SAND2015-5298C

Si Photonics for Advanced Communications

Sandia National Laboratories

LDRD

SECANT QKD

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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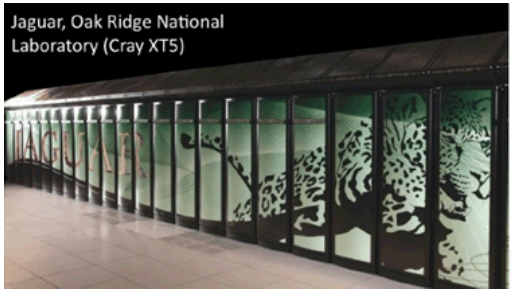
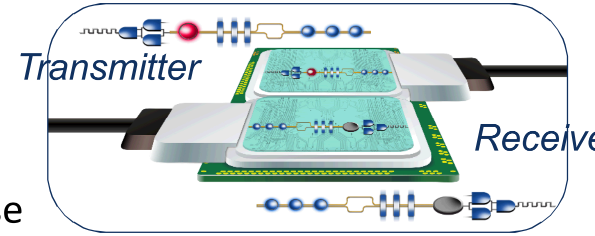
Paul S. Davids

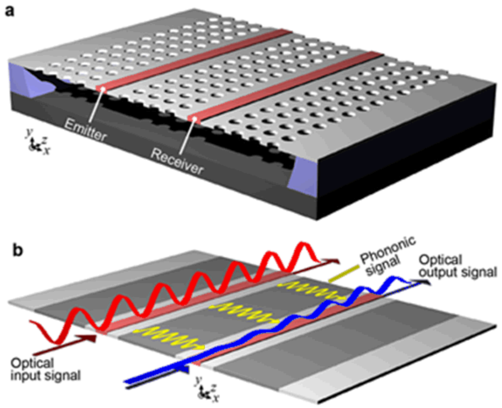
Silicon Photonics Research Directions

Integrated Optical Technology for Communication and Signal Processing

- **High Performance Computing**
  - Optical Interconnect
  - XGC Grand Challenge FY12-14 (wavelength stabilization, heterogeneous integration, low-power comm. link modeling/design)
- **RF Photonics**
  - 110 Channel Cueing Receiver FY12-15 (low-loss waveguide, phase correction)
  - DARPA MESO FY12-15 (photon-phonon coupling, RF filters)
  - High speed optical modulator FY15-16 (nonlinear material)
- **Quantum Photonics**
  - SECANT Grand Challenge FY14-16 (QKD transceivers)
  - Continuous and Discrete Variable Quantum Key Distribution.
  - Chip-scale Quantum Coherent Feedback and Control.







Sandia Si Photonics Integrated Circuits

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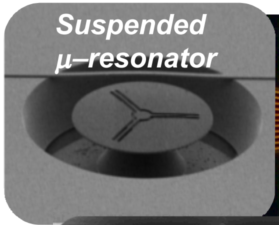
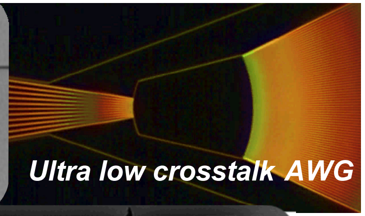
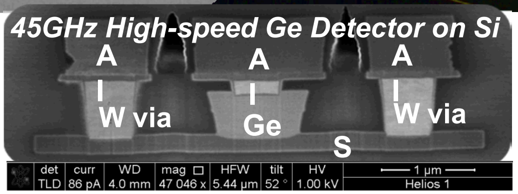
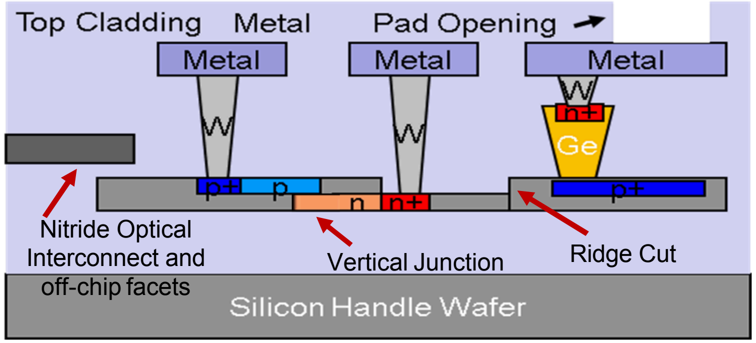
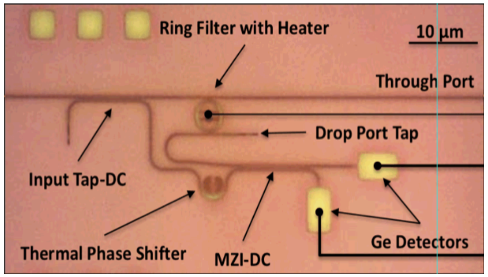


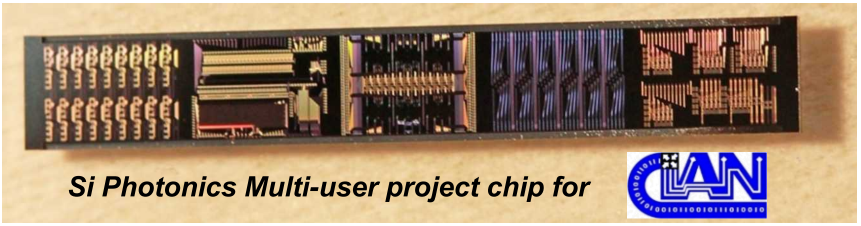


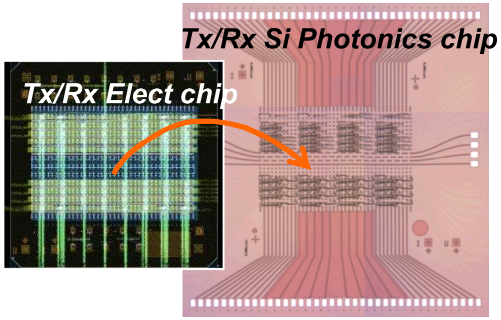


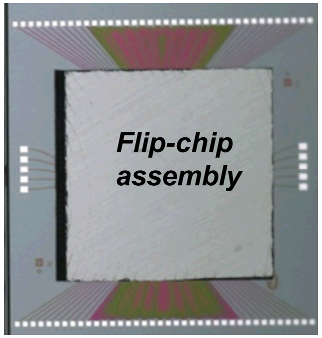




Filter with wavelength stabilization





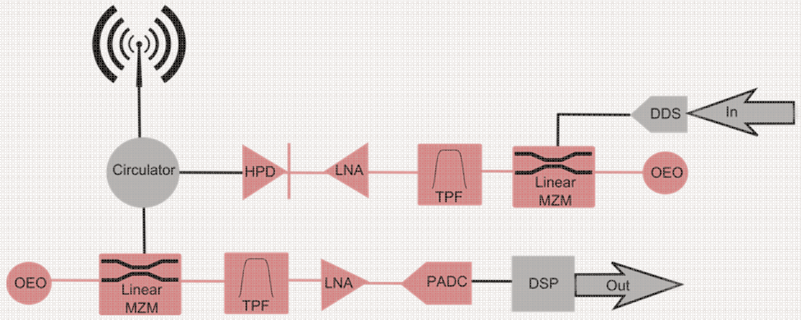


Silicon-based Optical Communication Devices

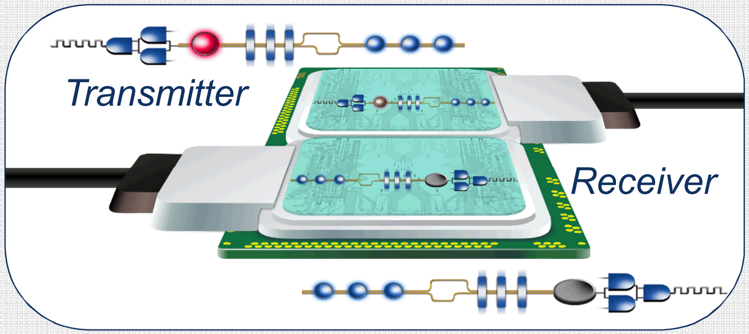
- **Active Components**: Linear and digital Mach-Zehnder modulators, ring and disk ultra-low energy modulators with/without integral micro-heaters for resonant wavelength stabilization, high-freq. and high power integrated germanium detectors, integration with rad-hard CMOS, 2 x 2 wavelength selective switches and broad-band switches, and tunable filters
- **Passive Components**: wavelength division multiplexers using resonant filters and arrayed grating routers, surface normal and in-plane polarization beam splitters, polarization rotators, polarization mode filters, directional couplers and splitters, integral SiN second photonics routing layer, Sagnac interferometers, AWG RF channelizers
- **Demonstrated Circuits**: transmitters, receivers, on-chip links, resonant wavelength stabilization circuits for both modulators and filters, optical active beam steering, optical logic (matrix multiply), low noise oscillators, optical network add-drop node (CIAN), optical channel monitor (spectrum analyzer) (CIAN)

Photonics Enabled System Applications

High Performance Computing

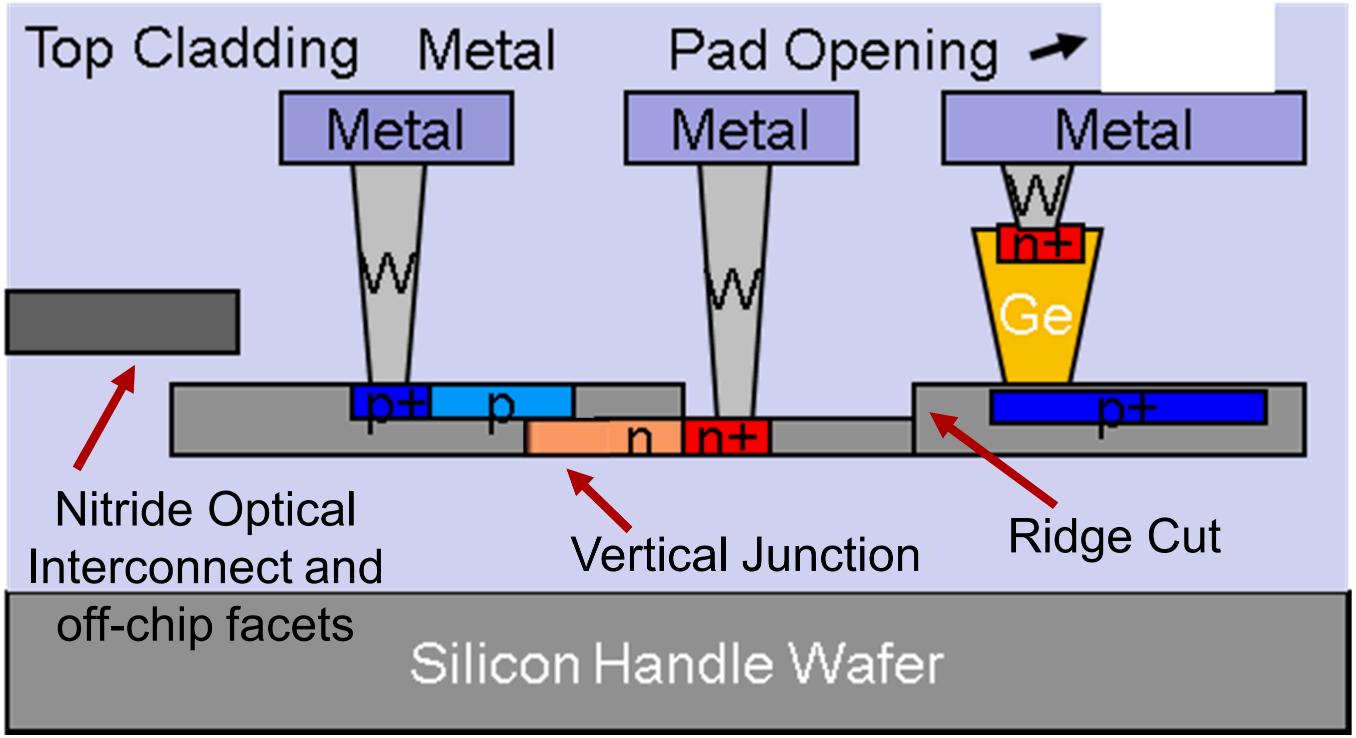


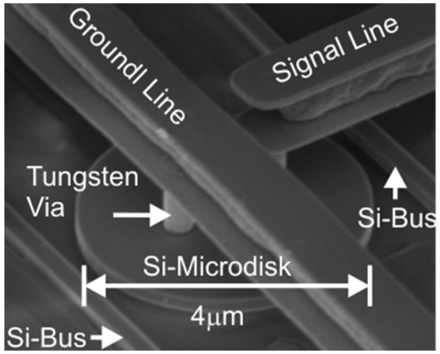
RF Sensing and Communication



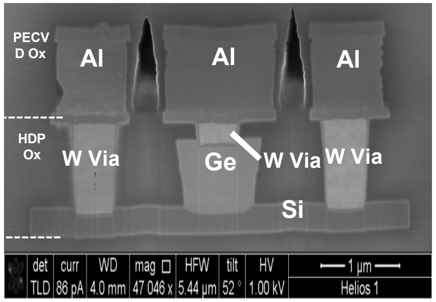
Secure Quantum Communication

SNL Silicon Photonics Process





Optical modulator 12.5GHz, 3fJ/bit



Ge photo detector with 45GHz BW, 3nA dark current

- CMOS compatible
- Passive and active photonics devices
  - Silicon and silicon nitride waveguides, couplers, splitters, gratings, filters, modulators, Germanium detectors, switches, etc.

10Gbps Resonant Heater Modulator

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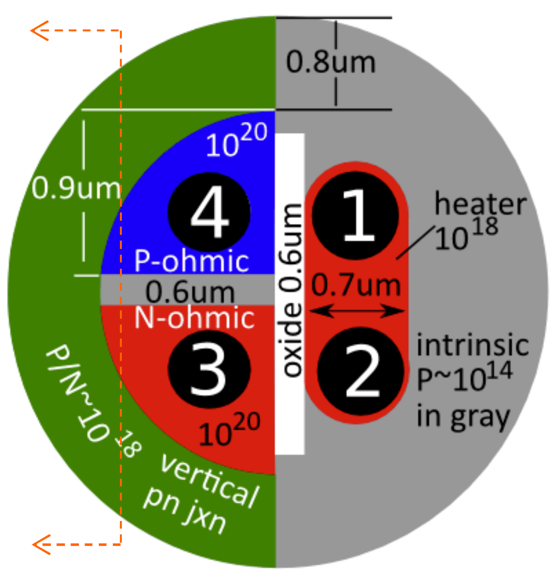
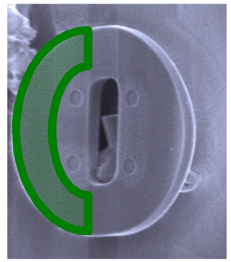
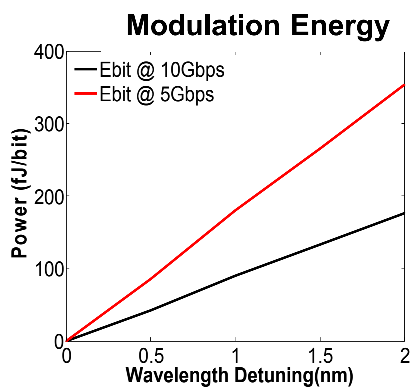
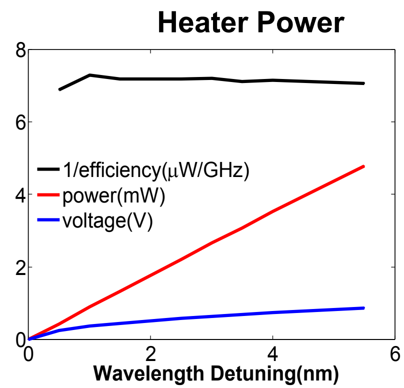


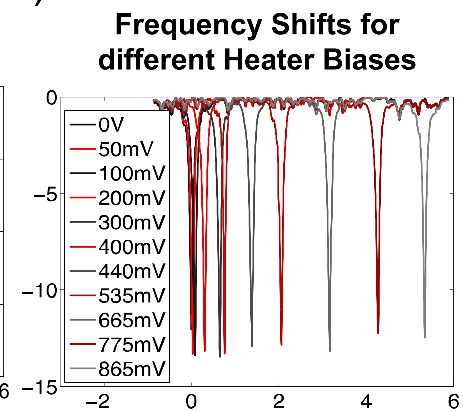
1,2 – heater contacts
3,4 – modulator contacts

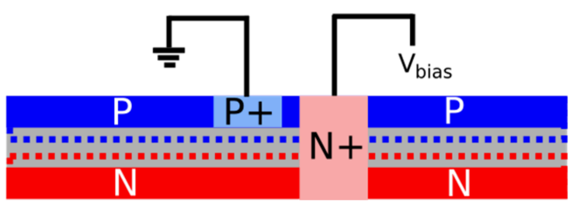


- FSR covers entire C-band
- Low footprint of ~14μm^2, CMOS-compatible
- Differential signaling compatibility
- Lowest intrinsic tuning energy
  7μW/GHz (0.7fJ/bit-GHz)

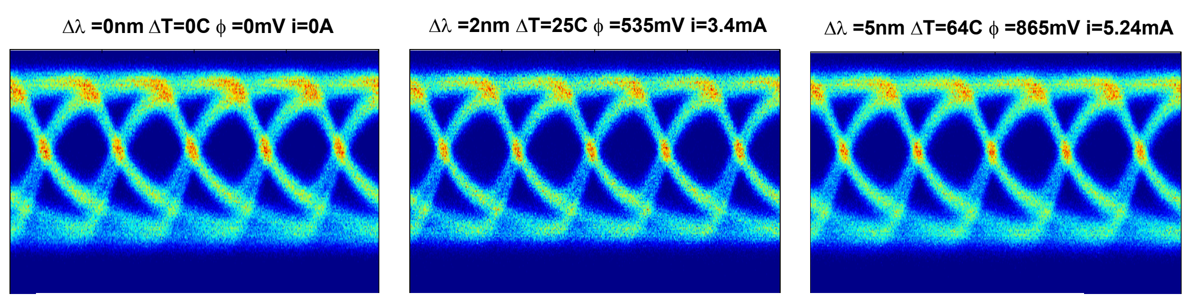








Cross-section of modulator with vertical P-N junction

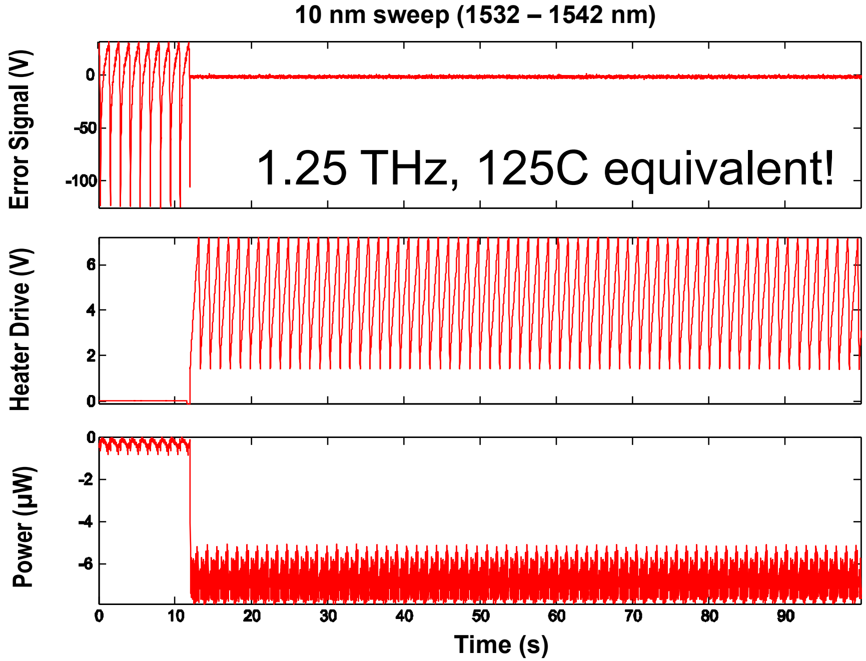


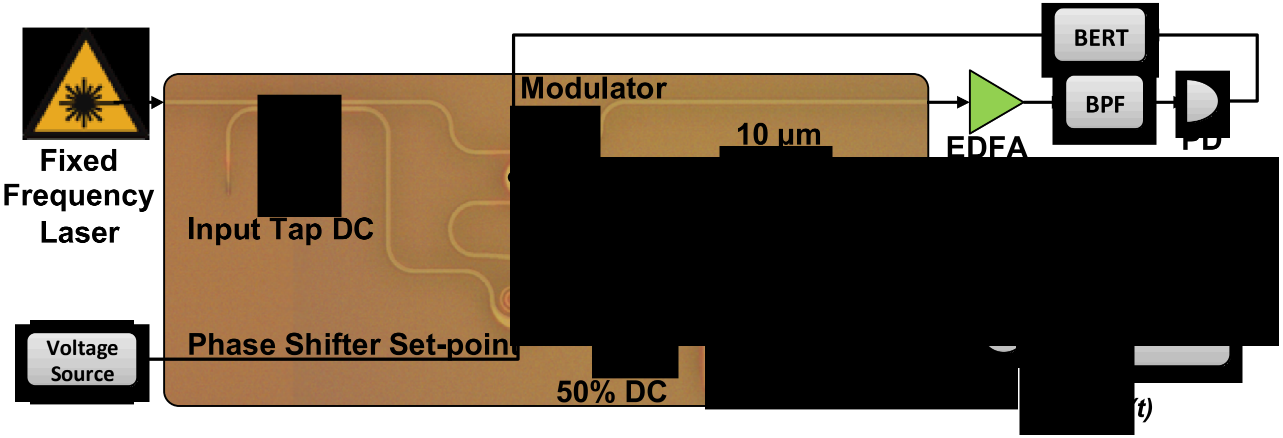
Similar eye diagrams achieved at different tuning temperatures

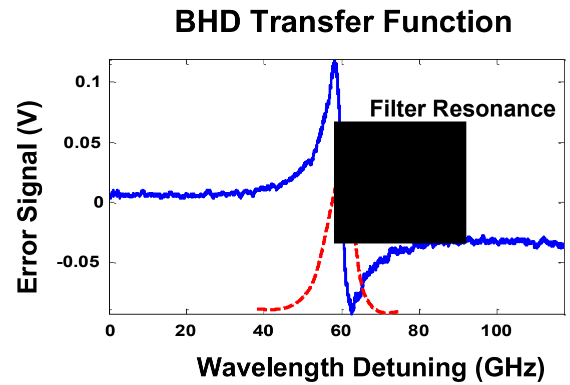
W. Zortman, et. al., OFC , OW4I.5 (March 2012)

Stabilization of Modulators

- ***Lock to zero:*** No calibration or reference level needed for locking
- ***Amplitude insensitive:*** Locking point not influenced by optical intensity
- ***Precision locking:*** Resonator is not disturbed
- ***Minimum circuit complexity:*** Power and area consumption of control electronics is minimized





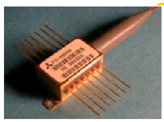


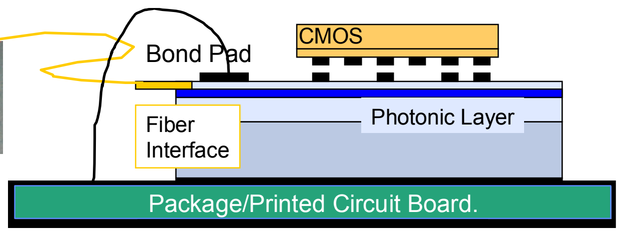
J.A. Cox et. al., Opt. Express 22, 11279-11289 (2014)

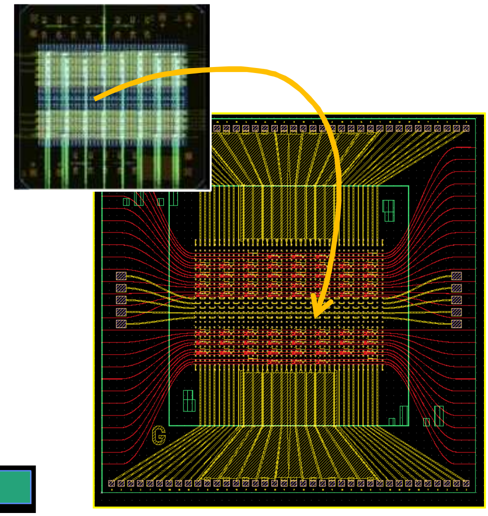
Electronics – Photonics Integration

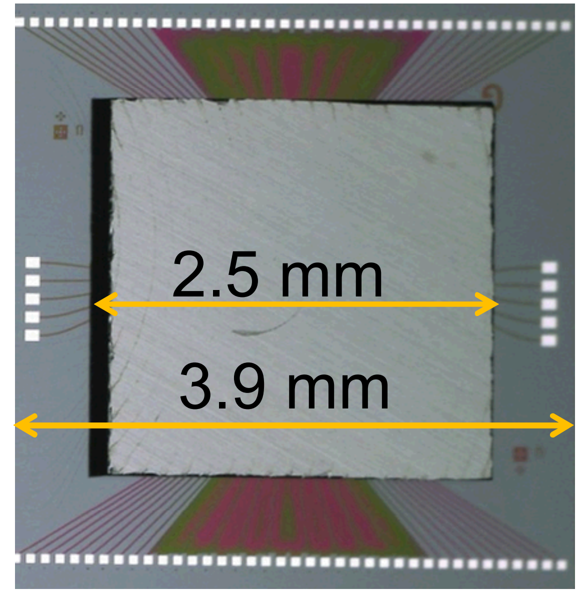
Heterogeneous Integration

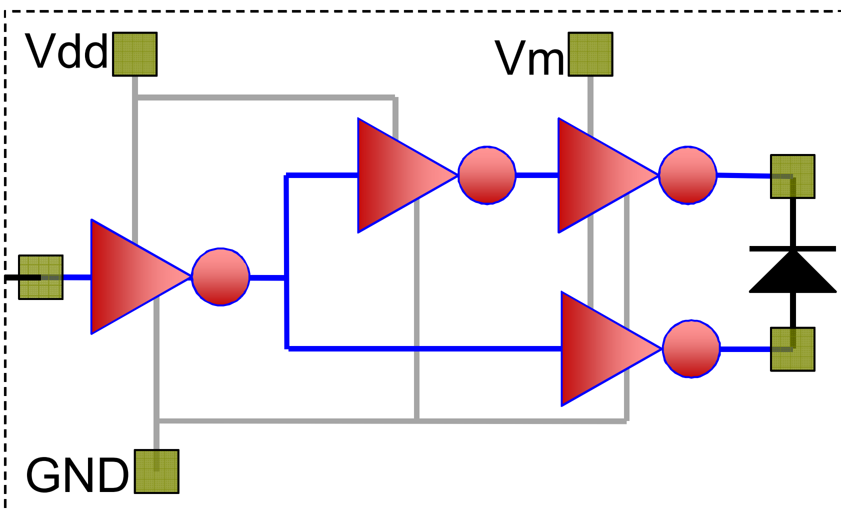
- Independent optimization of electronics & photonics
- Challenge: Need high yields and small bond size

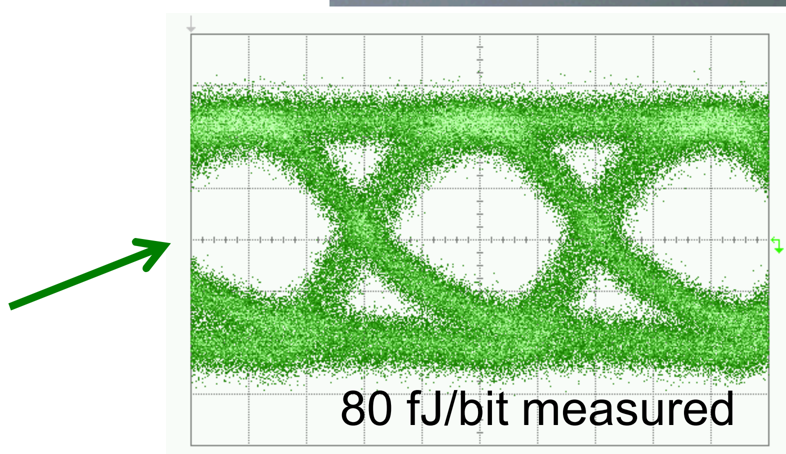










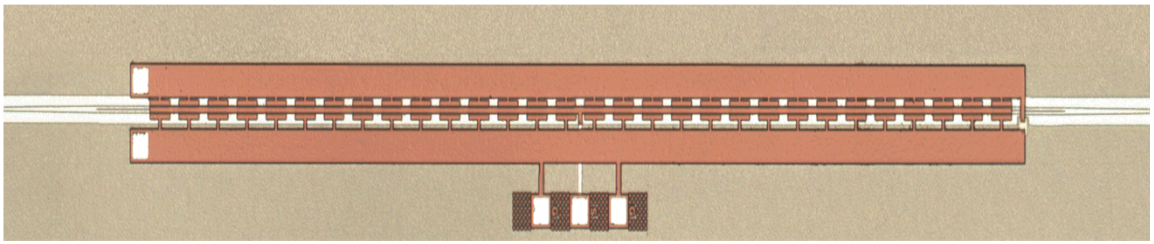


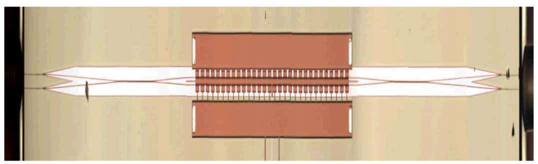
Modulated optical output at 5 Gbps

SNL RF Si Photonics Technologies

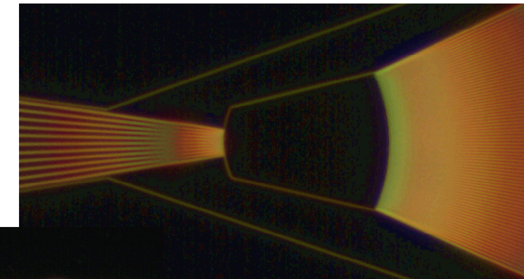
Silicon Photonics

Optical modulation and spectrum analysis up to 100GHz

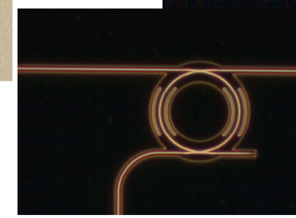




Mach-Zehnder Modulator with Traveling-Wave Electrodes 20GHz, Vpi x L = 0.8Vcm



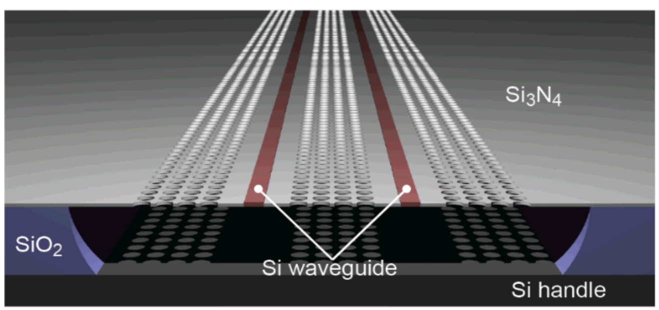
Array Waveguide Grating Coupler

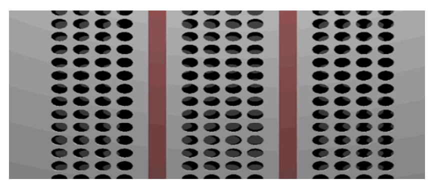


Micro-ring Tunable Filter (MHz – GHz)

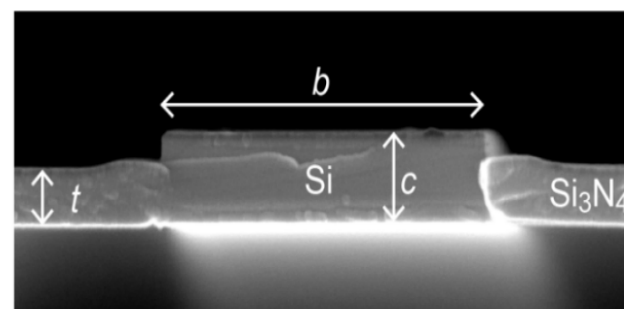
Silicon / SiN Nano-Optomechanics

Photon-phonon transduction for signal processing with up to 20GHz BW



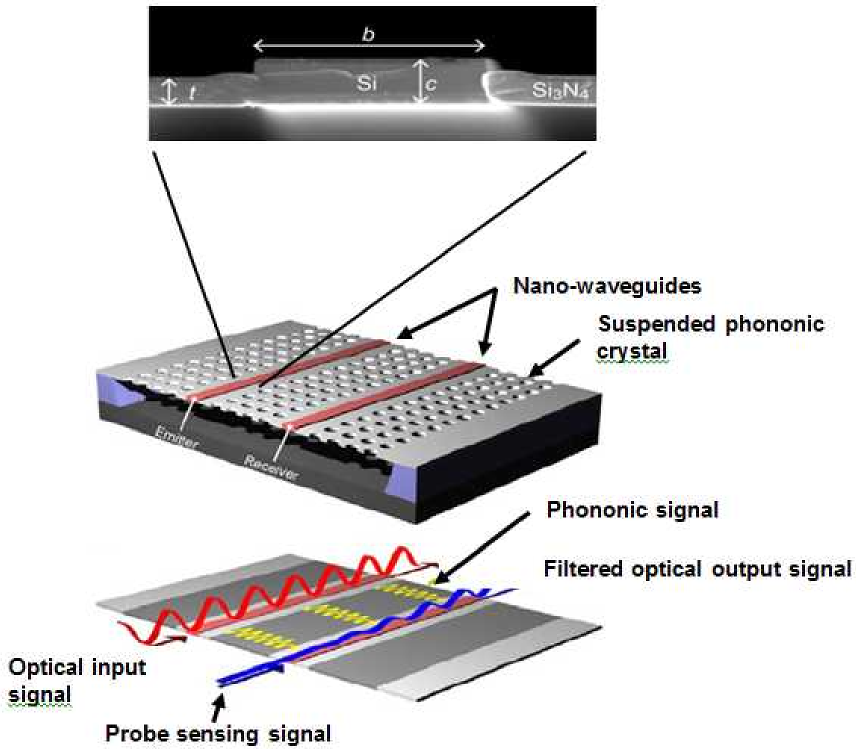


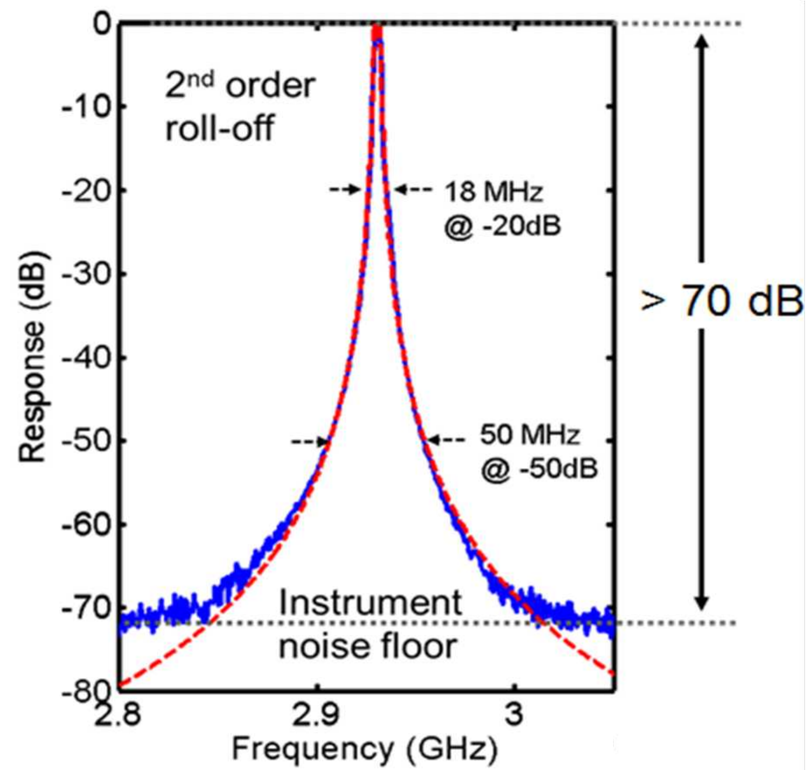
Suspended Si waveguides with phononic crystals



- New paradigm for RF signal processing (ex. filtering) in optical domain to reduce size, weight, and power, and improve performance

Photonic-Phononic RF Filter

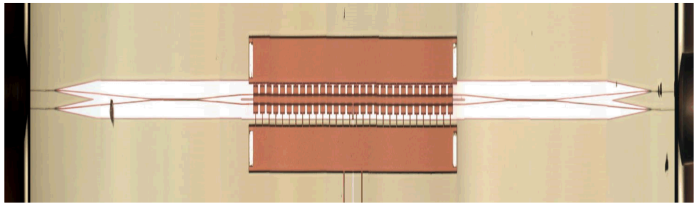




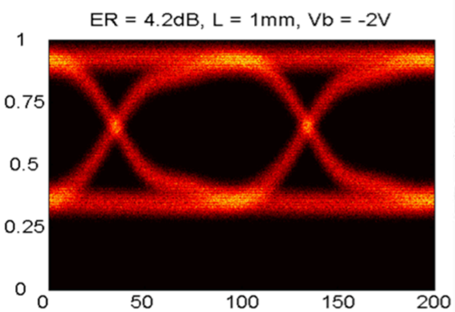
- Center frequency may be tunable between 1-20GHz;
- Q and filter shape may also be tunable
- Parallel / serial configurations to build filter banks/spectrum analyzer with significant size, weight, power, and performance benefits

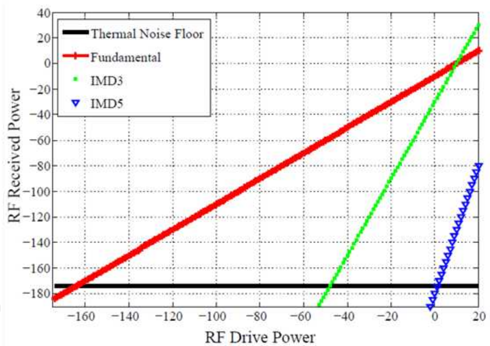
H. Shin et. al., *Nature Communications* 6 (6427), Mar. 2015

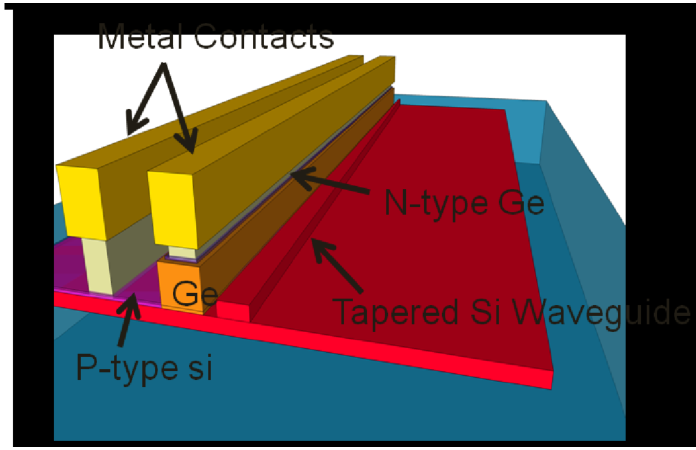
SNL RF Si Photonics Technologies

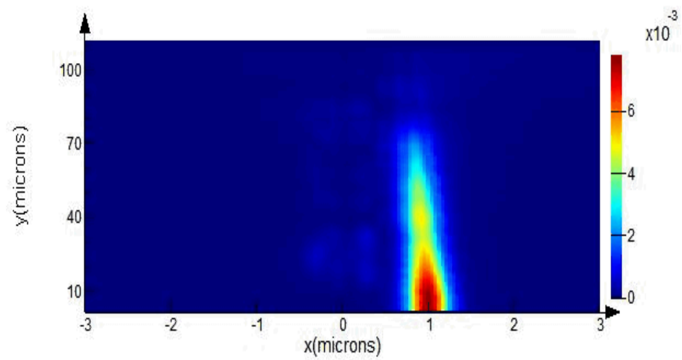


Mach-Zehnder Modulator with Traveling-Wave Electrodes







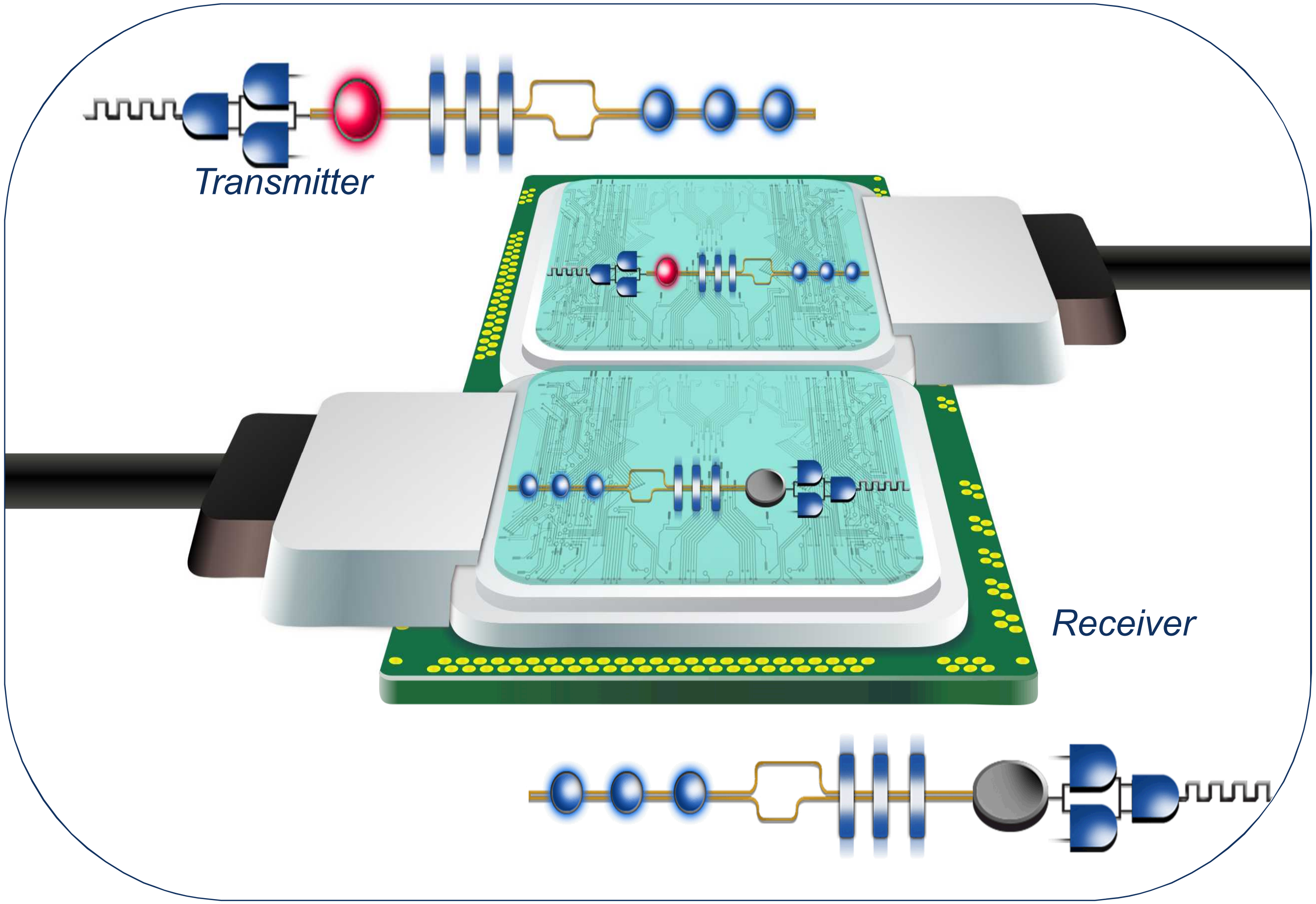


- High-bandwidth linear modulator
  - 23GHz, V_{pi} x L = 0.8Vcm, 108 dB/Hz$^{2/3}$
  - Analog to Digital Conversion, RF Filtering and Antenna Remoting
  - Side-band modulation in chip-scaled Continuous-Variable QKD
  - Next step – CMOS integration to control drive voltages and minimize signal attenuation

- High-power optical detector
  - Waveguide coupled
  - 20mW power-handling
  - 1500-1600nm operating wavelength

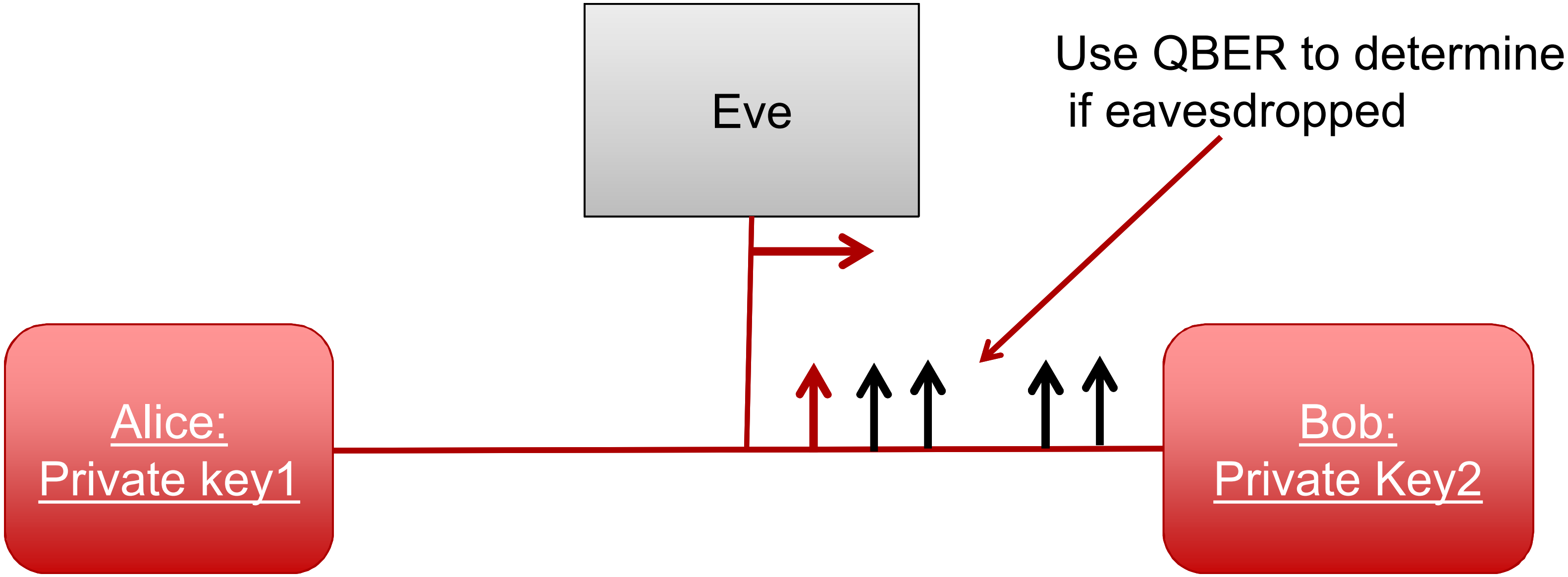
Chip-scale Quantum Tx/Rx for QKD

Develop new building blocks to enable quantum optics.
Using Si Photonics platform for integration.



Quantum Key Distribution (QKD)

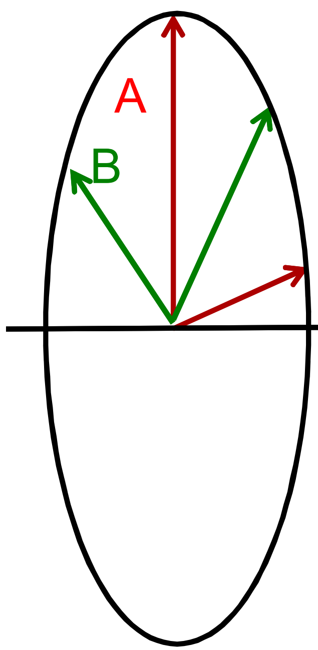
- A secure way to distribute a key that is Eve proof.
- Quantum state of photon
  - A photon is a quantum object (discrete state with wavefunction).
  - No cloning of unknown quantum state (cannot be perfectly copied).
  - Measuring quantum state perturbs state.
- Uses Physical principle (QM) to guarantee security



BB84 (Bennett and Brassard)

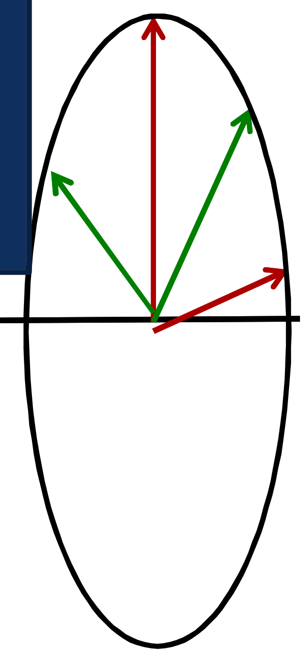
- Polarization state of photon:
- Two orthogonal bases: A (x-y) & B (rotated by 45^0)
- Alice and Bob define bases and define 0 & 1 in A & B

Alice



Alice's bits	010110001010110 0
Alice's bases	BAABAABAAAABBBBA
States sent	+10−10+0101+−−+0
Bob's bases	ABAABAAABABBBBAB

Bob



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Sandia National Laboratories

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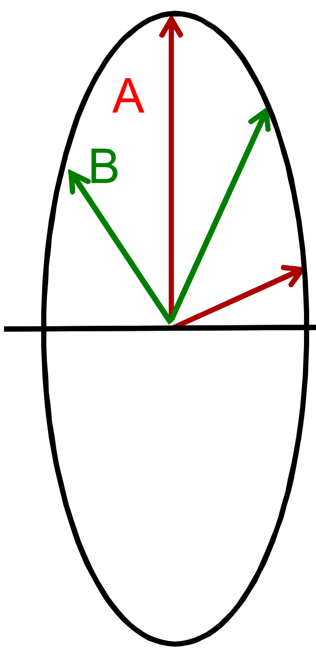
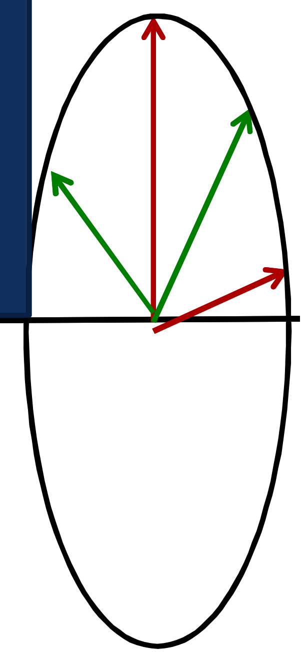


Alice's bits	0101100010101100
Alice's bases	BAABAABAAAABBBBA
States sent	+10-10+0101+--+0
Bob's bases	ABAABAAABABBBBAB
Bob's results	1-00-0+0+0-+--1+

Bob



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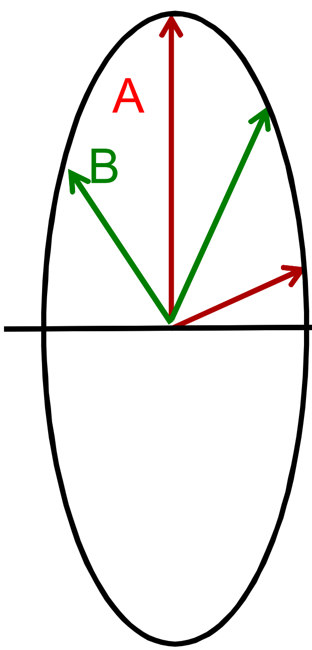

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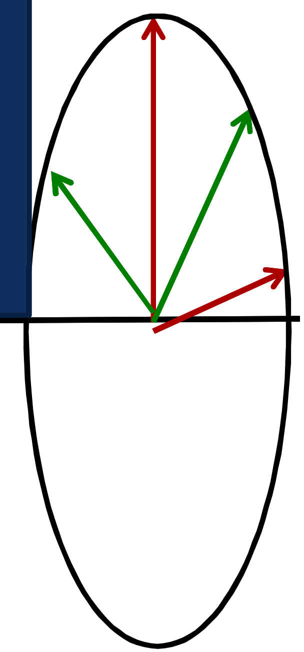
States sent	+10−10+0101+−−+0
Bob’s bases	ABAABAAABABBBBAB
Bob’s results	1−00−0+0+0−+−−1+

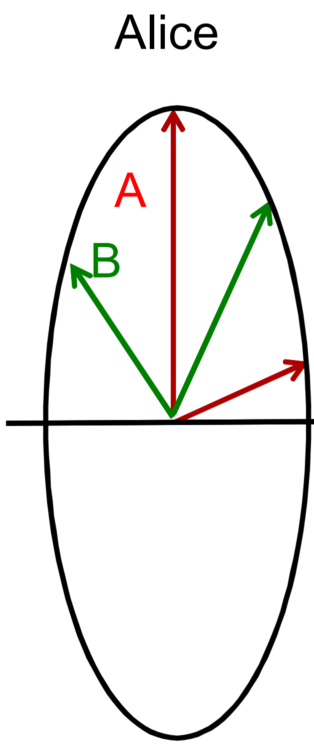
Bob



Alice and Bob compare bases and Bob discards
Bits where bases are different.

BB84 (Bennett and Brassard)

- Polarization state of photon:
- Two orthogonal bases: A (x-y) & B (rotated by 45^0)
- Alice and Bob define bases and define 0 & 1 in A & B



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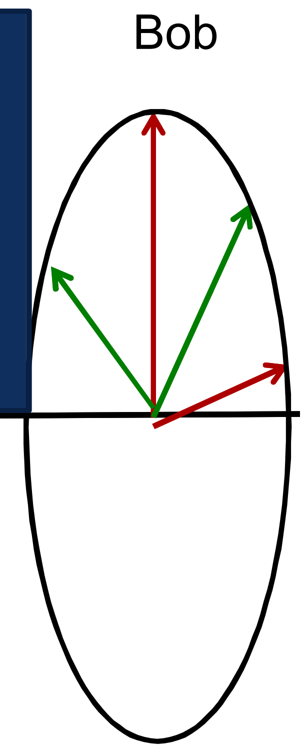
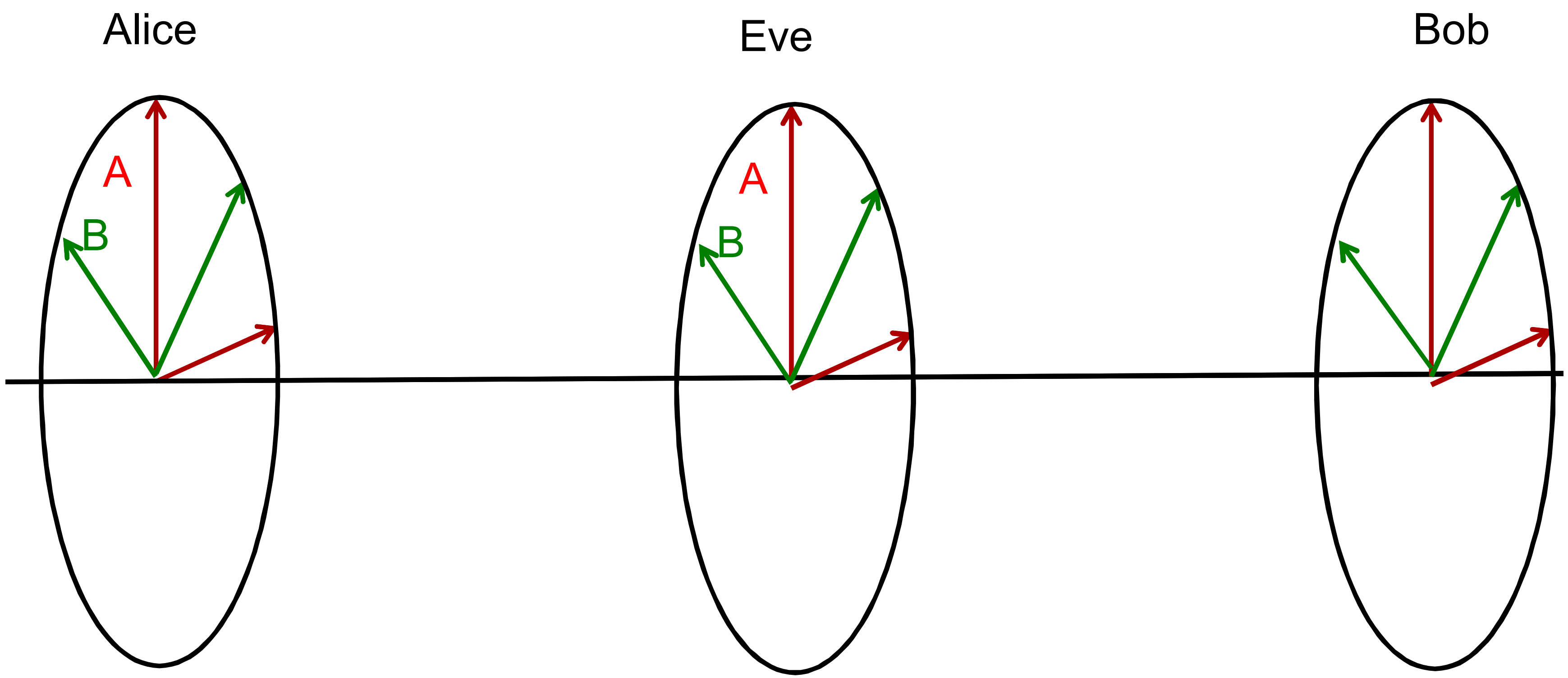


Bob on average has 50% of bits .
7 out of 16 bits **0**0*0*0*+−−**

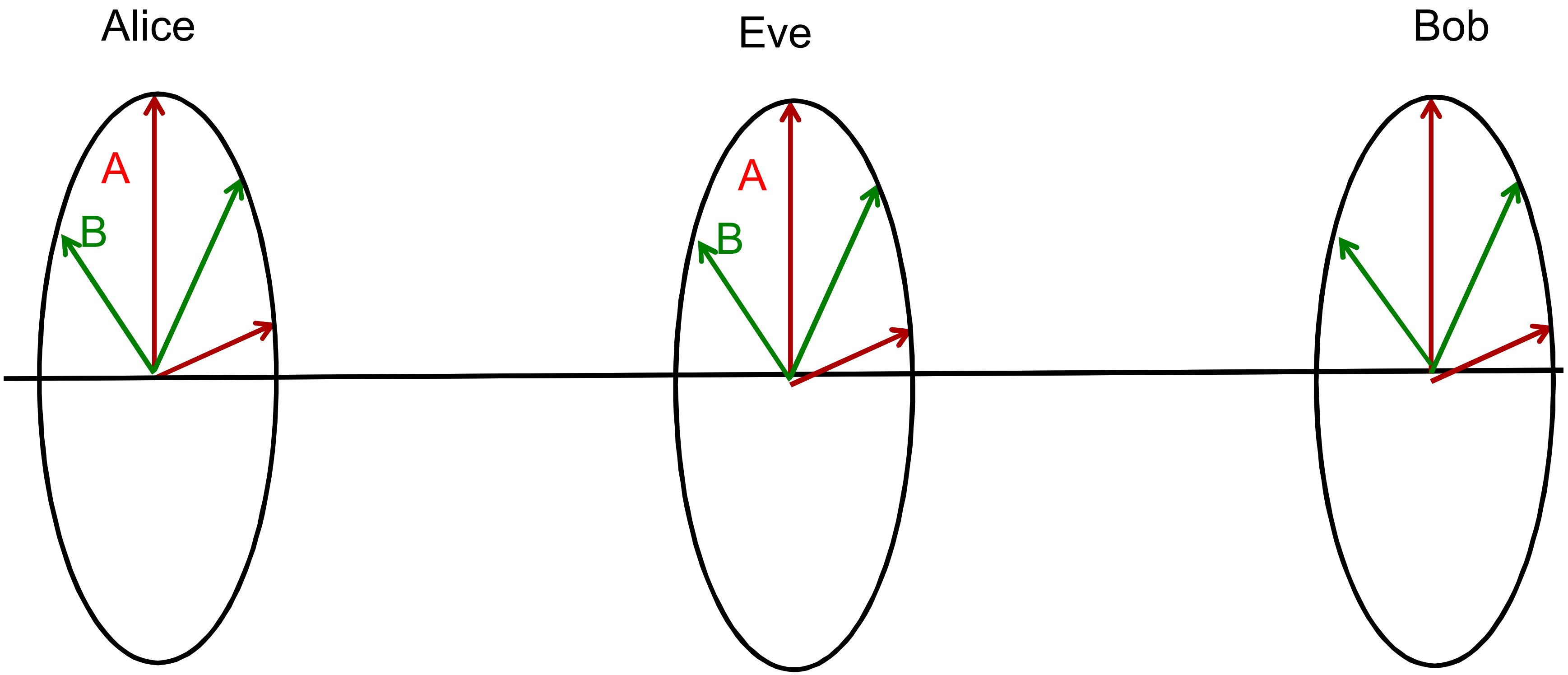
BB84 (Bennett and Brassard)

- Eve is in the middle
- Eve random selects polarization
- Based on Eve's measure and basis she sends photon.



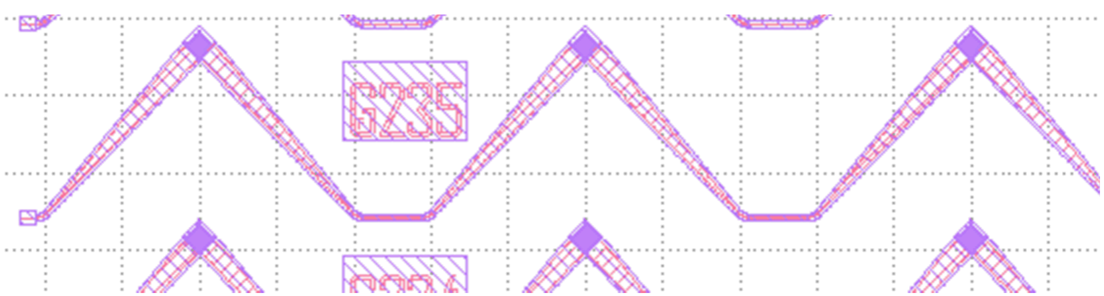
BB84 (Bennett and Brassard)

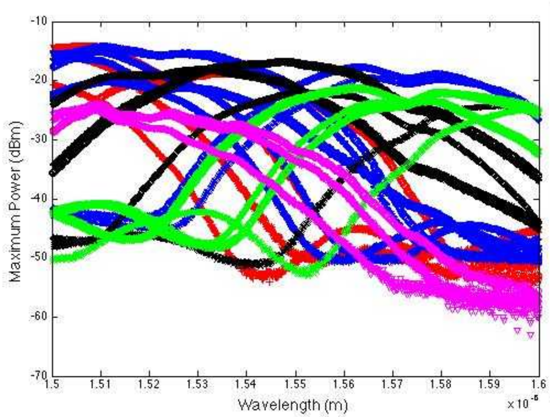
- Eve has 50% correct basis with Alice.
- Bob has 25% correct bits with Alice during reconciliation.
- No attack obtaining full information about the key can introduce less than 11% QBER.



DV-QKD Transceiver

- Free-space DV QKD Tx/Rx design complete using BB84 polarization.
- New chip-scale polarization components designed, fabricated and tested.
  - Polarization gratings, rotators and splitters. 14 dB grating loss at 1520 nm.
  - 1800 grating measured.
- Issues: DV-Tx/Rx run delayed due to cost overrun. Merge with MPW. No current integrated SPAD is risk of DV-RX





/ Tx/Rx

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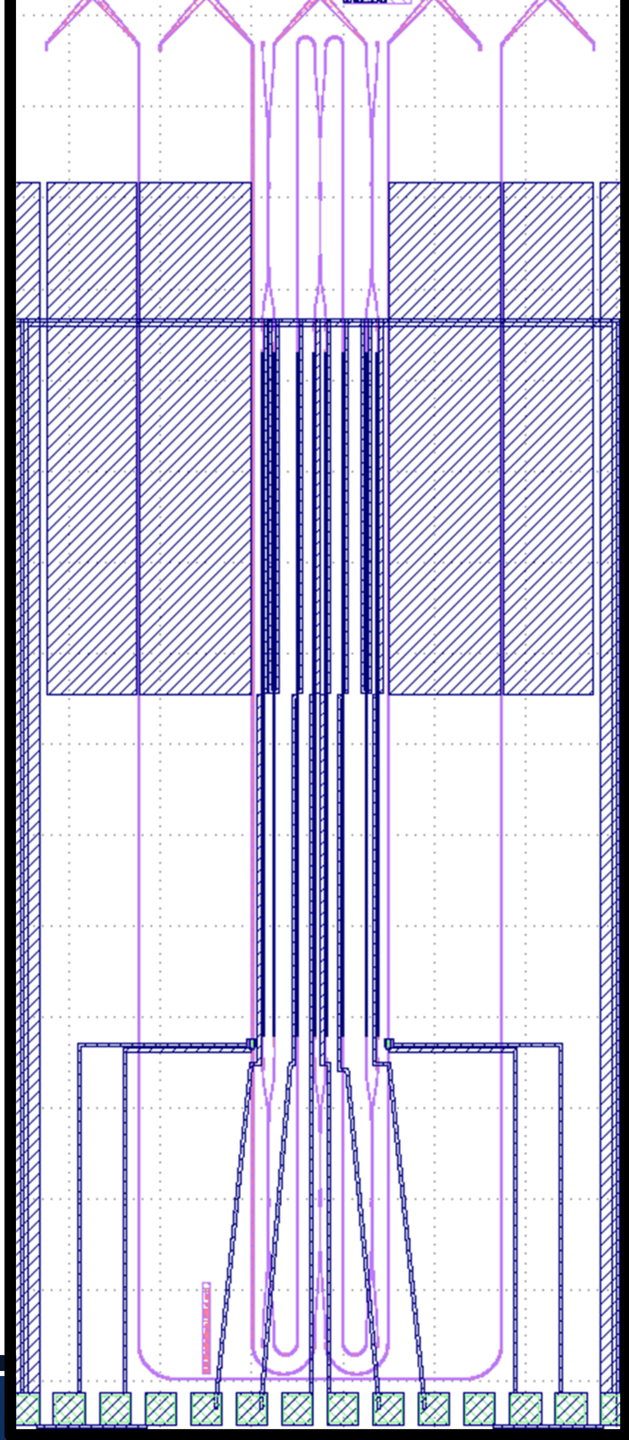
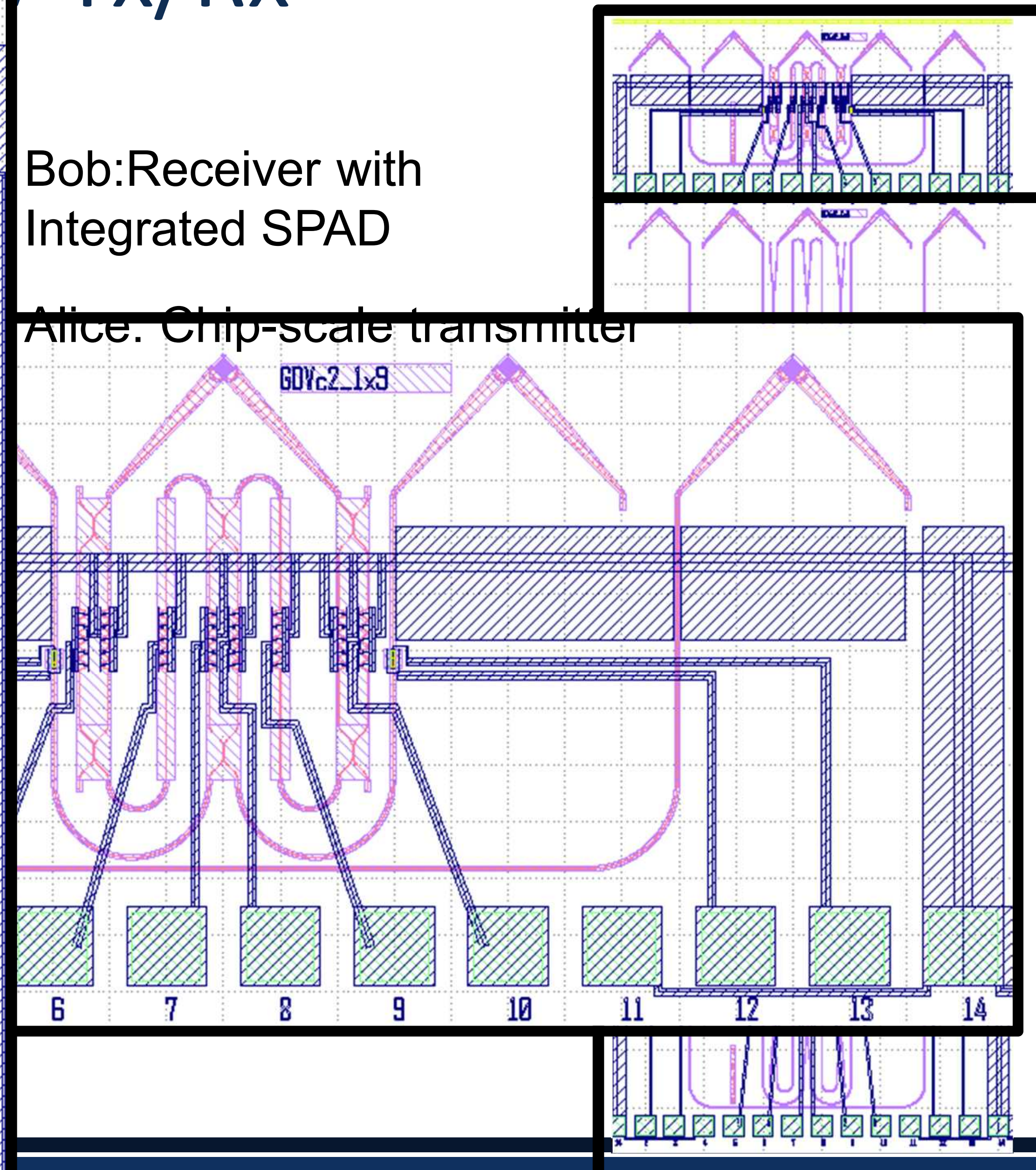
Bob:Receiver with Integrated SPAD

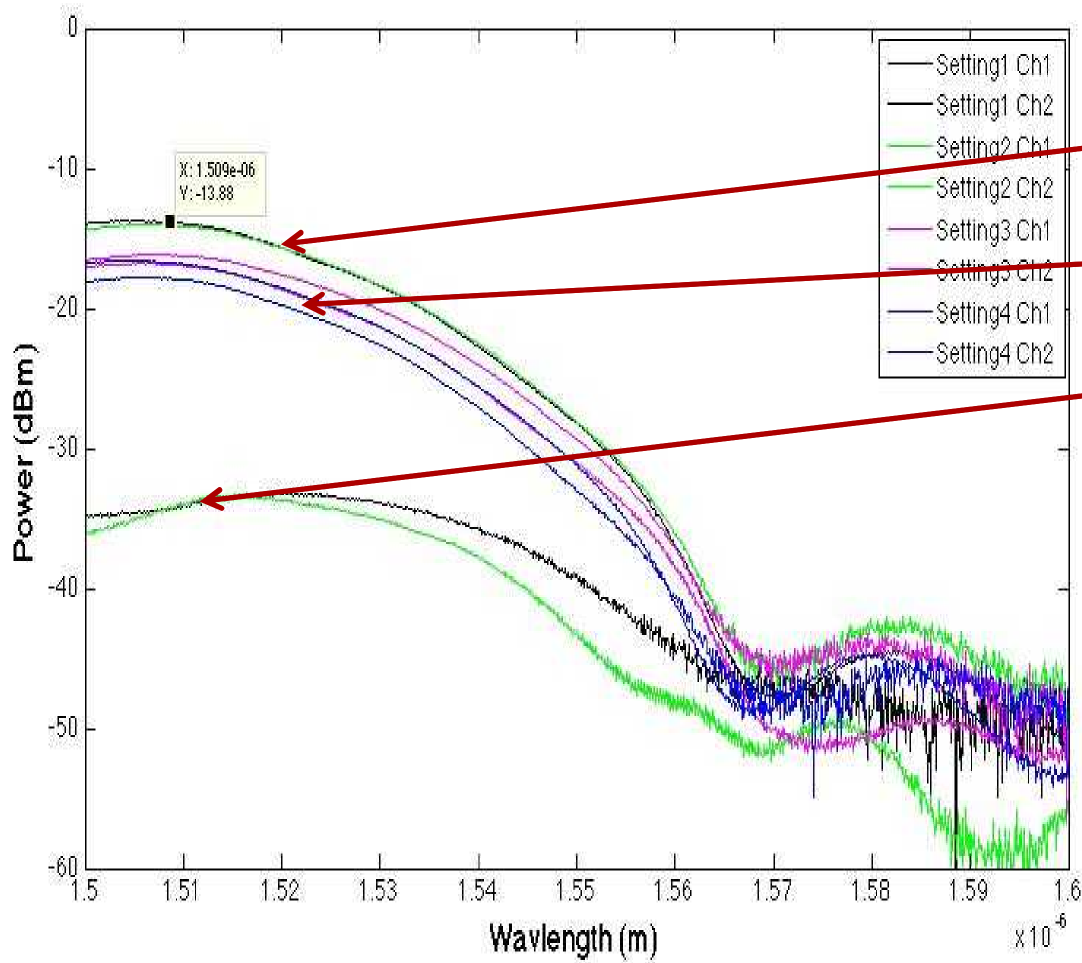
Alice: Chip-scale transmitter

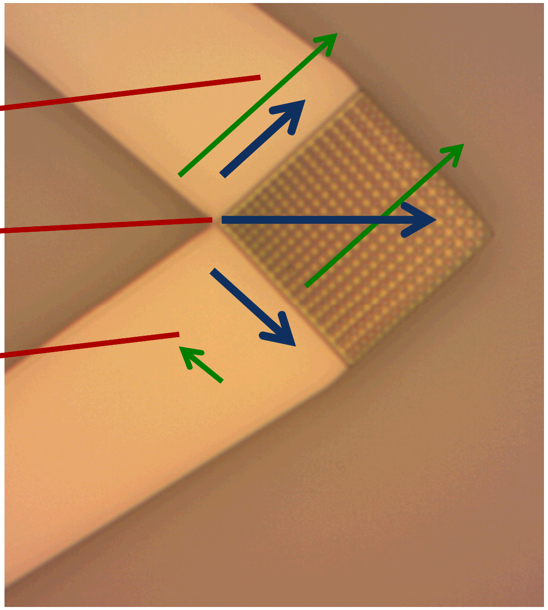




Waveguide polarization gratings

New polarization components developed for Free-space DV QKD with BB84

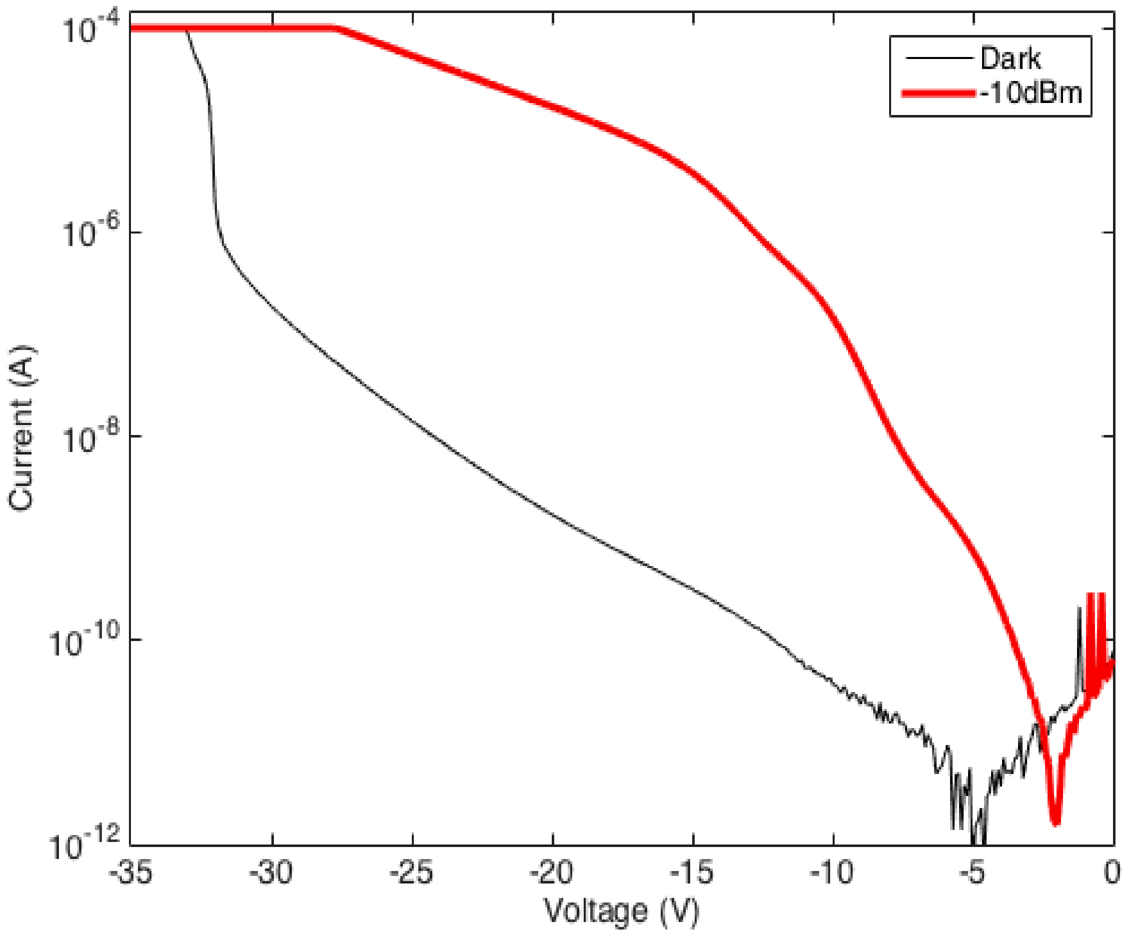


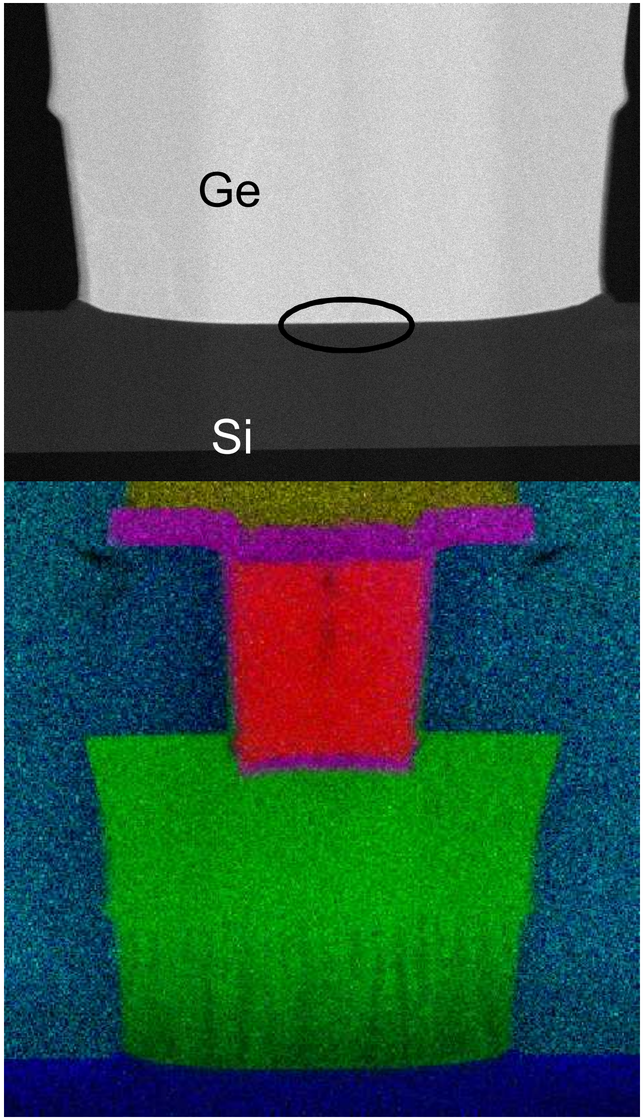


3dB split for blue polarization

SPAD Development

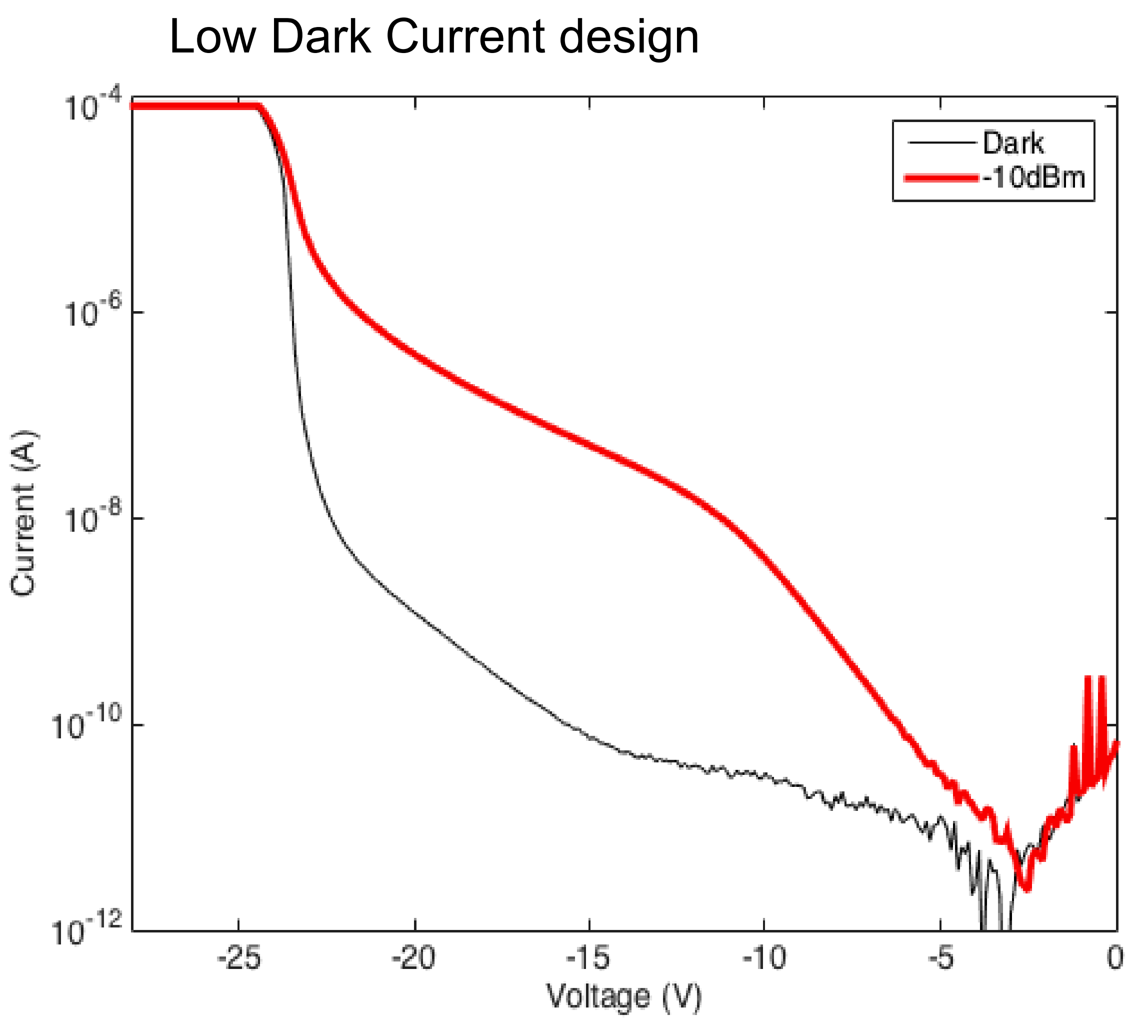
High responsivity design

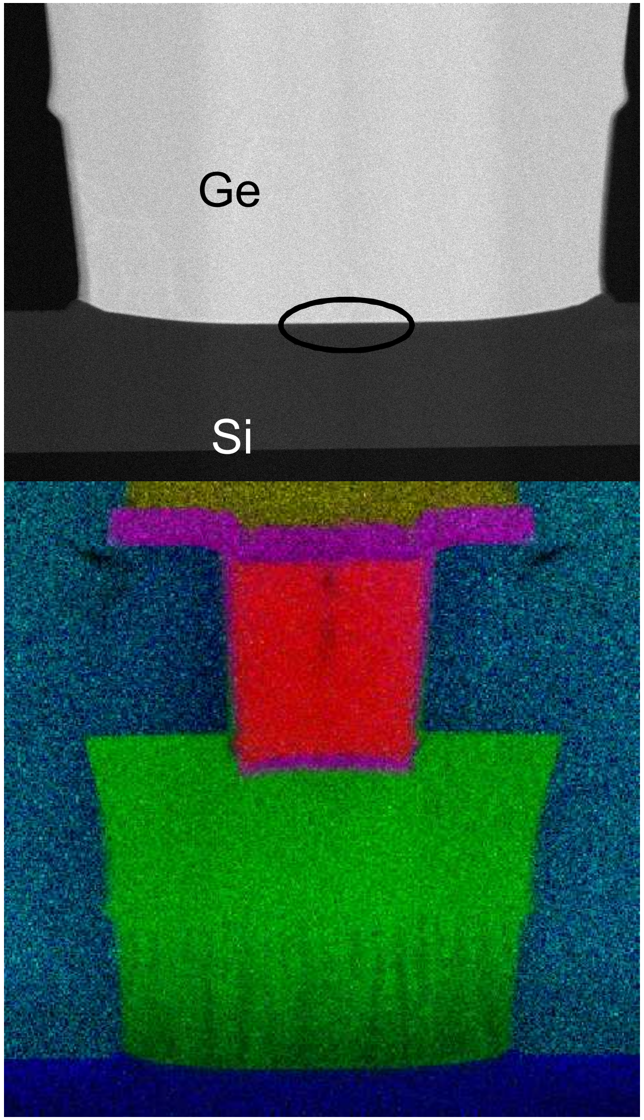




-5dBm applied

SPAD Development





Integrated SPAD Development

- Pad re-design (GSSG) on new SPAD devices enable high speed testing for lateral APDs.
  - High speed testing on probe station possible for lateral APDs.
  - New pulsed laser will enable jitter measurements through sync.
  - DCR measurements on new lateral APD chips underway.
- Tested 1st evanescent ntirde coupled vertical APDs.
- 2nd Ge Epi source qualification evaluation.
  - Preliminary results not promising for Ge epi.
  - Si Epi looks good.
- Issues: CMP over-polish of Ge on vertical Epi Si/Ge structures removed nearly all Ge. Need new process runs with full Ge to develop process.

Time Bin Encoding

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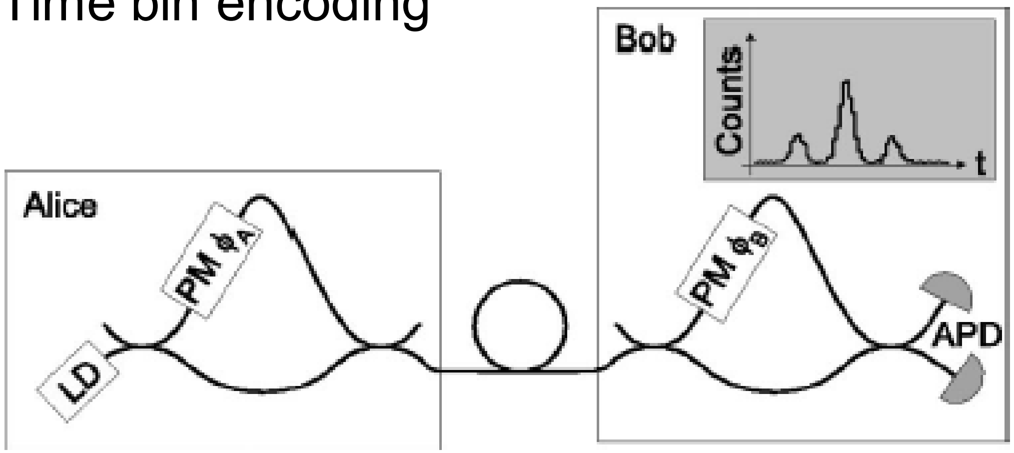
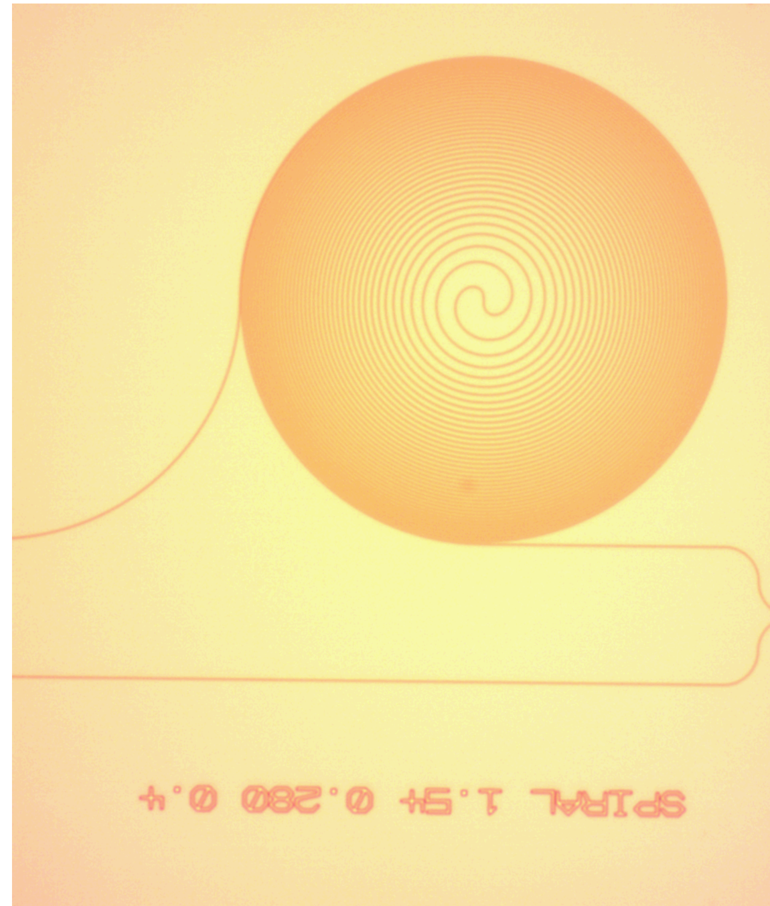
N.Gisin, et. al. “Quantum Cryptography, Rev. Mod Phys,75 2002

ss ls ll

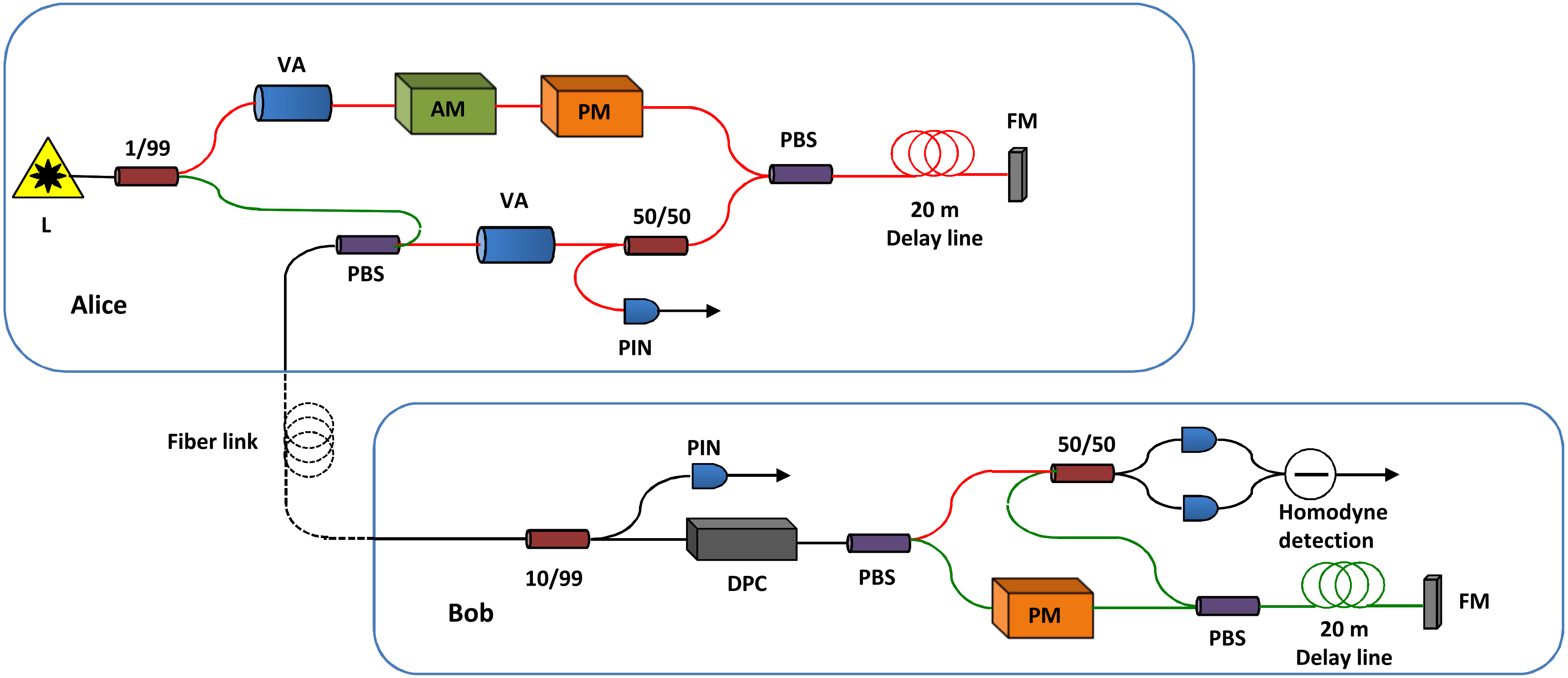
Time bin encoding





Long delay (ns) in waveguides leads to large loss
Must reduce loss for chip-scale time-bin encoding

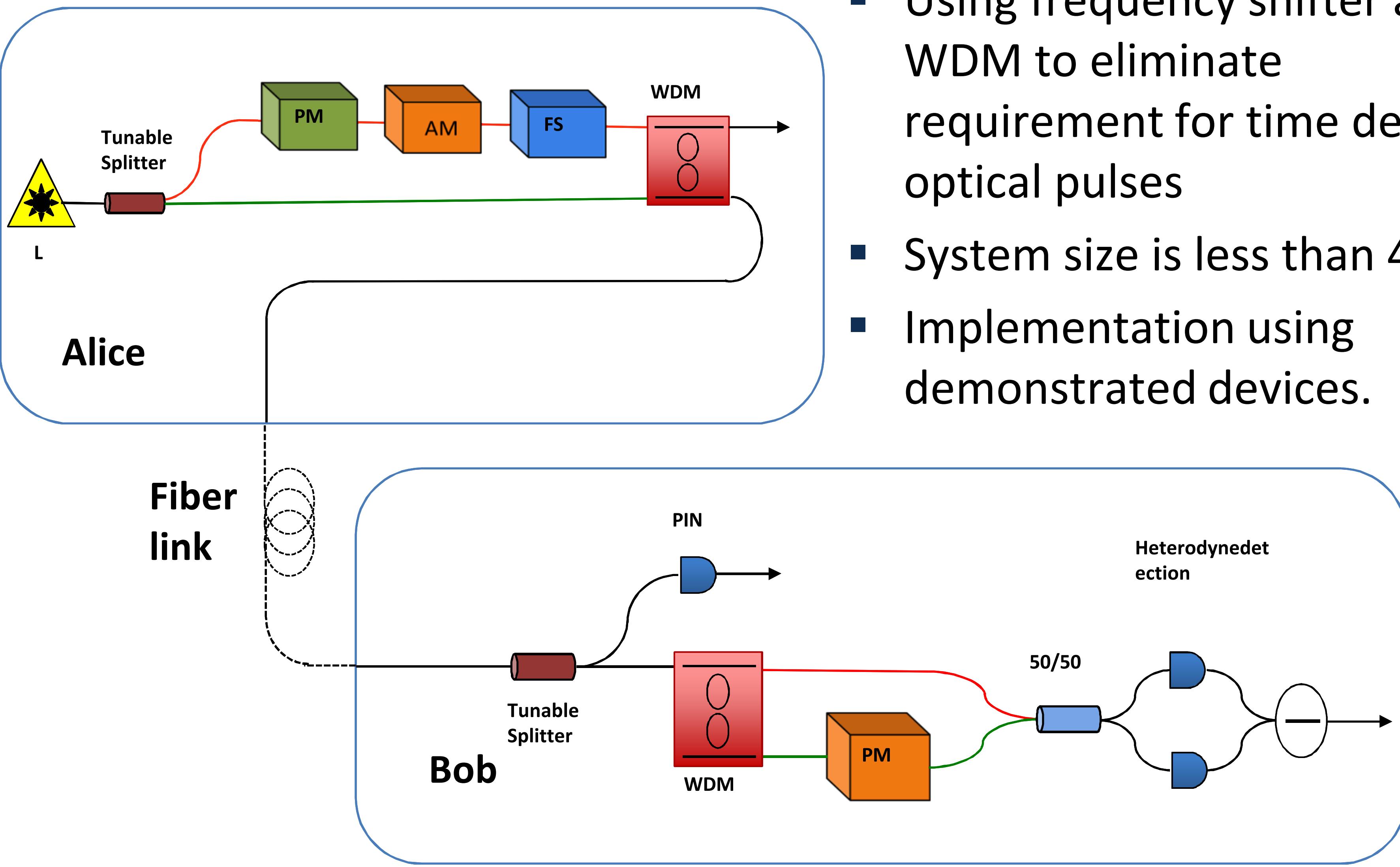
Bench-top CV-QKD link



Current State of the Art CVQKD link using coherent state source

P. Jouguet, S. Kunz-Jacques, A. Leverrier, P. Grangier, and E. Diamanti. Experimental demonstration of long-distance continuous-variable quantum key distribution. Nature Photonics, 7(5):378–381, 2013.

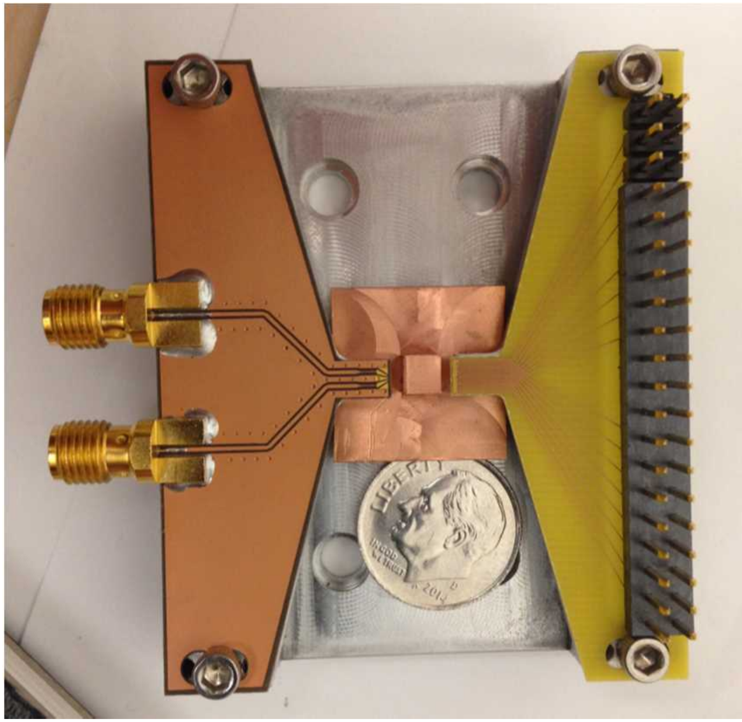
On-Chip CV-QKD System



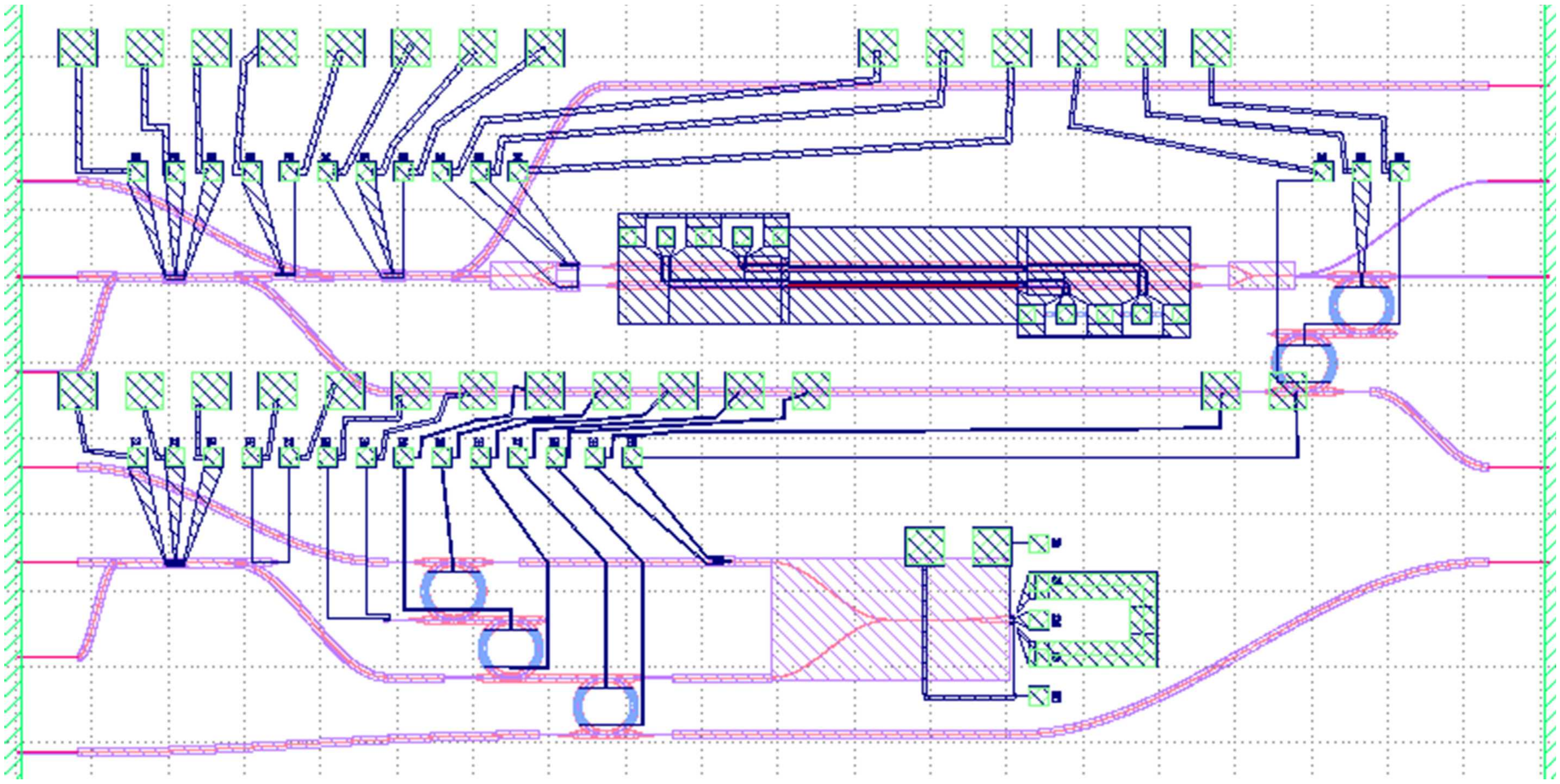
- Using frequency shifter and WDM to eliminate requirement for time delayed optical pulses
- System size is less than $4mm^2$
- Implementation using demonstrated devices.

Chip-scale CV-QKD Transciever

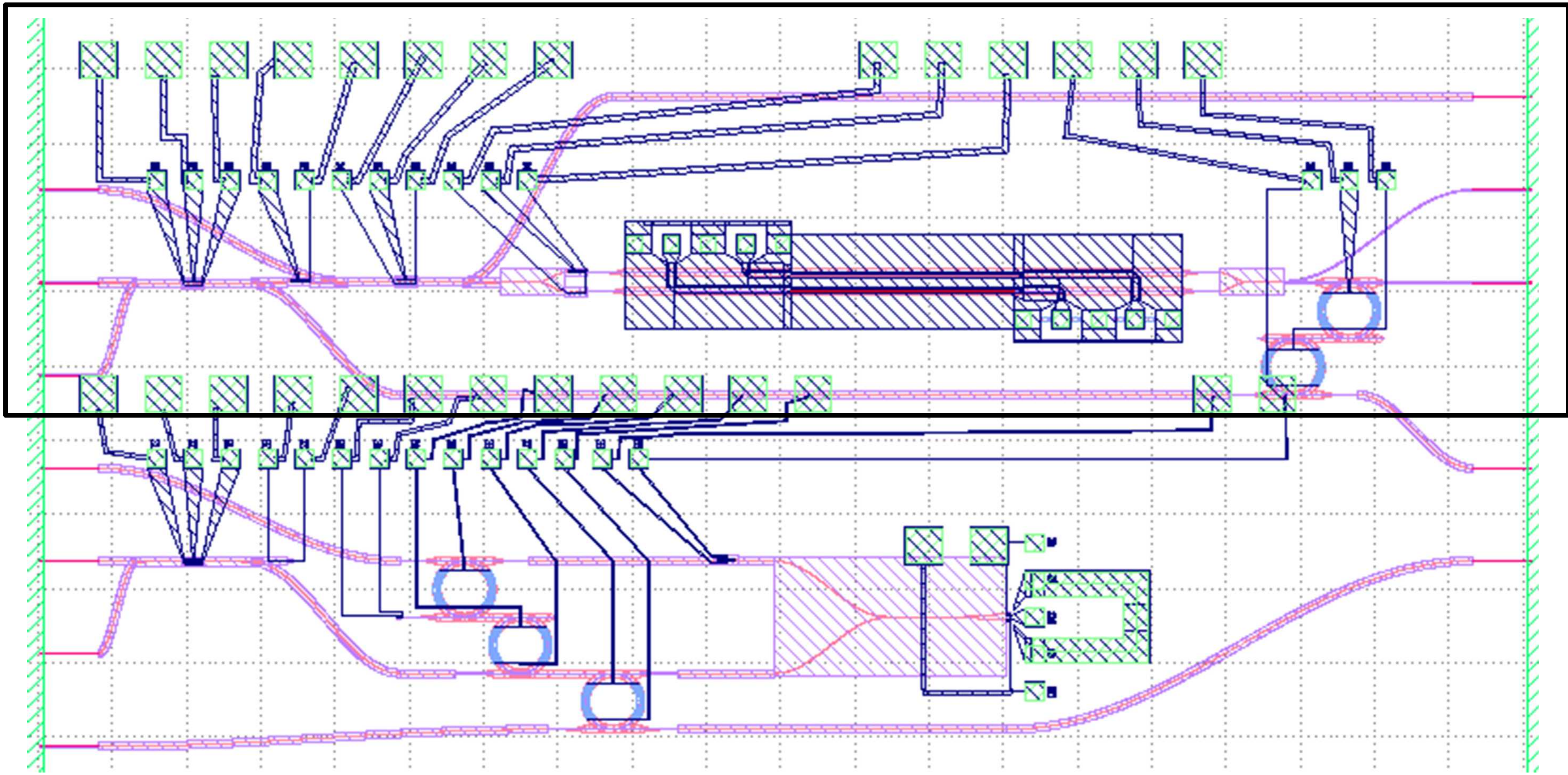
- Modified from Granger-Diamanti bench-top design due to difficulty in long delays on chip.
- Uses well-characterized existing devices within Sandia's Si Photonics platform.
- Can use coherent states or squeezed states.
- Need to develop simple package for protocol testing.



CV-TX/RX Layout



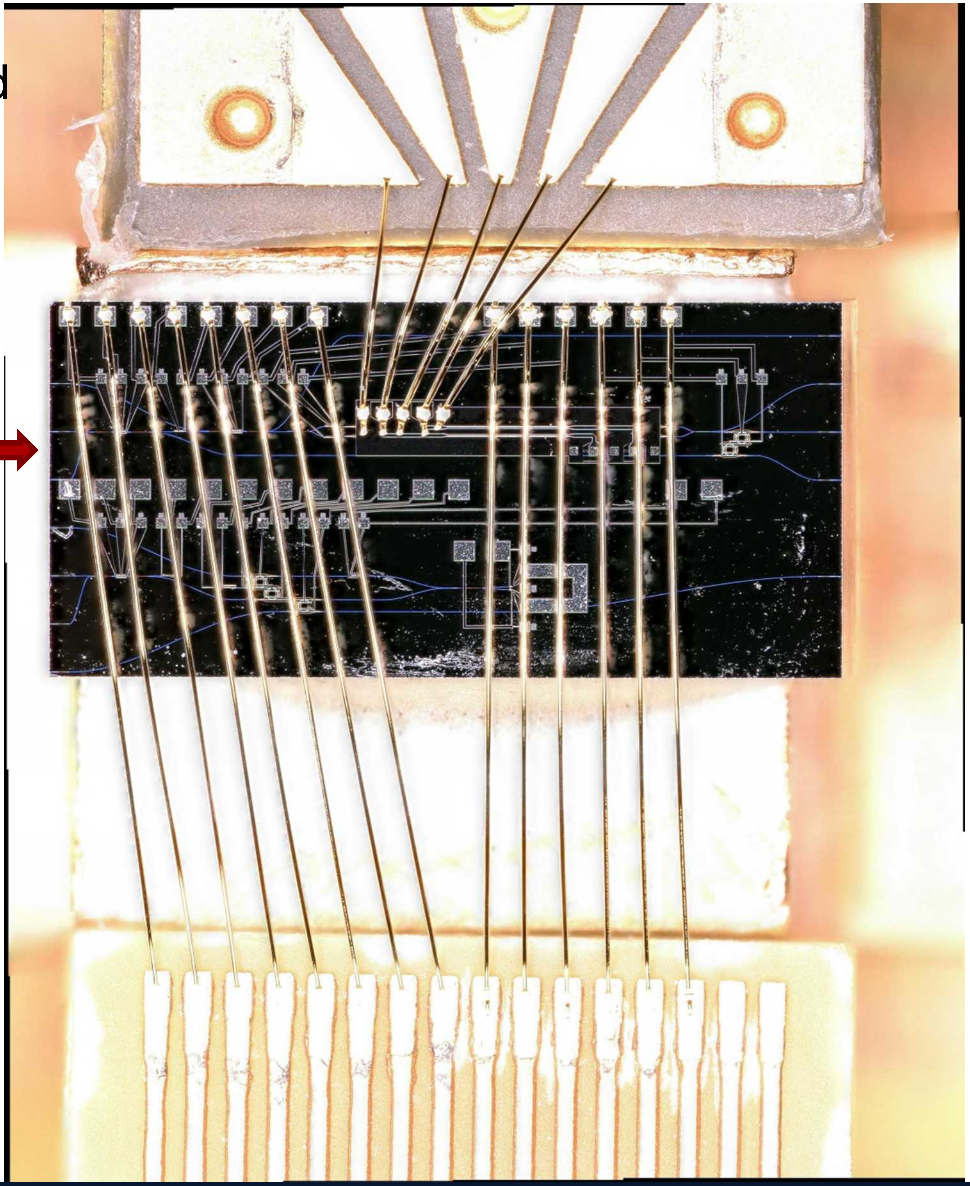
Alice CV-Tx



Wire-Bonded CV-TX

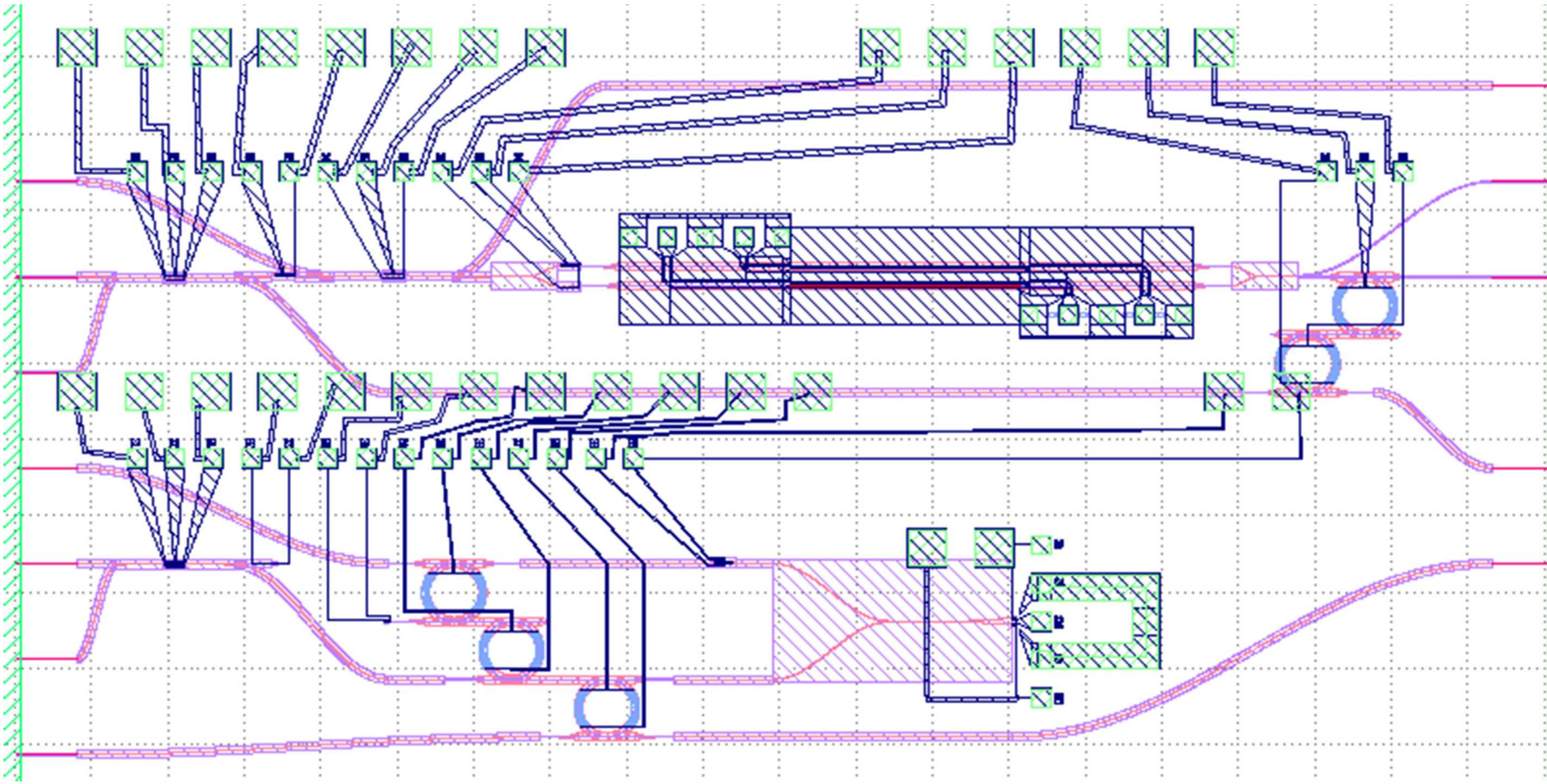
High speed board
> 25 GHz

Fiber input

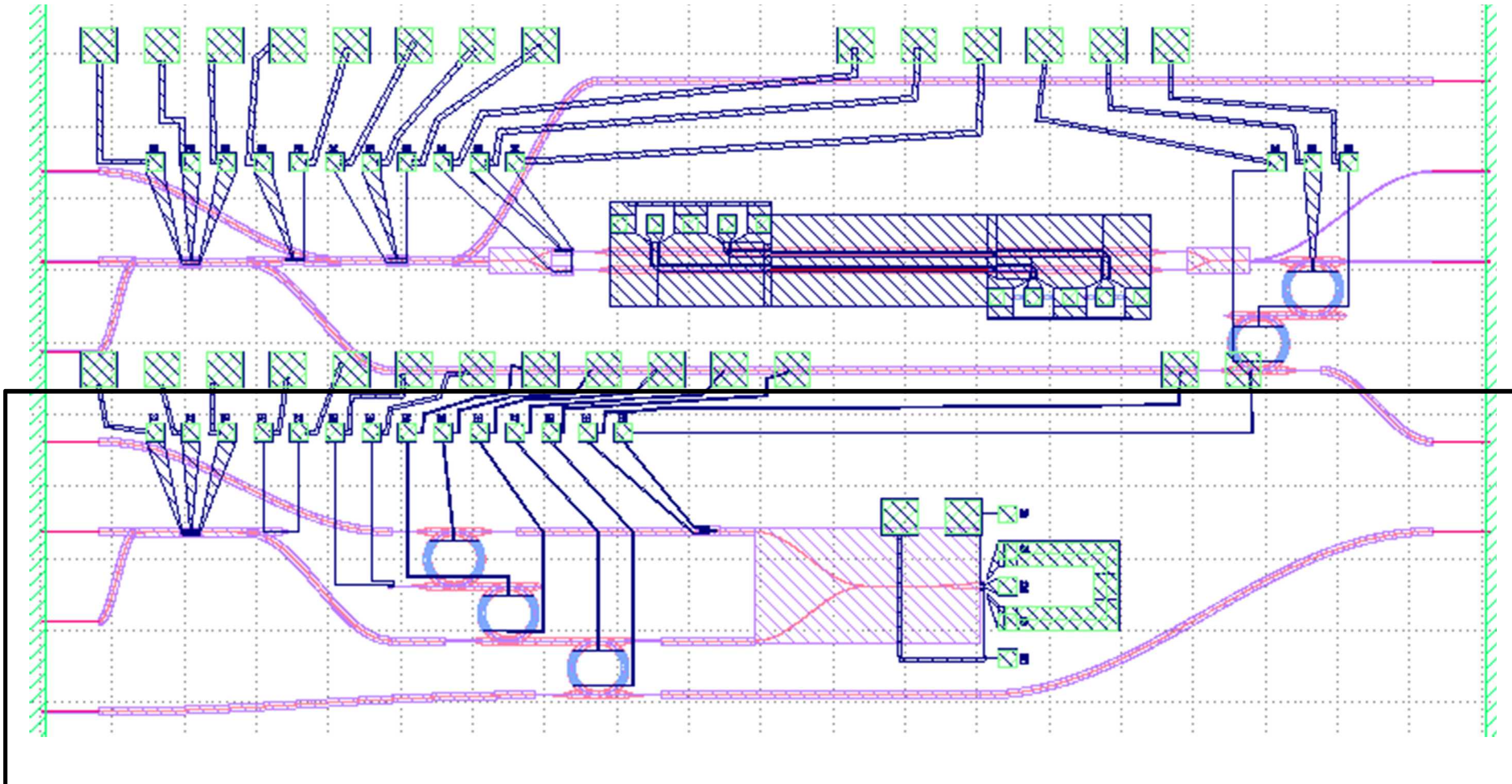


DC /Low speed
< 1MHz

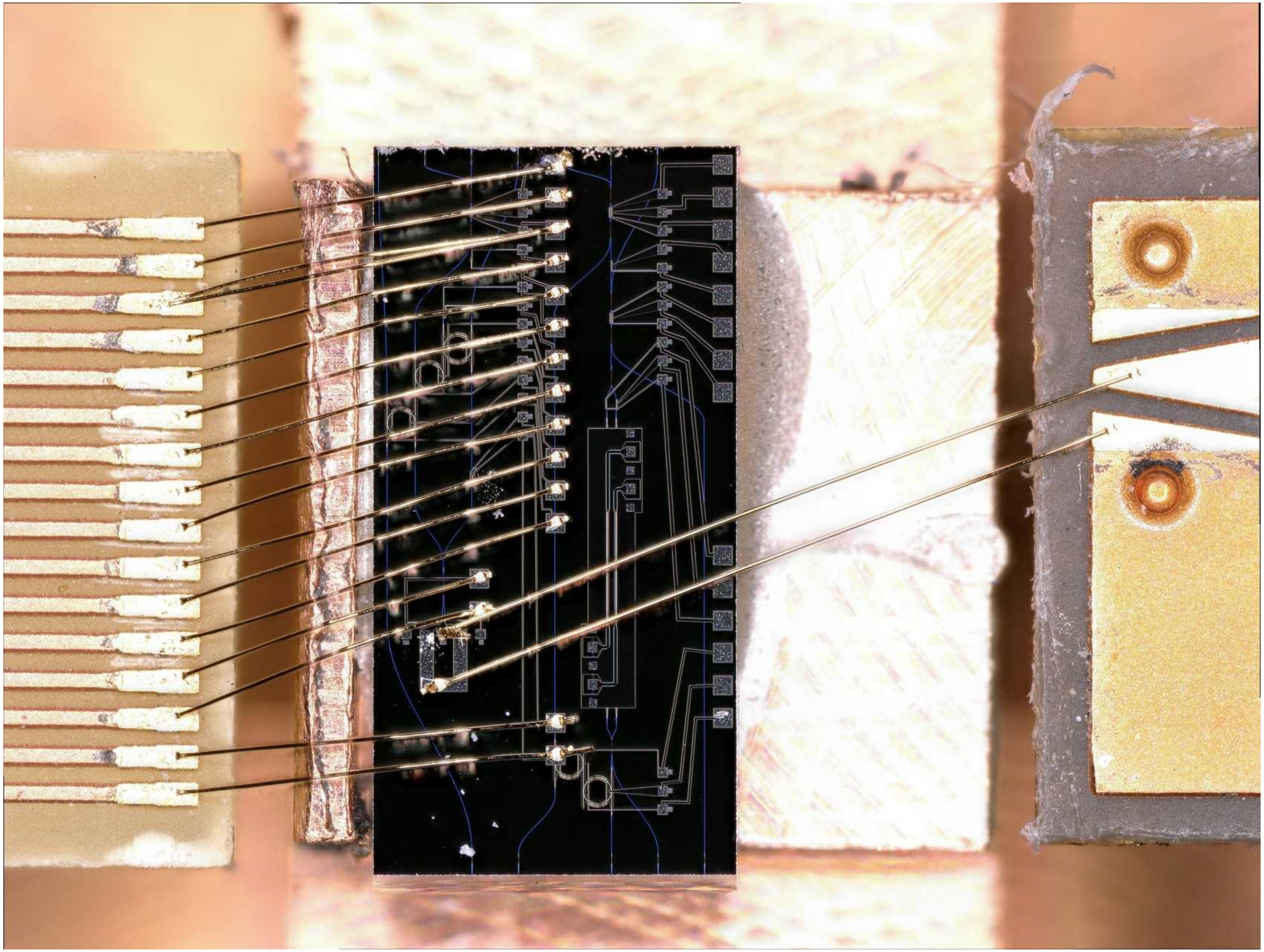
CV-TX/RX Layout



Bob CV-Rx



CV-Receiver



Summary

- Reviewed Sandia's Si Photonics platform.
- Highlighted Quantum Communications research direction.
- Chip-scale Quantum Key Distribution as a demonstration vehicle.
  - Two different chip-scale protocols
  - Free-space BB84 using new chip-scale polarization control devices.
  - Requires integrated Single Photon detection capability.
  - Fiber Continuous variable QKD
  - New Protocol development for on-chip CV.
- Designed & Testing Transceivers!