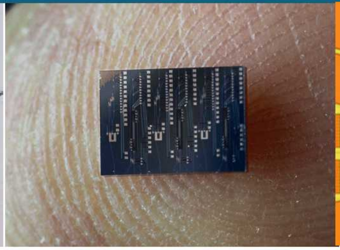
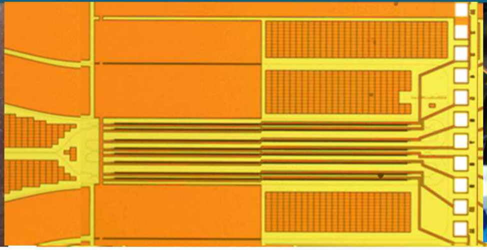
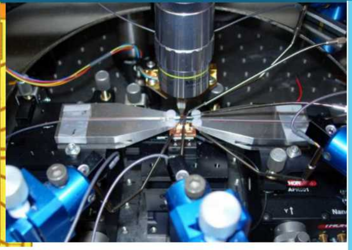
SAND2019-10486C

Enabling Chip-scale Transceivers for QKD Testbeds







Presented by

Junji Urayama

Sandia National Laboratories, Albuquerque, NM, USA

SPIE Security and Defense, September 9-12 2019

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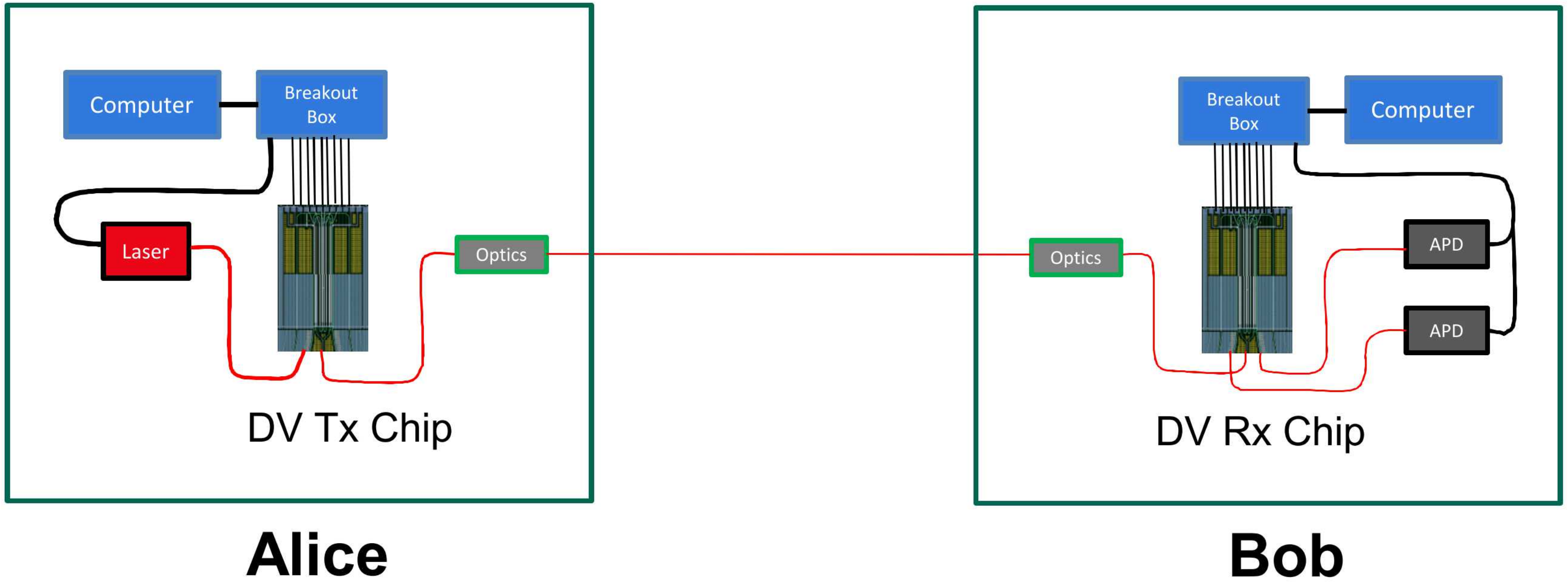
Outline



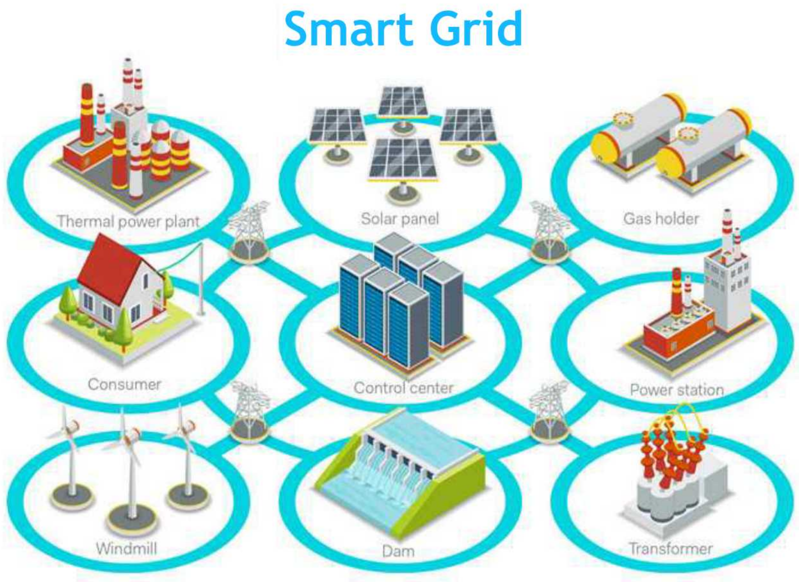
- Introduction/Motivation
- On-Chip Encoder/Decoder Devices for QKD
- Chip-to-chip QKD Test Results
- Metro-Scale Testbed

Motivation: Driving QKD Applications through Miniaturization

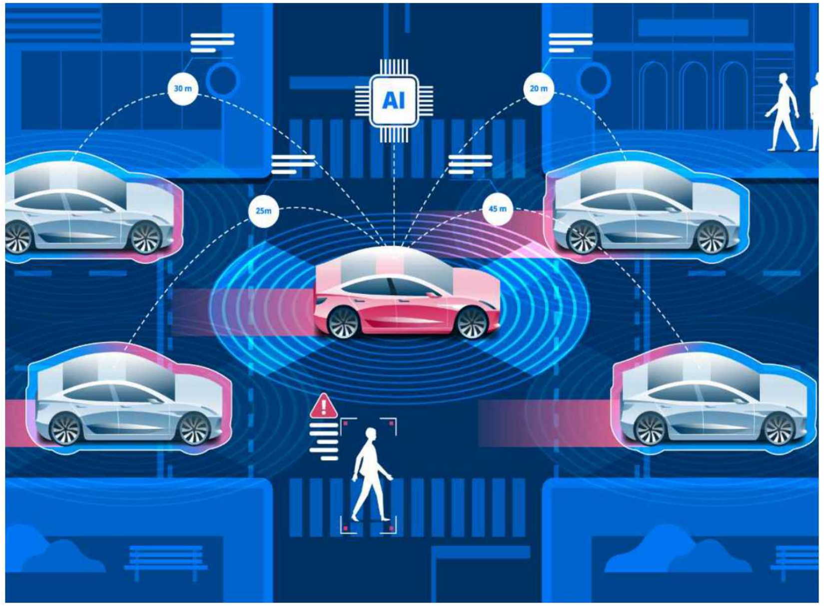
Size, Weight and Power + Cost for Secure Communication

Defense

Security



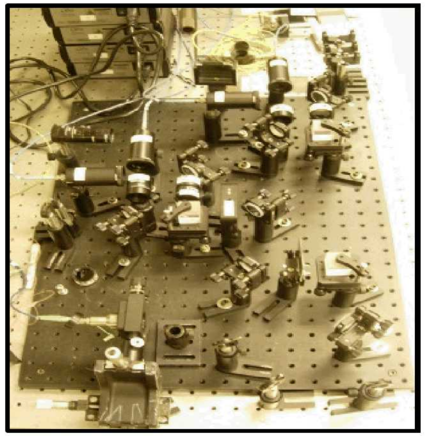
Safety



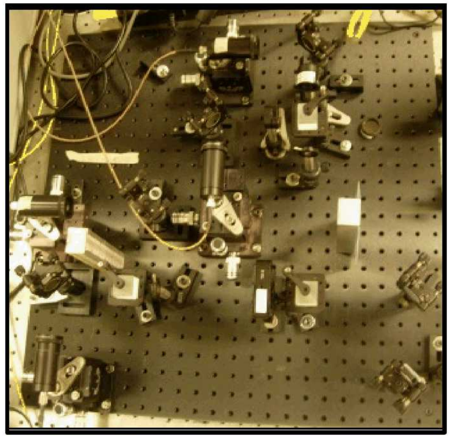
Many mobile and multi-purpose applications require miniaturization
Widespread adoption, acceptance

Context: SECANT QKD Program

Alice

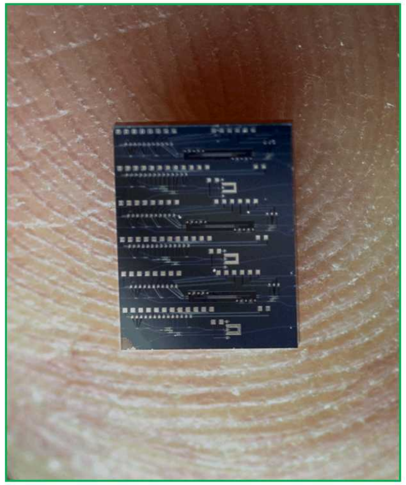


Bob



Miniaturization

Implementation of chipscale devices in working links

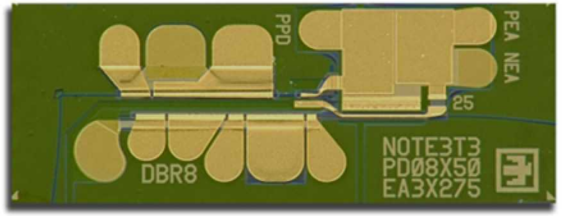


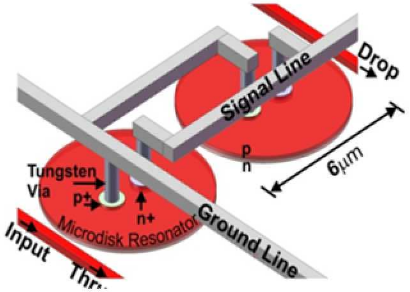
Bridge SiP technology to application space

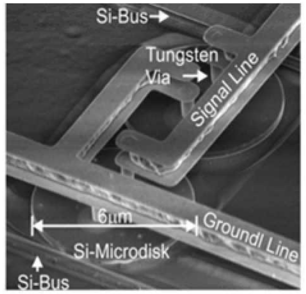
P. Sibson, C. Erven, M. Godfrey, S. Miki, T. Yamashita, M. Fujiwara, M. Sasaki, H. Terai, M. G. Tanner, C. M. Natarajan, R. H. Hadfield, J. L. O'Brien, and M. G. Thompson, “Chip-based Quantum Key Distribution," ArXiv e-prints, Sept. 2015.

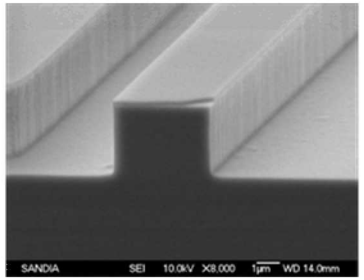
C. Ma, W. D. Sacher, Z. Tang, J. C. Mikkelsen, Y. Yang, F. Xu, H.-K. Lo, and J. K. S. Poon. “Integrated silicon photonic transmitter for polarization-encoded quantum key distribution,” ArXiv e-prints, June 2016.

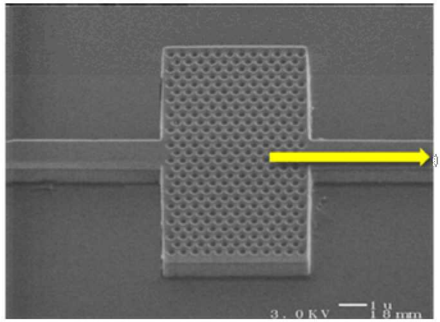
Sandia's Fab Capabilities for Si Photonics and III-V Platforms

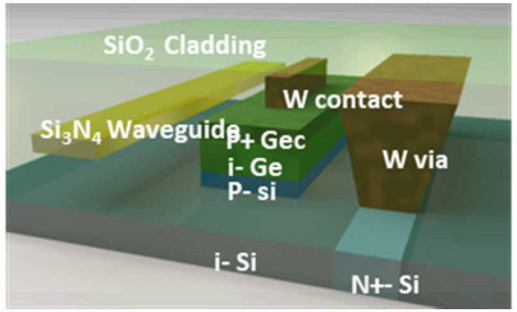




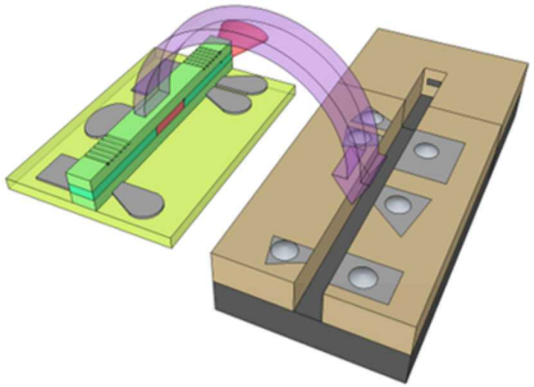








Lock and Key

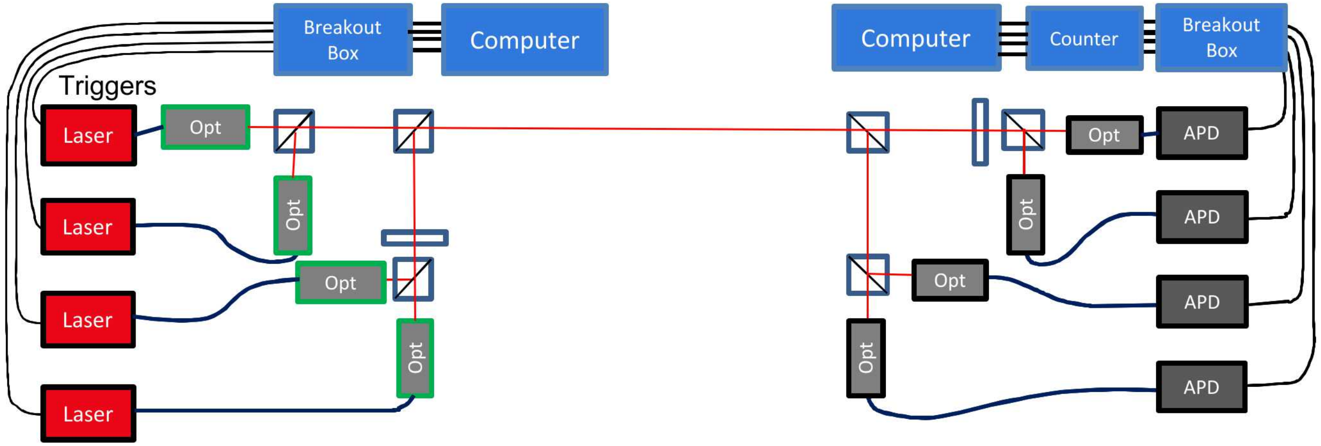


- Silico
- Silicon actives (modulators, switches, tuning devices)
- Vertical junctions for efficient devices
- Passive waveguides
- Grating and edge coupling
- Polarization beam splitters
- SiN to Si transitions and crossings
- Directional, Adiabatic couplers

- Ring filters
- Mode filters
- Mach-Zehnder modulators
  - Thermal, EO, traveling wave
- Micro-disk modulators
- Disk modulator and ring filter silicon thermal tuning elements
- Germanium detectors

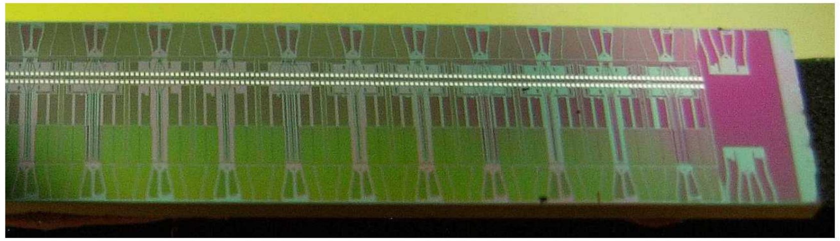
Enabling On-Chip Discrete-Variable QKD

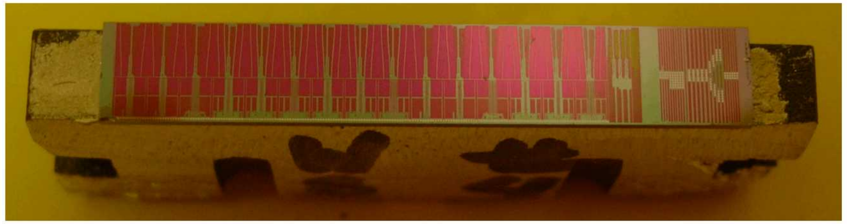
Standard BB84 DV-QKD setup with polarization encoding



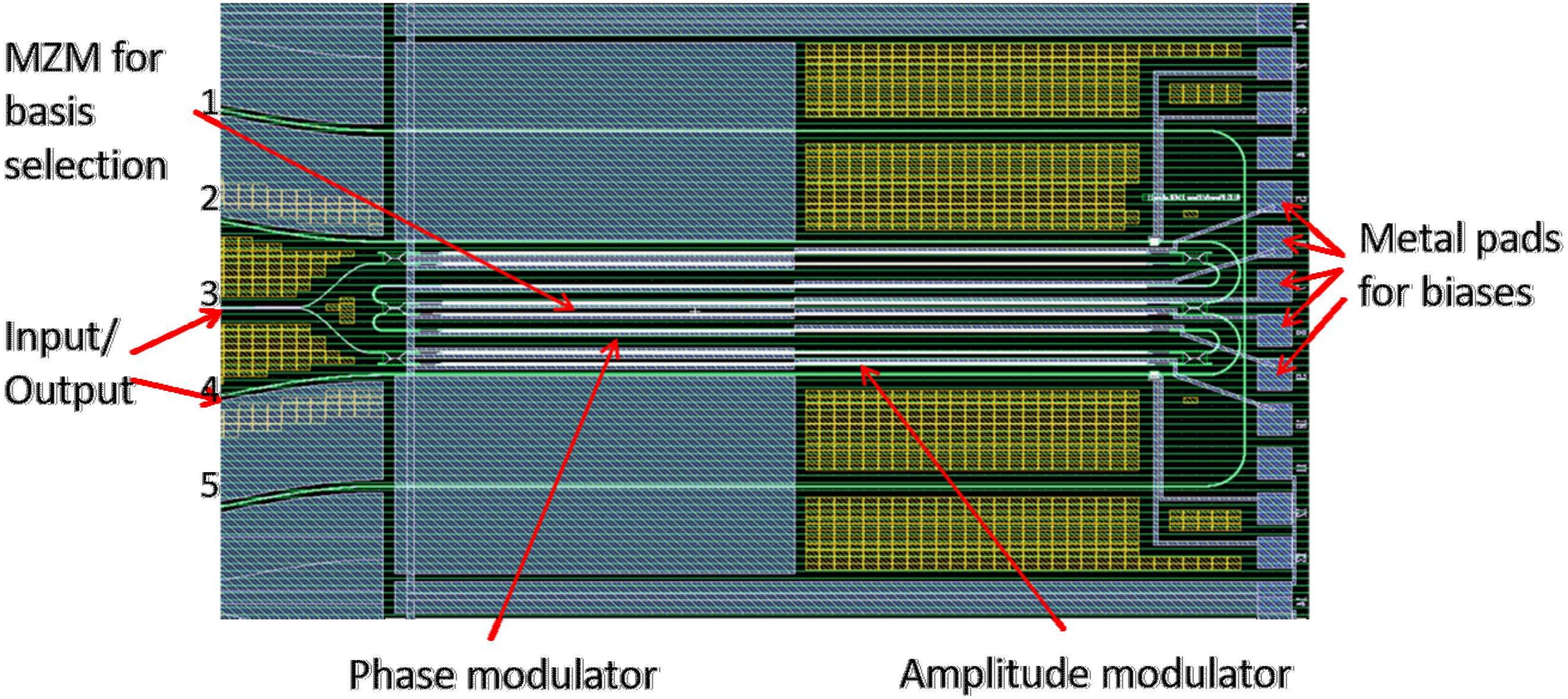
Free-space, bulk encoder components
- Amplitude and phase modulators
- Polarization controllers
- Beam splitters and combiners
- Spatial mode controllers
- Channel

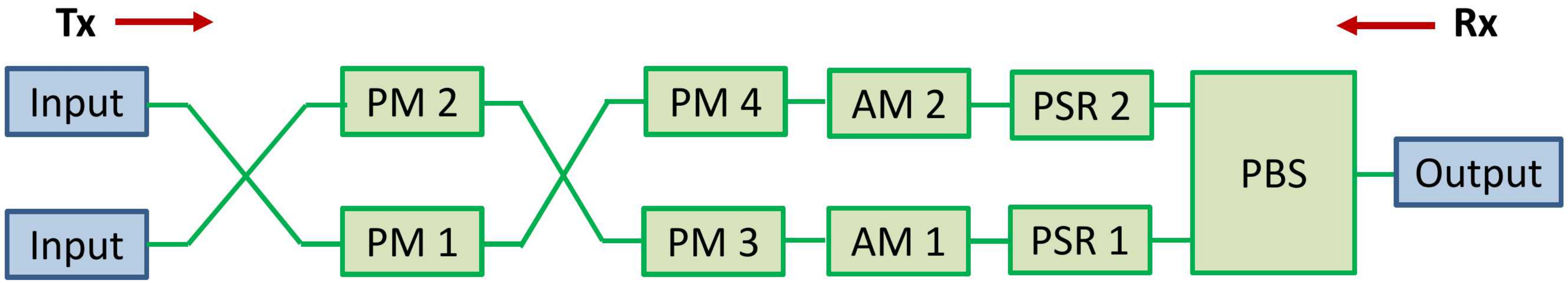
On-chip encoder components
- Mach-Zehnder modulators
- Polarization beam splitters
- Couplers
- Grating and edge couplers
- Waveguides





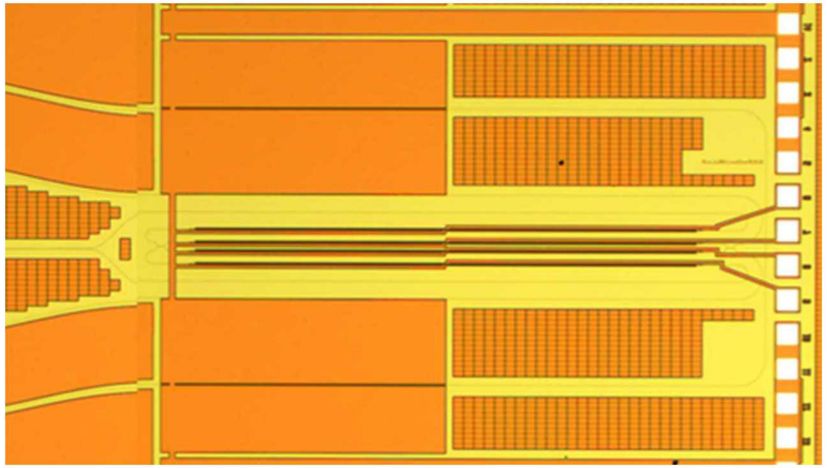
DV Encoder/Decoder Chip: Layout and Components

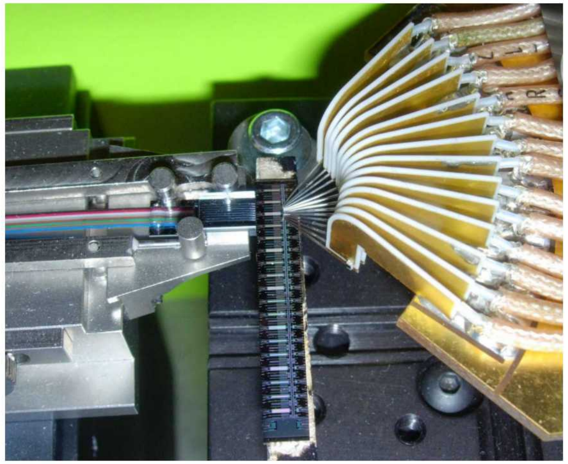




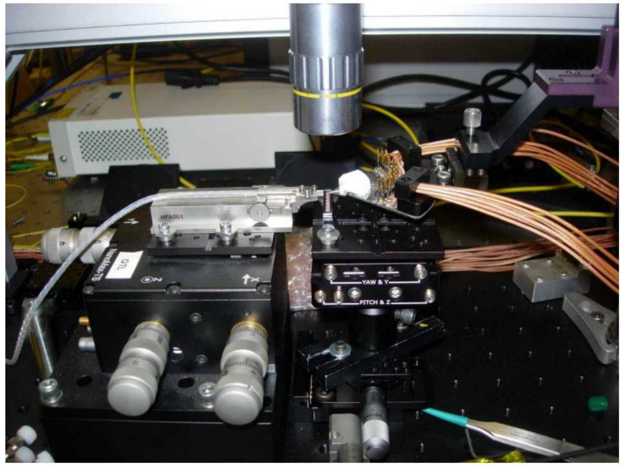
DV Chip Characterization Setup

Device Characterization
- Losses
- Stokes Parameters
- Modulation rates

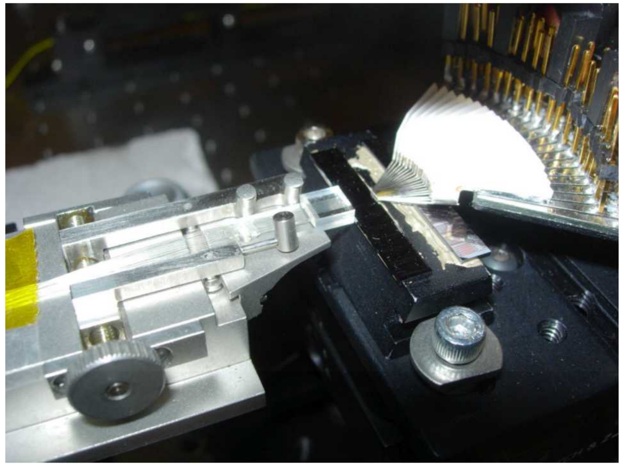




Mounted chip for Alice

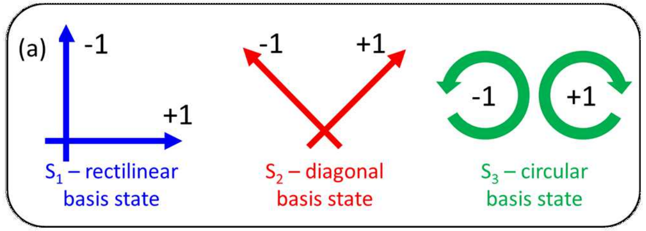


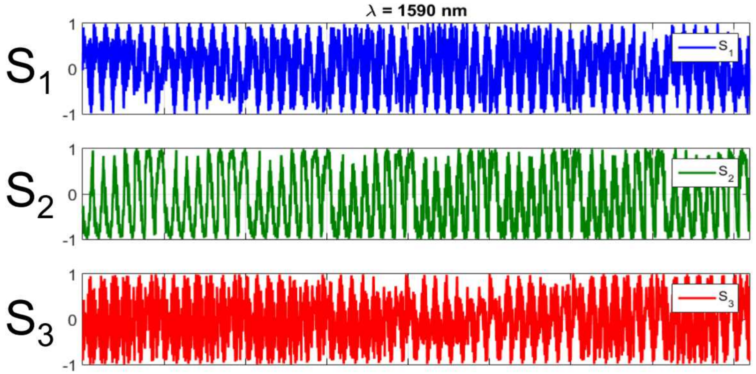
Probe station



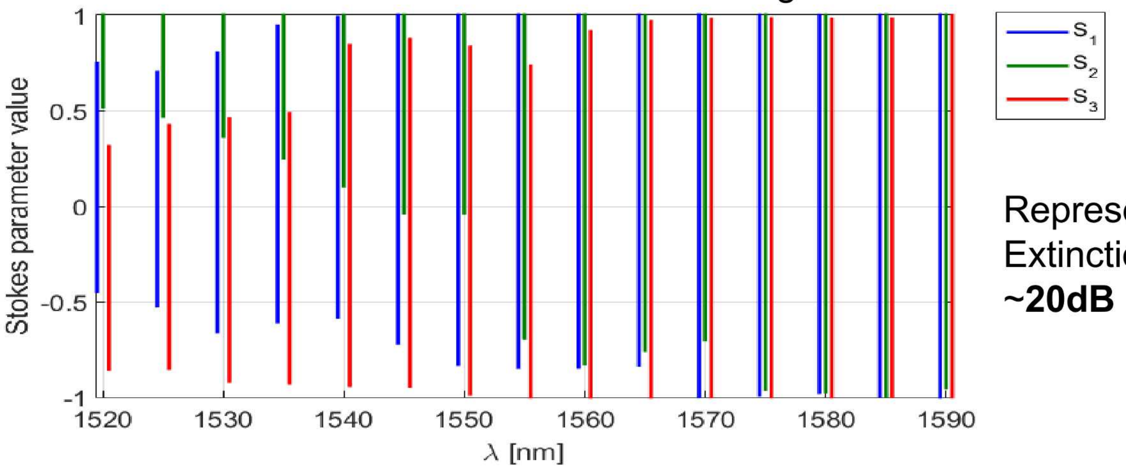
Mounted chip for Bob

DV Transmitter: Polarization Control and Accessible States





Stokes Parameters with Wavelength

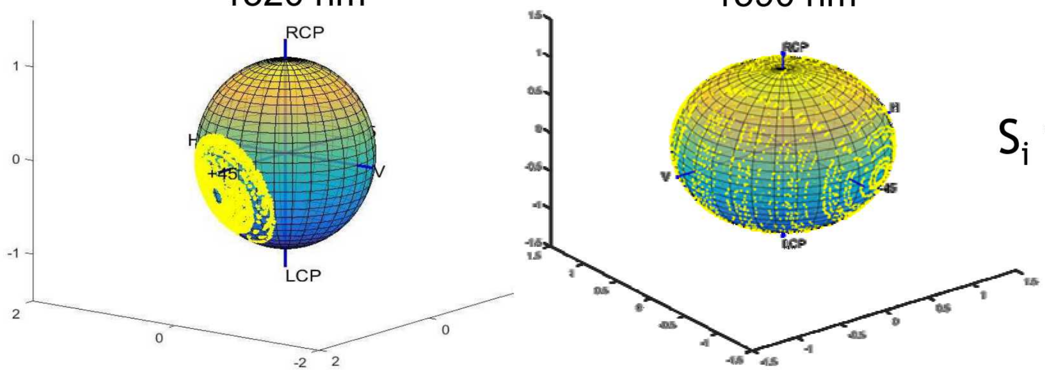


Reference

Measurements on Polarimeter

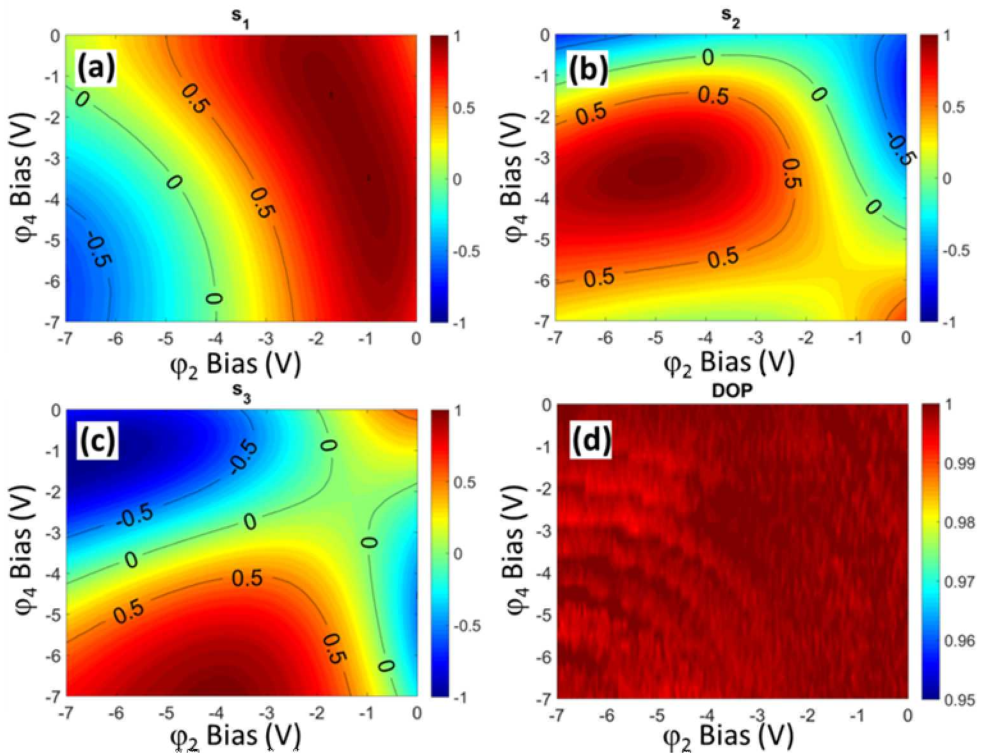
1520 nm

1590 nm

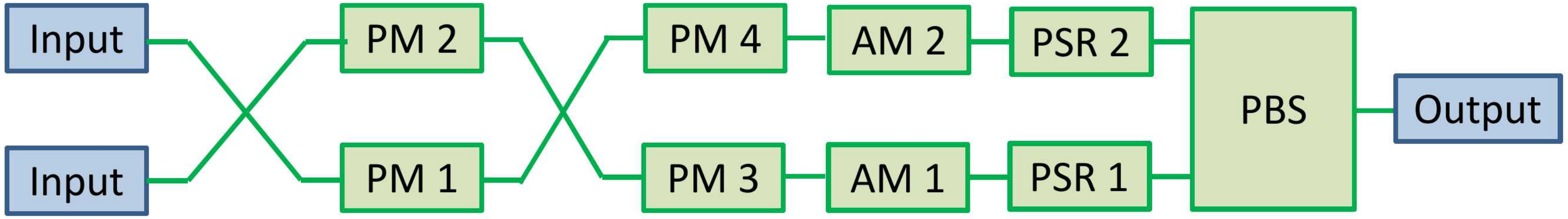


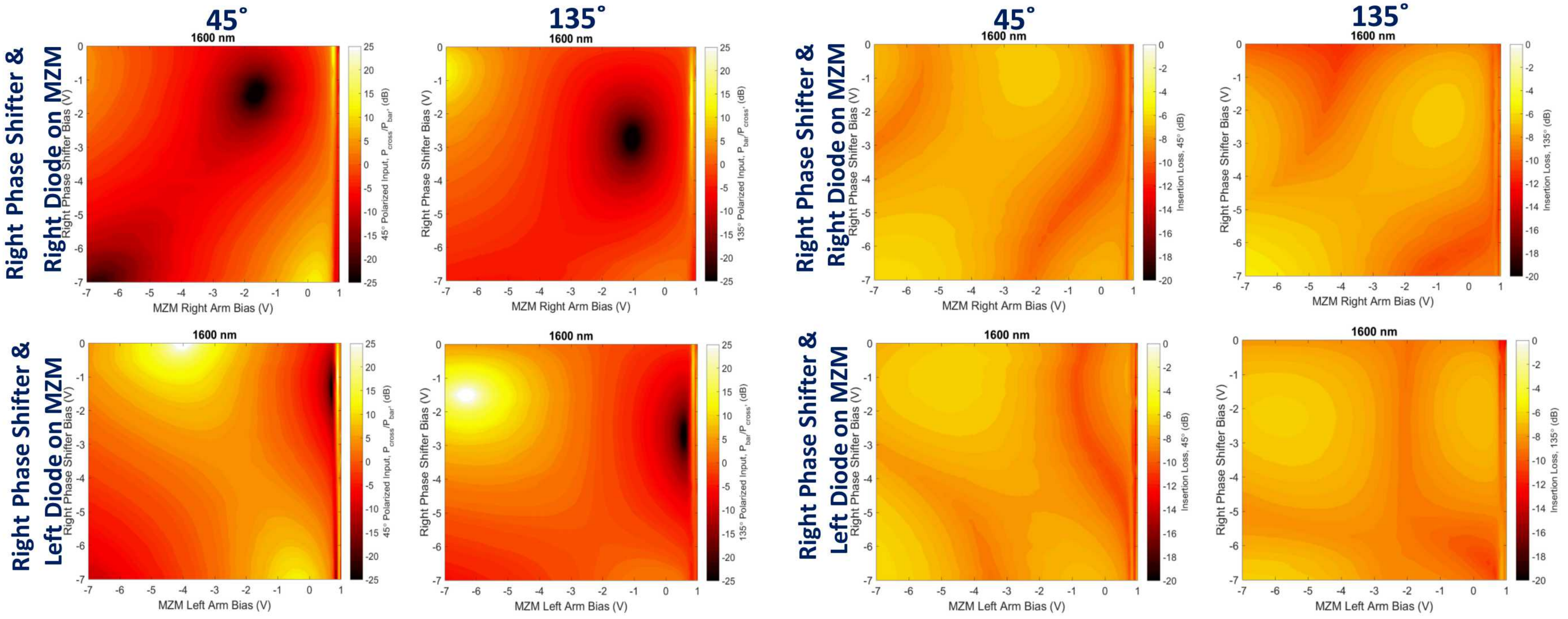
S_i ~ 0.99

Representative Extinction Ratio: **~20dB**



DV Receiver Mapping for Basis and Polarization Control

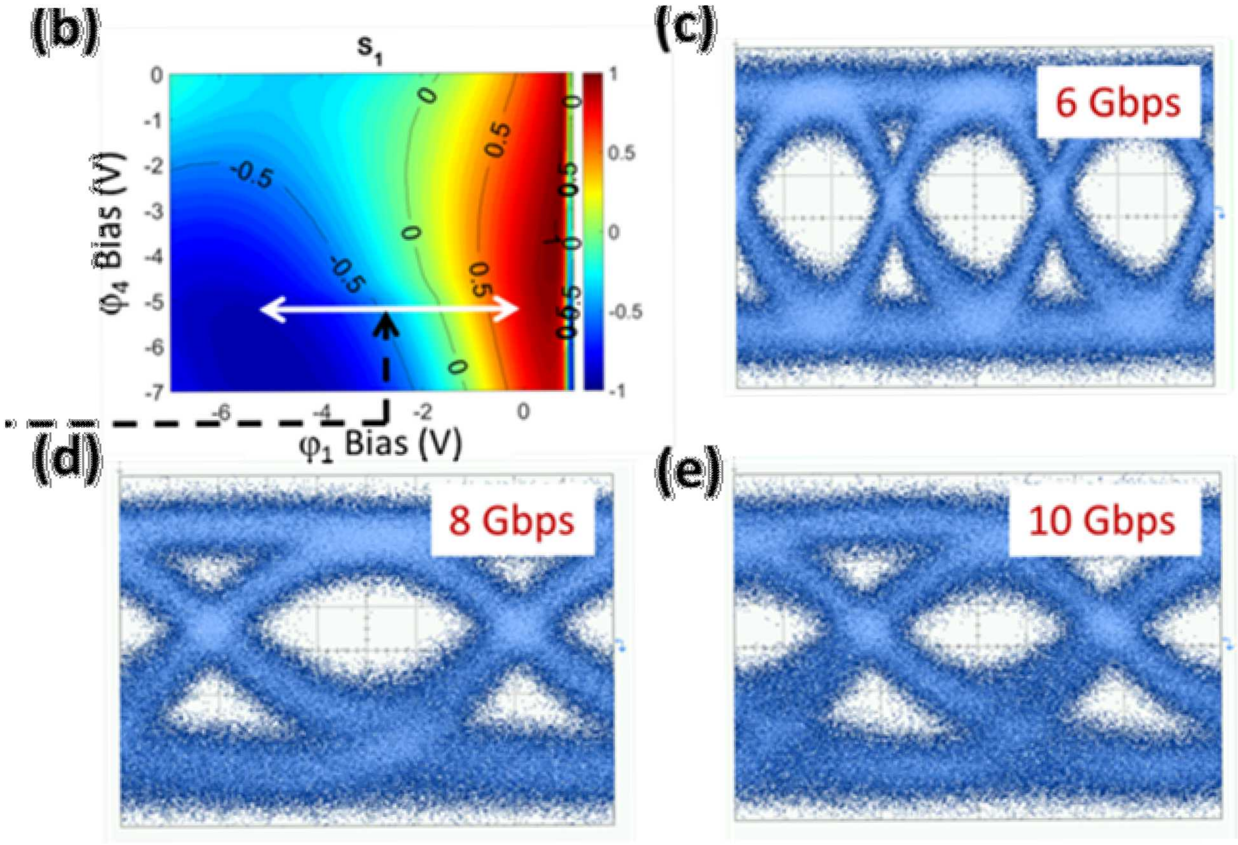




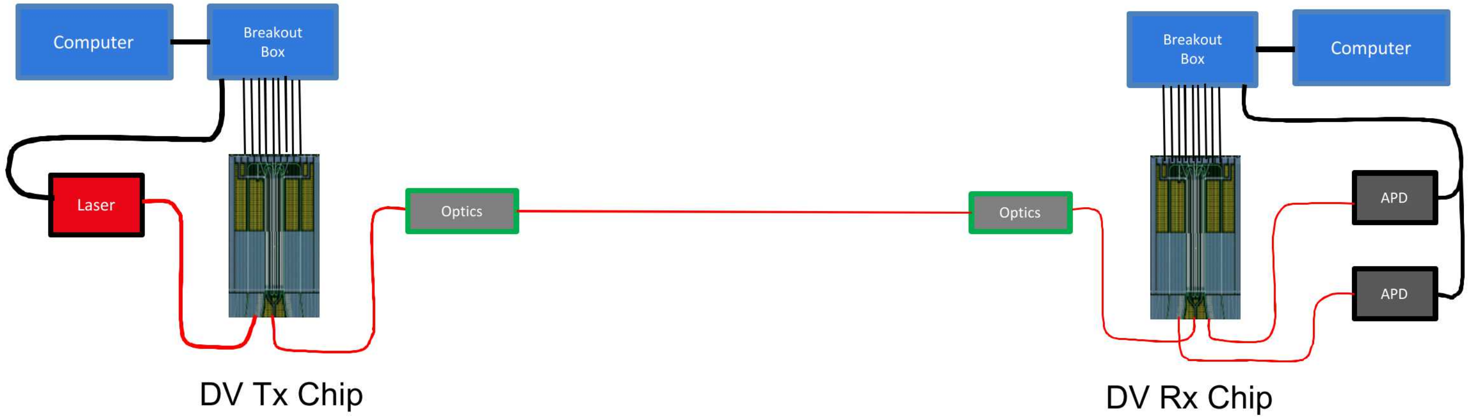
Polarization	Optimal ER (dB)	Optimal operational ER of polarization basis (dB)	F2F loss at optimal operational ER setting (dB)
TE	30.9	20.7	20.7
TM	35.3		18.2
45˚	31.0	20.5	19.2
135˚	31.9		19.4

Tabulation of AM and PM settings for Desired Encoding/Decoding

DV Chip Modulation Characteristics



DV Chip-to-Chip Assembly and Testing



Key pieces:

Alice side
1. Pulse generation
2. Modulator Calibration
   a. EO AM, PM
   b. Wavelength dependence
   c. LUT development

Bob side
1. Modulator Calibration
   a. EO Analyzer
   b. Wavelength dep.
2. Losses: ~20 dB

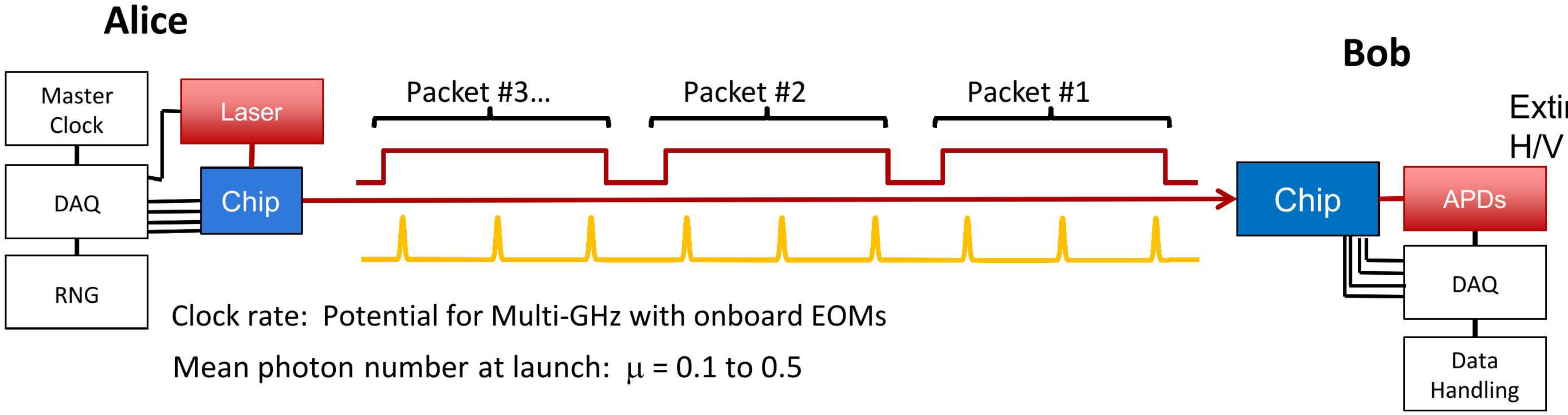
Integration for QKD
1. DAQ/Timing/Synchronization
   a. AM/PM control
   b. Detection timing
   c. Processing

- Polarizations established with **Stokes parameters of 0.99** for BB84
- Polarization **extinction ratio at Bob ~20 dB** at 1585 nm

Challenges:
- **Losses**
- **Polarization reference frame setting over link**
- **Acquisition and synchronization at DAQ speeds**
- **QBER**

DV Chip-to-chip Development on Tabletop Testbed

Stokes parameters |S_i| ~ 0.999 for the four states

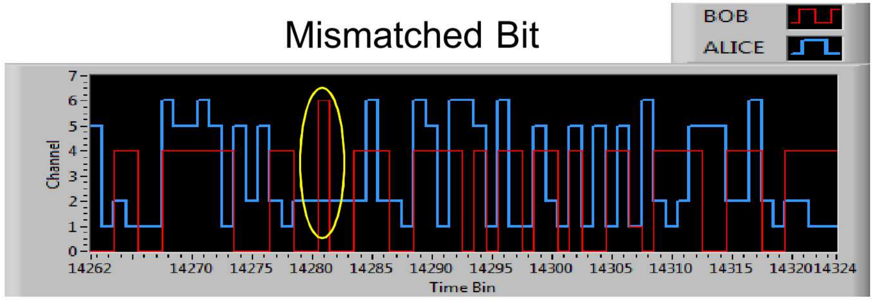


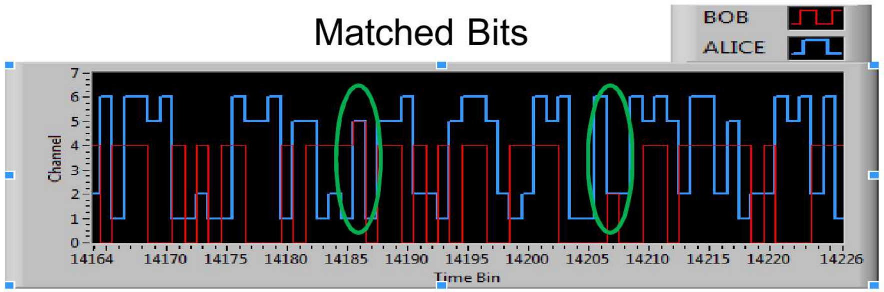
Clock rate: Potential for Multi-GHz with onboard EOMs

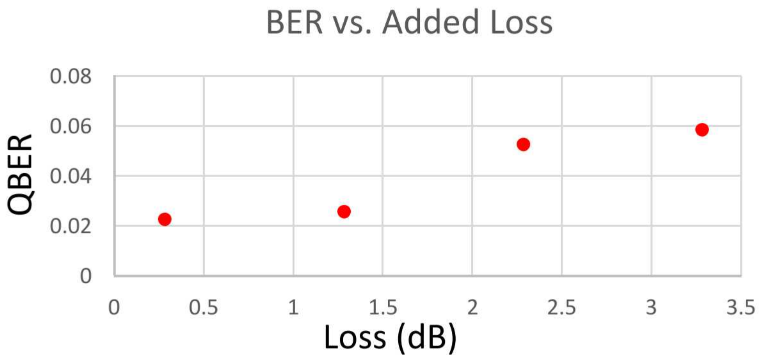
Mean photon number at launch: μ = 0.1 to 0.5

Extinction Ratio for H/V and +45/-45: **20 dB**

Detector Efficiency: 10%







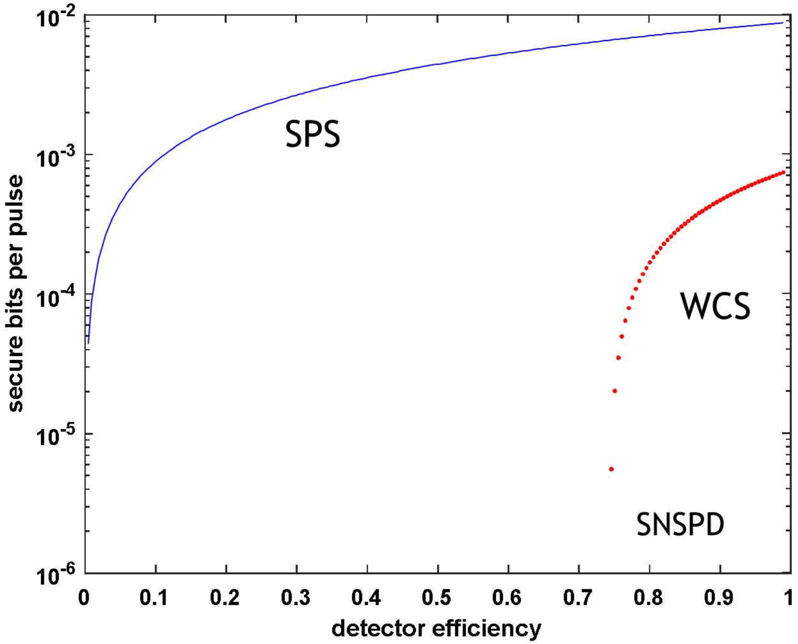
Clock rate: 100 kHz
Raw key rate: ~300 bps
QBER: as low as 1%
Multi-detection rate: ~10^{-6}
ER within basis > 27 dB

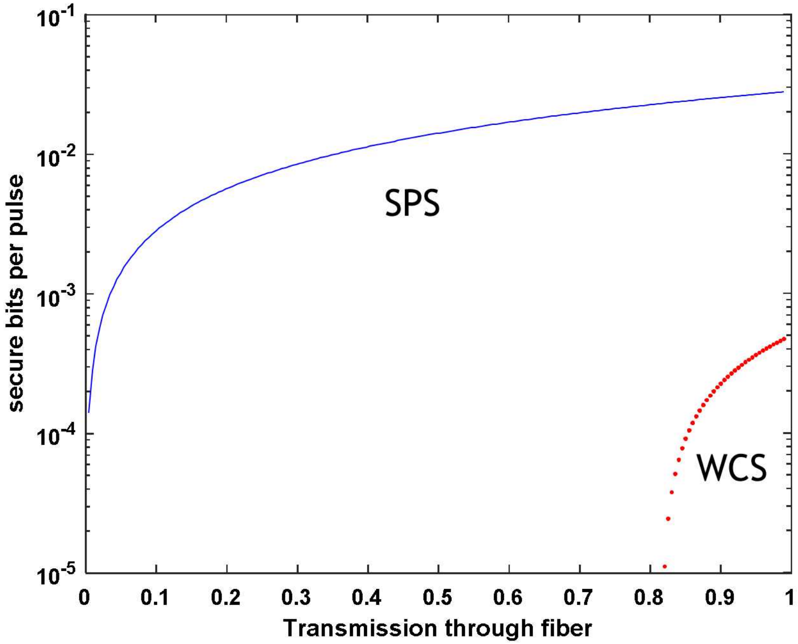
Polarization-dependent fiber-to-fiber loss at Bob:

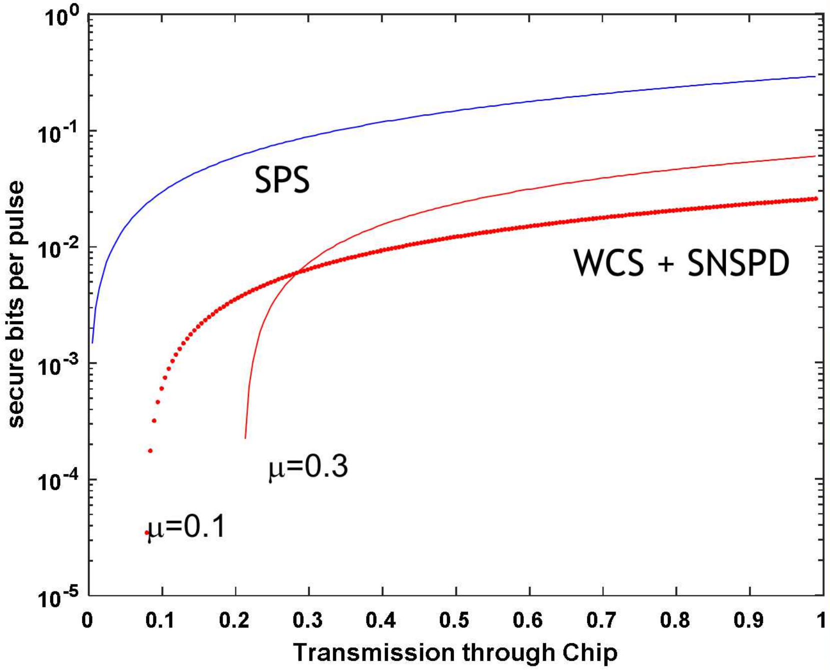
TE: 16.2 dB
TM: 14.7 dB
+45: 16.2 dB
-45: 15.3 dB

Analysis for Key Rate

Individual attack, Asymptotic case







Blue: SPS
QBER = 2%
Chip loss = 16.2 dB
Error corr eff = 1.19

Red: WCS
QBER = 2%
Chip loss = 16.2 dB
μ=0.1
DCR = 2 x 10^{-5}

Blue: SPS
QBER = 2%
Chip loss = 11 dB
Error corr eff = 1.19

Red: WCS
Chip loss = 11 dB
μ=0.1
DCR = 2 x 10^{-5}
DE=0.9 with SNSPD

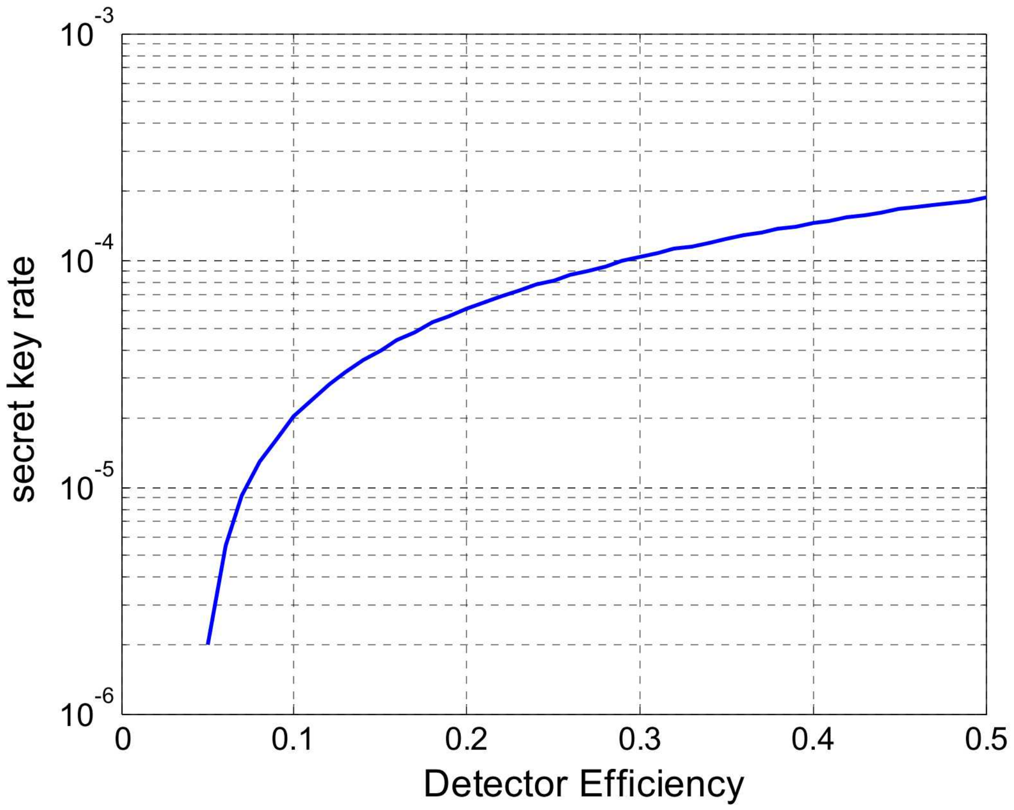
Blue: SPS
QBER = 2%
Error corr eff = 1.19

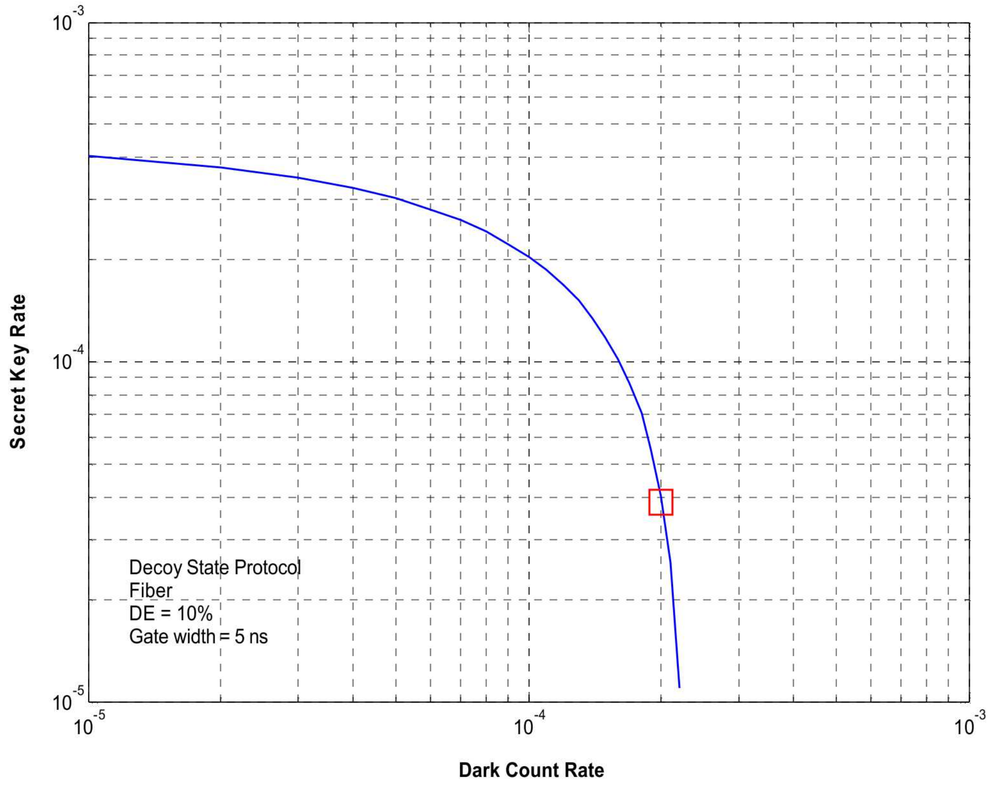
Red: WCS
QBER = 2%
μ=0.1, 0.3
DCR = 2 x 10^{-5}
DE=0.8

Supports fiber transmission of 4.5 km

Key Rate with Decoy State Protocol

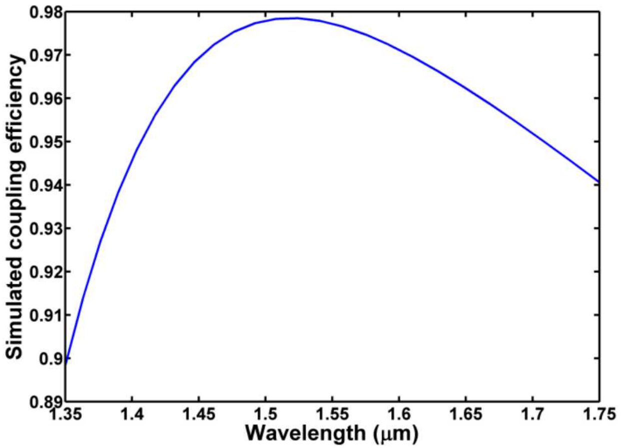
- SPAD Quantum Efficiency
- Dark Count Rate
- Background detection
- Transmission

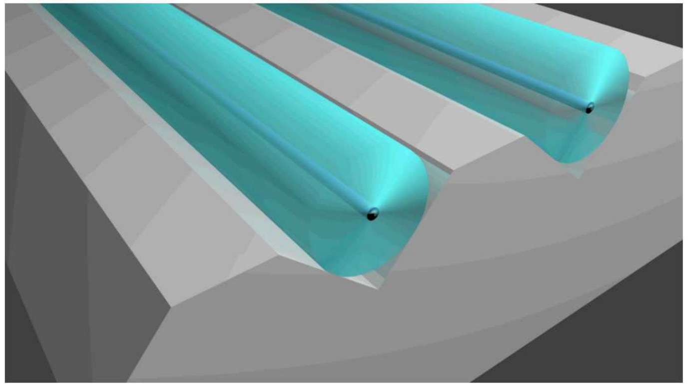




Improvements and Pathforward

- Reduce loss





- High efficiencies approaching 100% with proper mode matching.
- TE and TM can both couple efficiently
- Can couple with Ultra-High NA fiber
- Measurements show less than 0.5 dB loss at facet

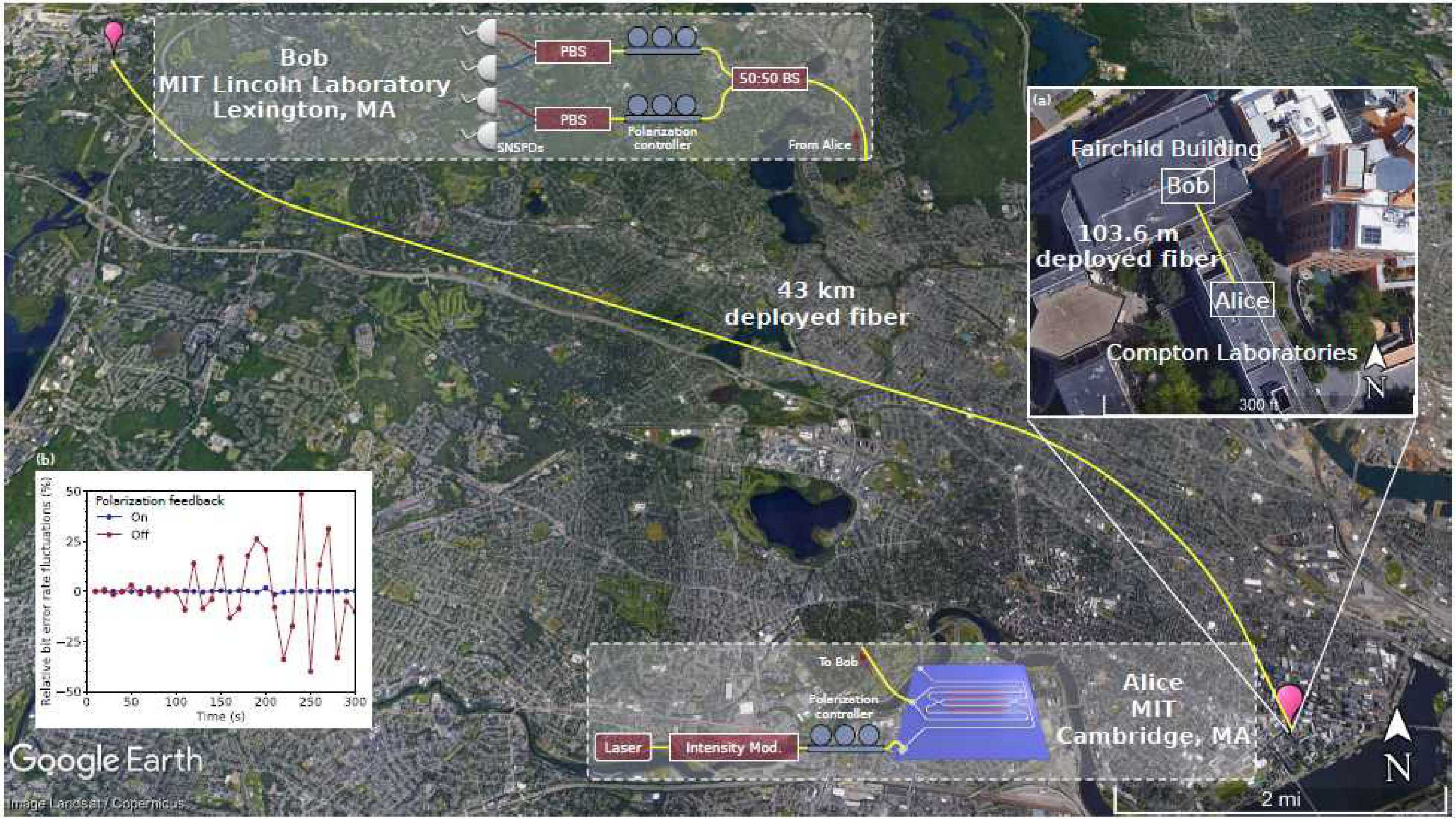
  - Include nitride taper for edge coupling
  - Minimize number and lengths of carrier-depletion modulators

- Implement decoy state protocol

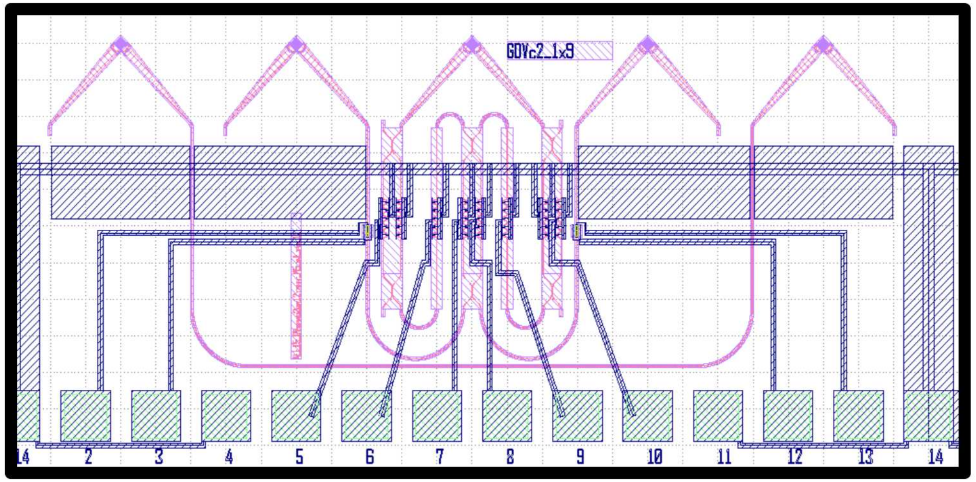
- Increase detection efficiency: SNSPD

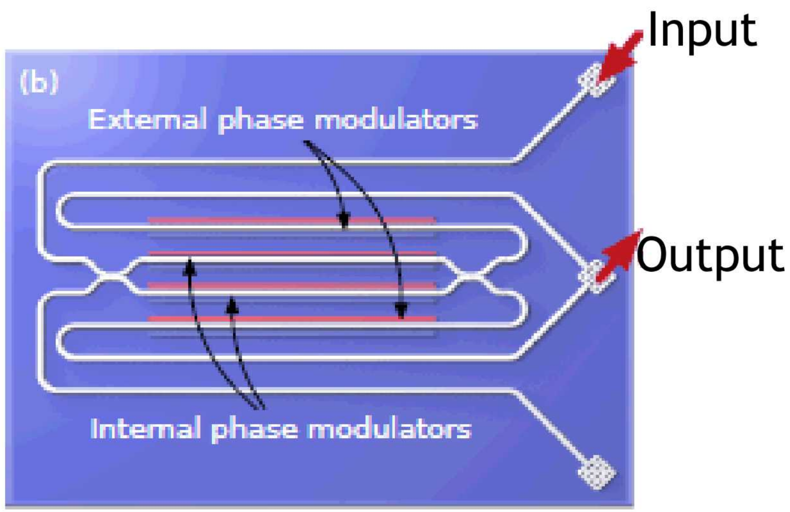
- Implement SPS

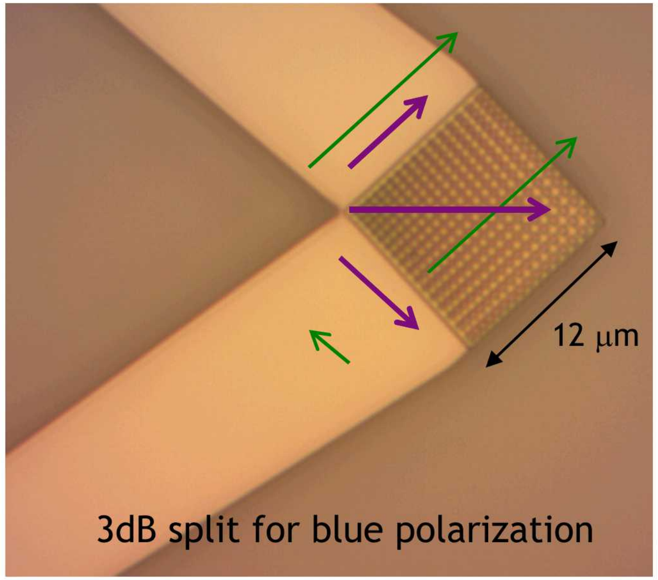
Metro-Scale Testbed

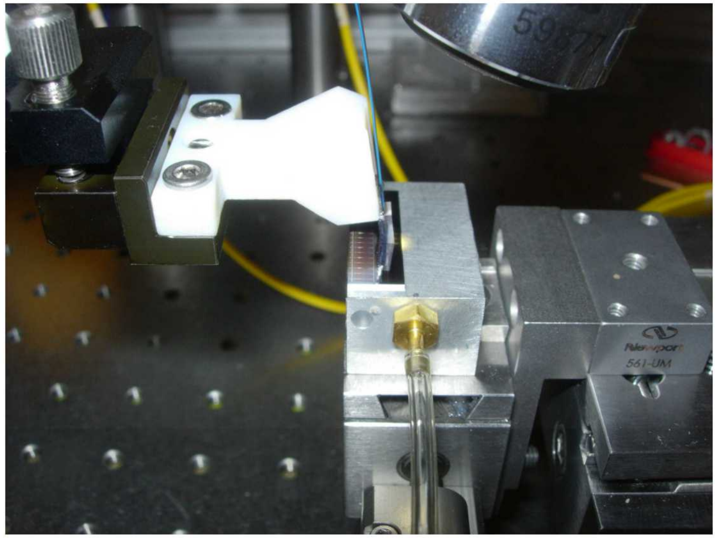


DV Transmitter with Top-down Polarization Grating Coupler

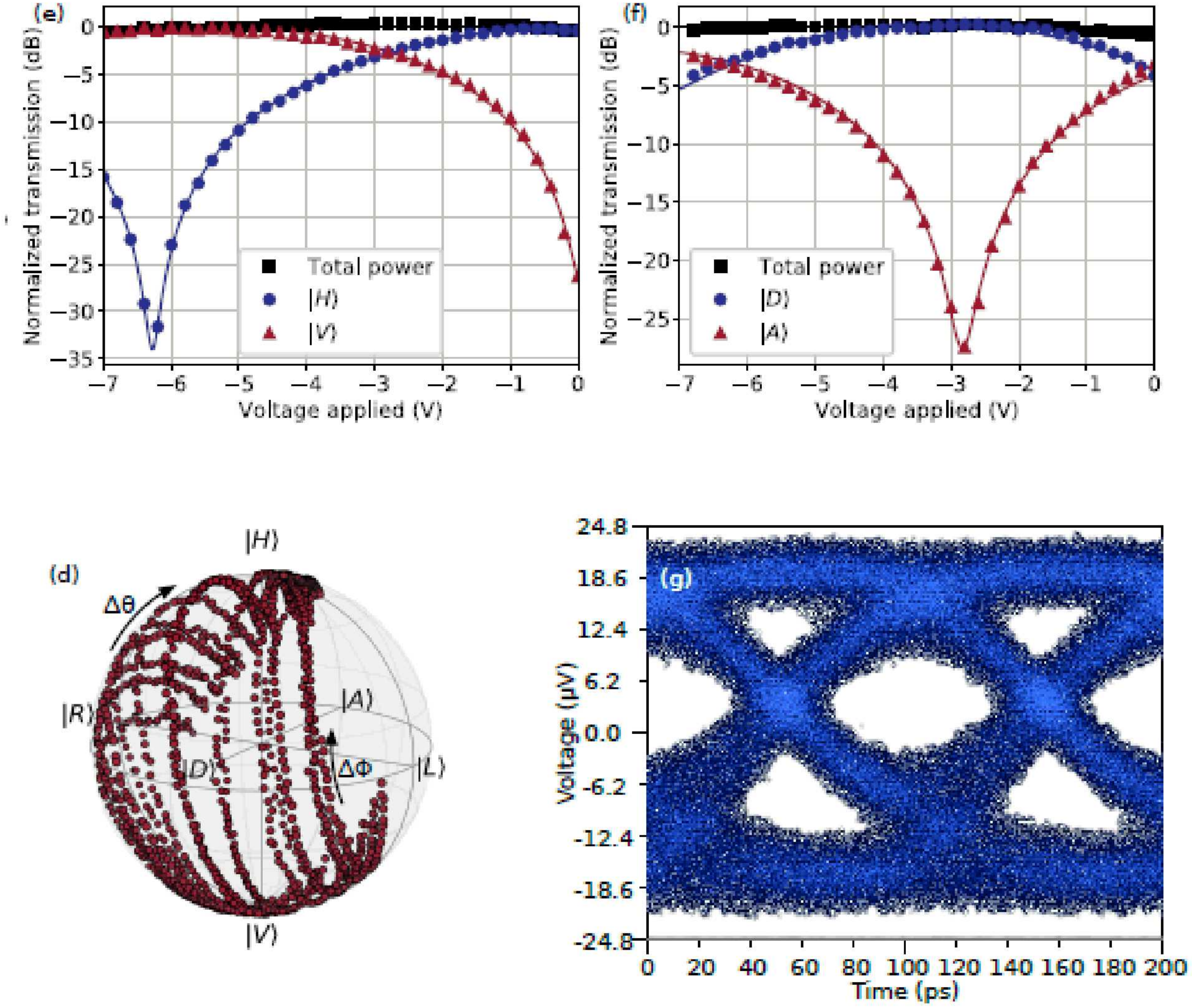








DV Transmitter Characterization

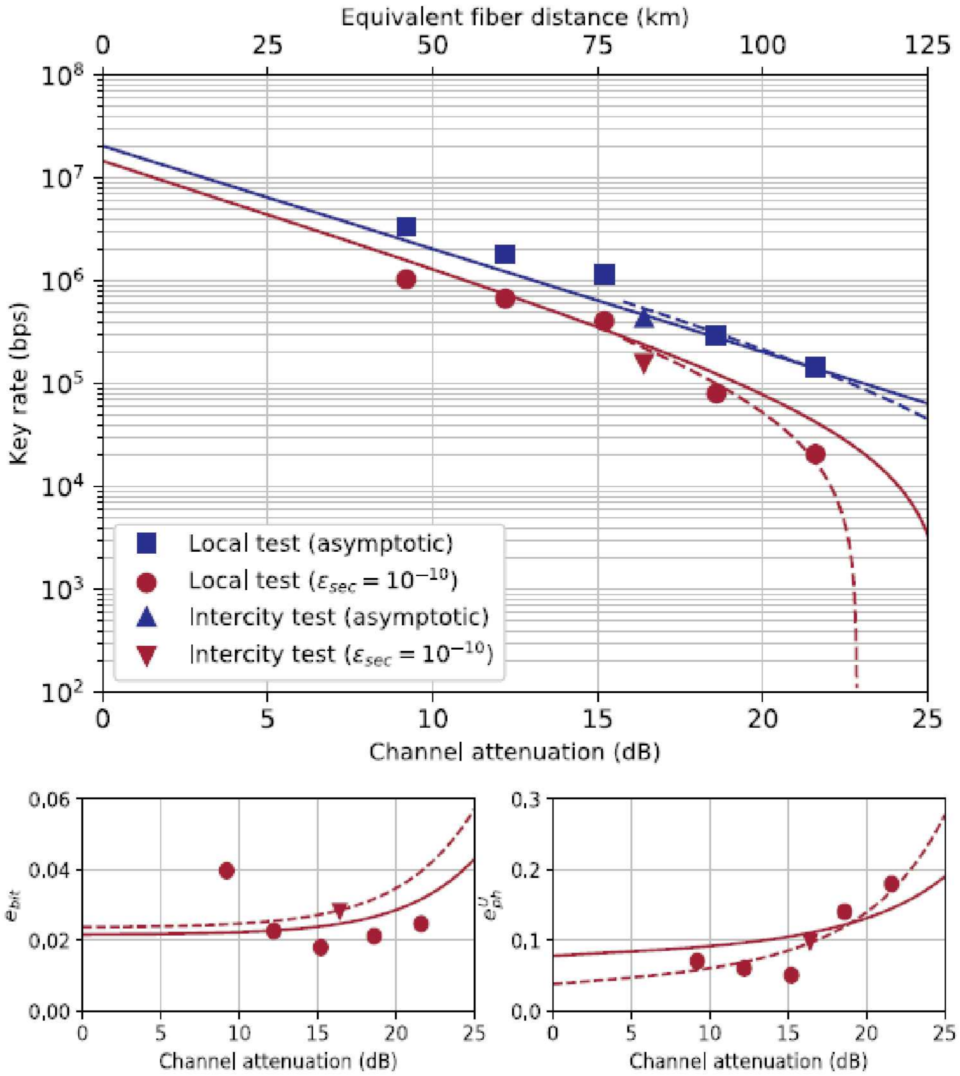


Achieved Key Rates with On-Chip Transmitter

Asymmetric BB84 QKD protocol with decoy states

157 kbps over 43 km fiber

685 kbps at 10 dB loss

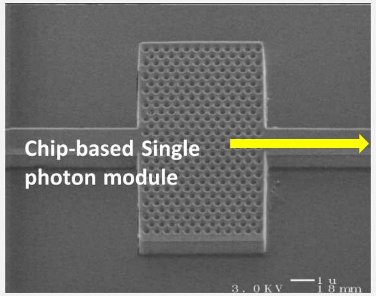


Conclusions

- SiP on-Chip QKD transmitter and receiver designed and characterized
- Tests on chip-to-chip implementation show that receiver losses need to be managed
- Chip-to-chip implementation can be realized with overall efficiency improvement
  - Loss reduction
  - Use of decoy state protocol
  - Use of SNSPD
  - Use of SPS
- Metro-link with on-chip transmitter successfully implemented.

Components of Grand Challenge

Chip-scale single photon sources



YEAR 1

- Electrically pumped, g(2) < 0.1, 2 MHz

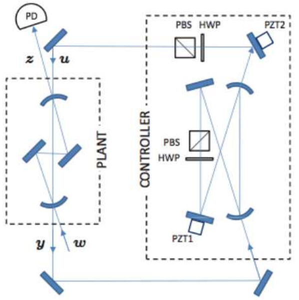
YEAR 2

- +/- 100 nm placement accuracy
- 30% quantum efficiency
- Q > 10^3

YEAR 3

- 50% collection efficiency
- 1 GHz photon rate

Table-top Continuous Variable Sources (Squeezed state source)



YEAR 1

- Design of CQF network and controller

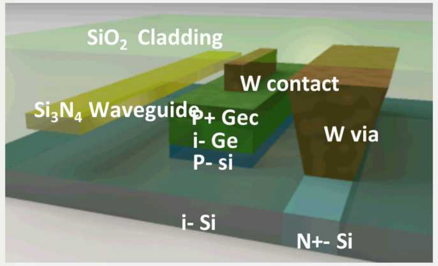
YEAR 2

- CQF controller with 8-10 dB of squeezing

YEAR 3

- 3X distance improvement of CV-QKD
- Design integrated photonics CQF controller

Chip-scale single photon detectors



YEAR 1

- Single 1 GHz APD

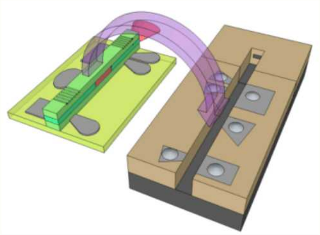
YEAR 2

- Multi (8/16) branch quantum tomography
- Number resolving detection

YEAR 3

- Temporally multiplexed single photon detection (Q < 0)
- Homodyne single photon detection

Functional quantum transceivers



YEAR 1

- Design custom InP diodes
- Design interlock to Si photonics platform

YEAR 2

- Bond InP laser to Si substrate with < 20dB insertion loss
- Photon generation and detection on single chip

YEAR 3

- Security proof for repeater architecture
- XOR operations using two repeater nodes

All components upgrading modular quantum transmission link throughout the program