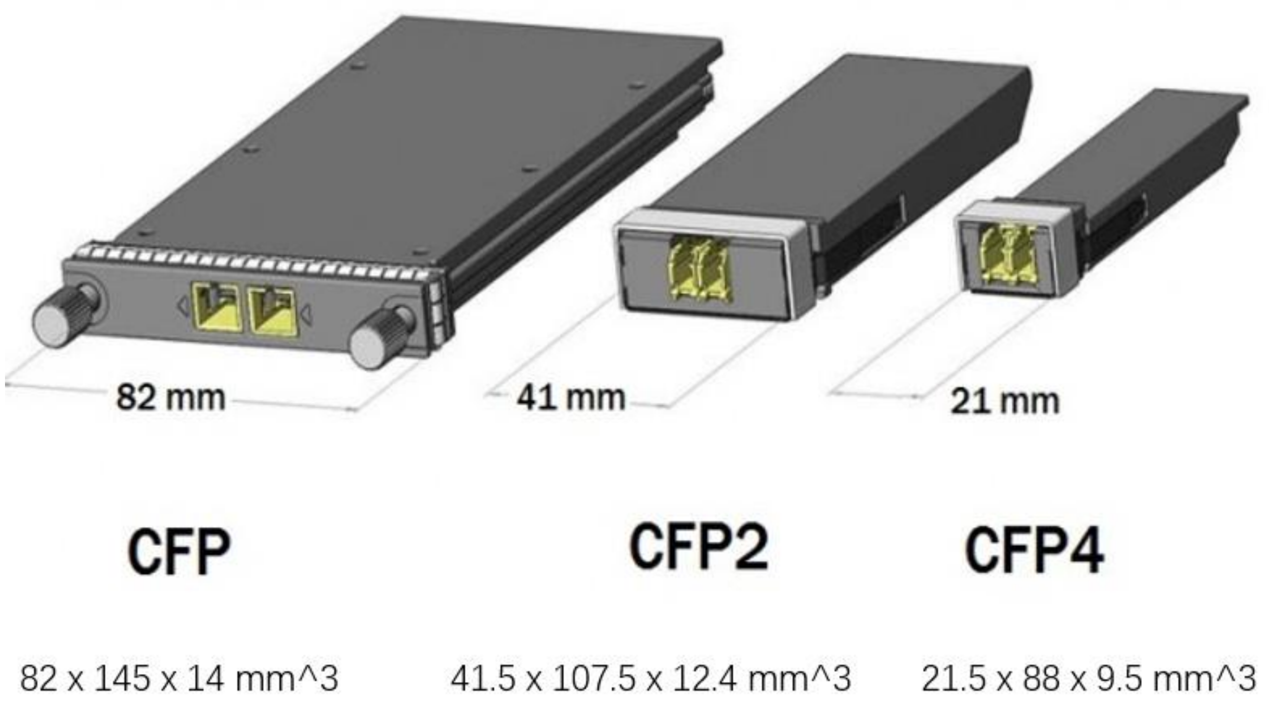
The route towards standardization of QKD module

	DV-QKD Polarization	CV-QKD-LLO
QKD module for transmitter	CFP	CFP2-ACO
QKD module for receiver	CFP	CFP2-ACO
Potential market	• 50km~120km • Dark fiber	• <=50km • Co- existance with data optical communication via DMDM



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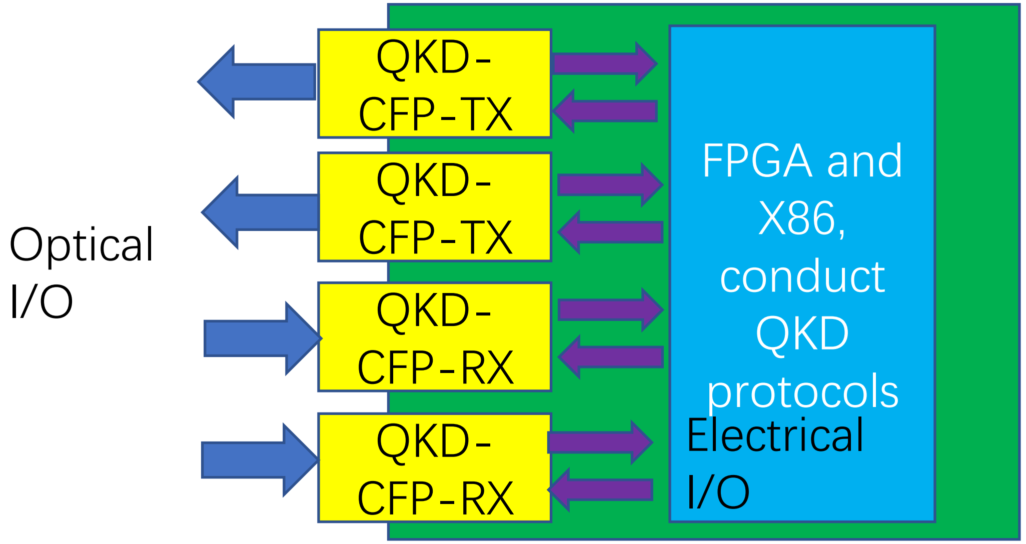

0.5U size QKD blade with pluggable QKD modules. Flexible to construct QKD network or do parallel QKD.

The 1U size QKD box

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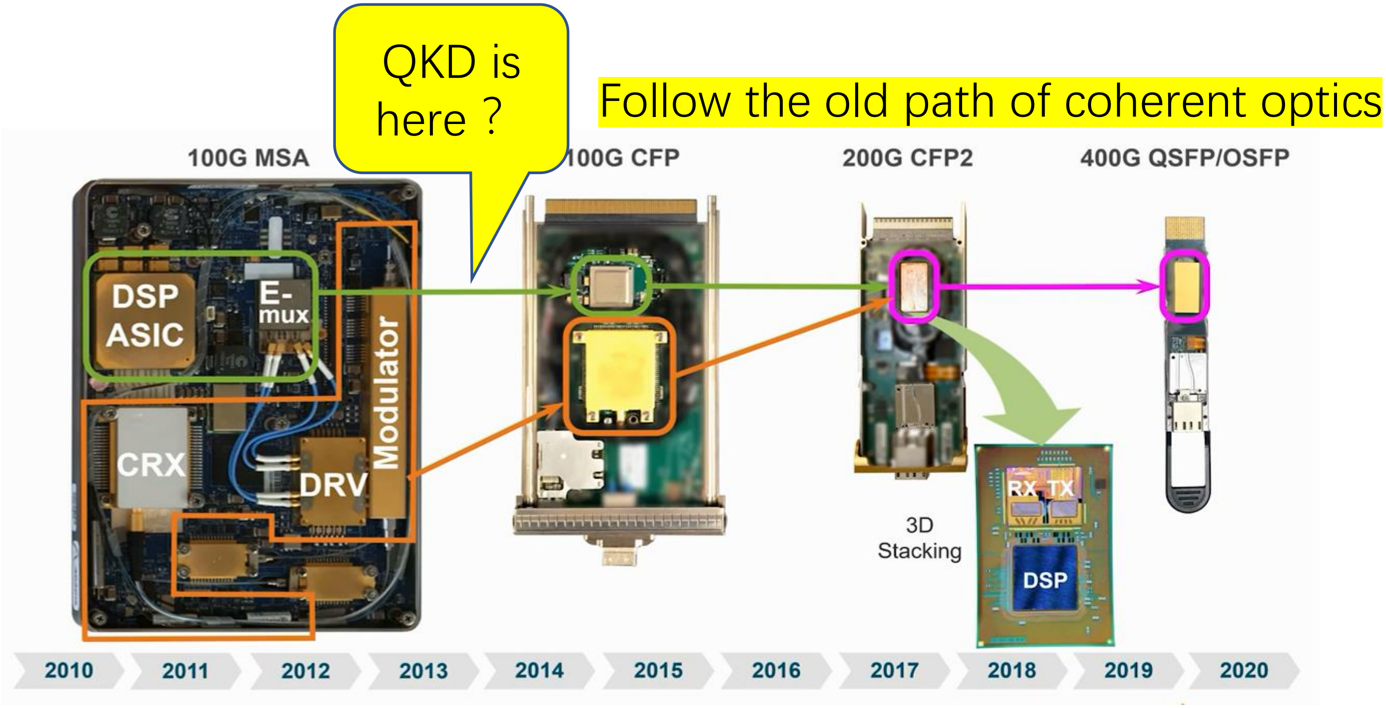
Summary:

- Silicon photonic chip helps to reduce both size and cost of QKD system.
- Silicon photonic chip with compact III-V components makes QKD module possible at CFP size.
- Other materials are also promising candidate for QKD, such as monolithic InP platform, and Si + thin film lithium niobate.



Thanks!