SAND2014-16673PE

Exceptional service in the national interest

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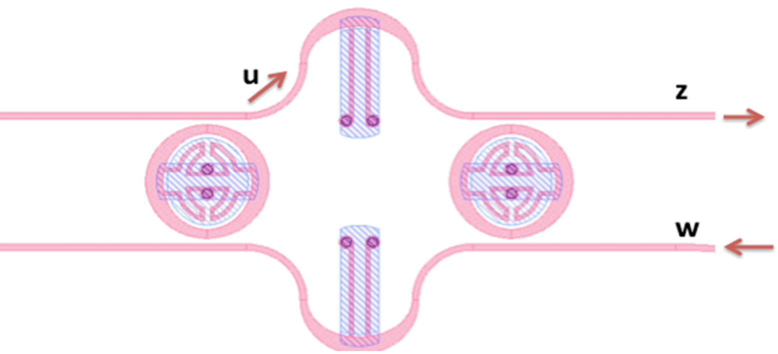

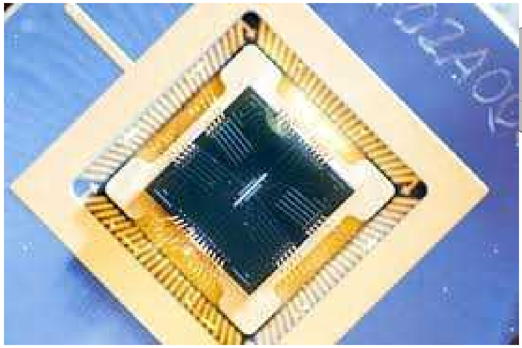

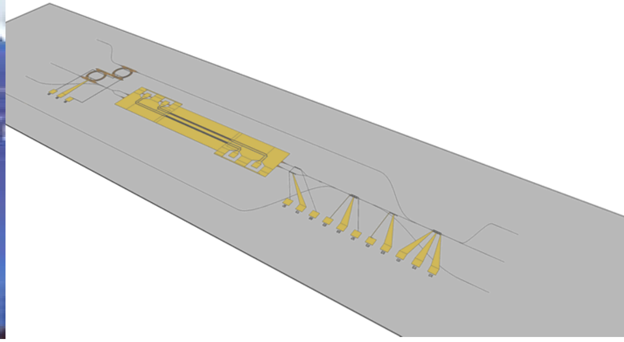

Maturing quantum technologies

A National Lab perspective

Mohan Sarovar

Sandia National Laboratories, Livermore, CA, USA

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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The national lab perspective

- Between academia and industry
- Cannot compete with industry
- Some unique capabilities
  - Large scale fabrication, testing & computing facilities
  - Several areas of expertise in the same organization
  - Well suited to tackle system-level and scaling problems

Outline

- Example project: next-generation QKD hardware
  - Integrated photonics and coherent quantum feedback control
- Looking ahead: a couple of problems of interest
  - **Quantum computing**: Fault detection in medium-to-large scale quantum systems
  - **Quantum simulation**: When is a quantum simulation robust?

Outline

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SECANT QKD
A Grand Challenge in Quantum Communications

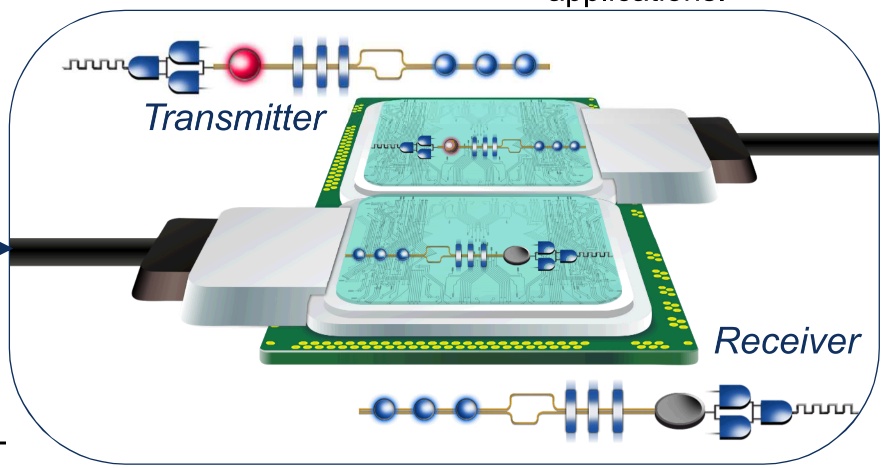
PI: Ryan Camacho, Sandia National Labs

Goals

1. Construct chip-scale, handheld **quantum transceivers** that can implement DV, CV, free-space, and fiber based QKD.
2. Demonstrate hybrid QKD network with chip-scale transceiver nodes.

Potential Impact

1. Quantum-based key generation for hybrid networks of mobile devices without central hub.
2. First step towards micro-fabricated low cost QKD for ground-to-plane, plane-to-plane, metro, satellite etc. applications.
3. Toolbox for other applications in photonic QIP.



Challenges

1. Develop robust CMOS compatible room temp single-photon detectors.
2. Develop integrated quantum sources.
3. Low-loss quantum signal processing.
4. Combine all components onto one integrated chip.

Capabilities

1. World class teams in integrated photonics, quantum theory, and systems.
2. MESA/CINT microfabrication facilities.

3 yr program, 10 months in...
(FY 2014 – FY 2016)

The Current State of Quantum Communications Hardware

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- Bulk Optics Based (>10g / component)
- Expensive (> $50k per system)
- Slow or Short distance (Mbt/s or 10's of km)
- Secure?

SECANT program

Quantum Communications

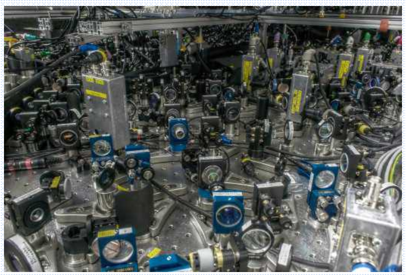
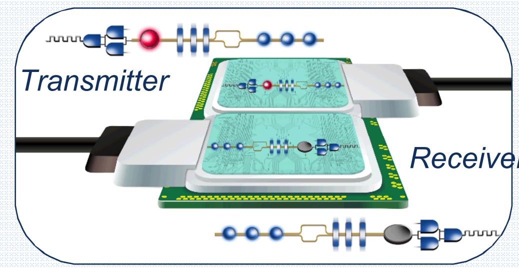


Photo: Toshiba

LANL

ID Quantique



Electronic Circuits

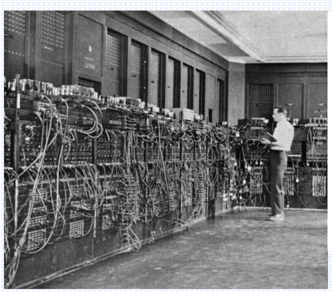


Photo: U.S Army

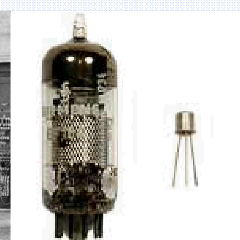


Photo: Texas Instruments

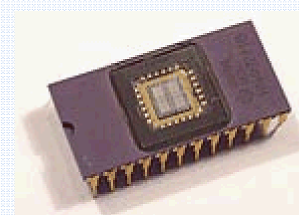
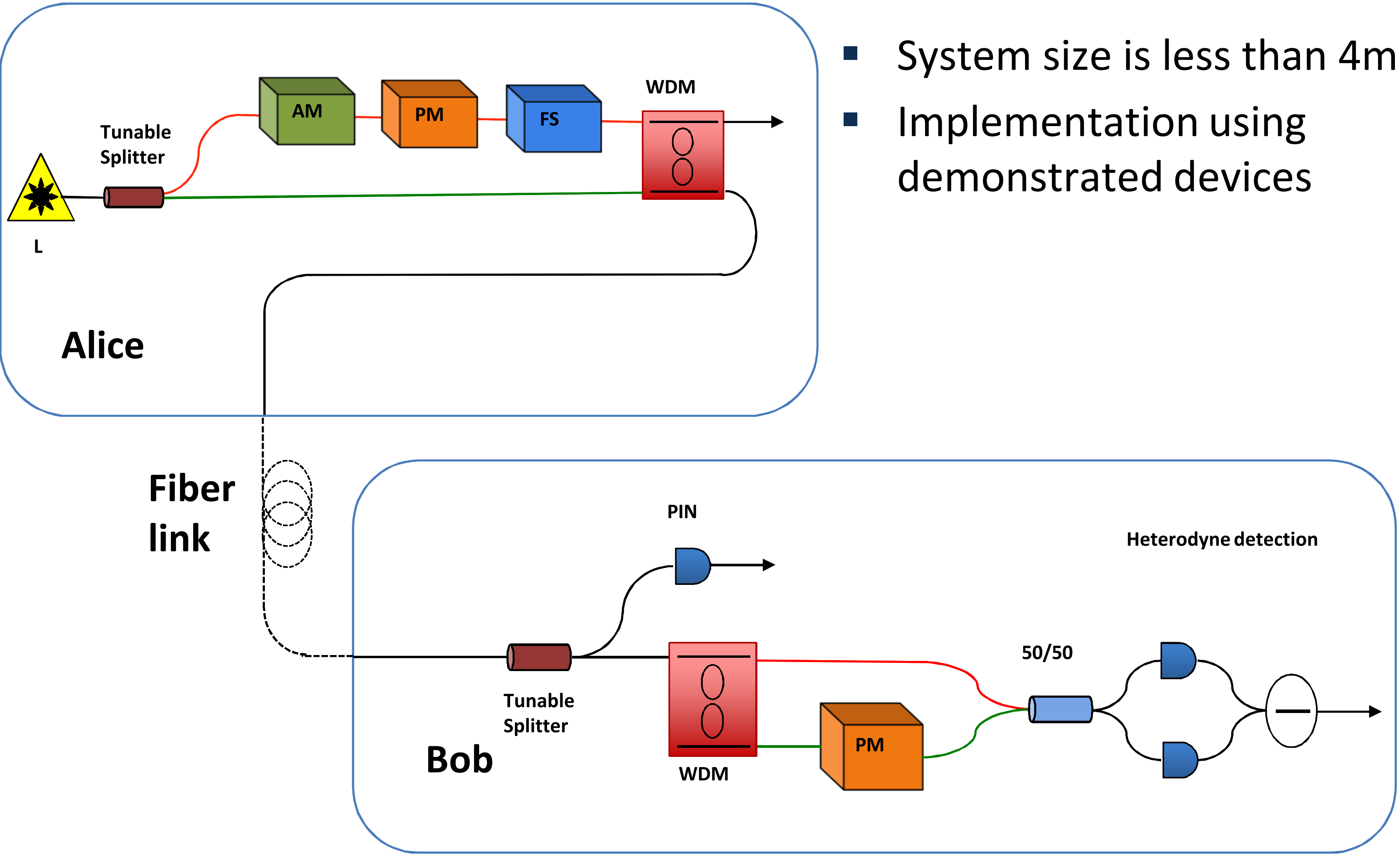


Photo: nobelprize.org

Example: On-Chip CVQKD System



- System size is less than $4mm^2$
- Implementation using demonstrated devices

[Chris DeRose, Daniel Soh, MS, Paul Davids, Ryan Camacho, Sandia]

On-Chip CV-QKD Transmitter (Alice)

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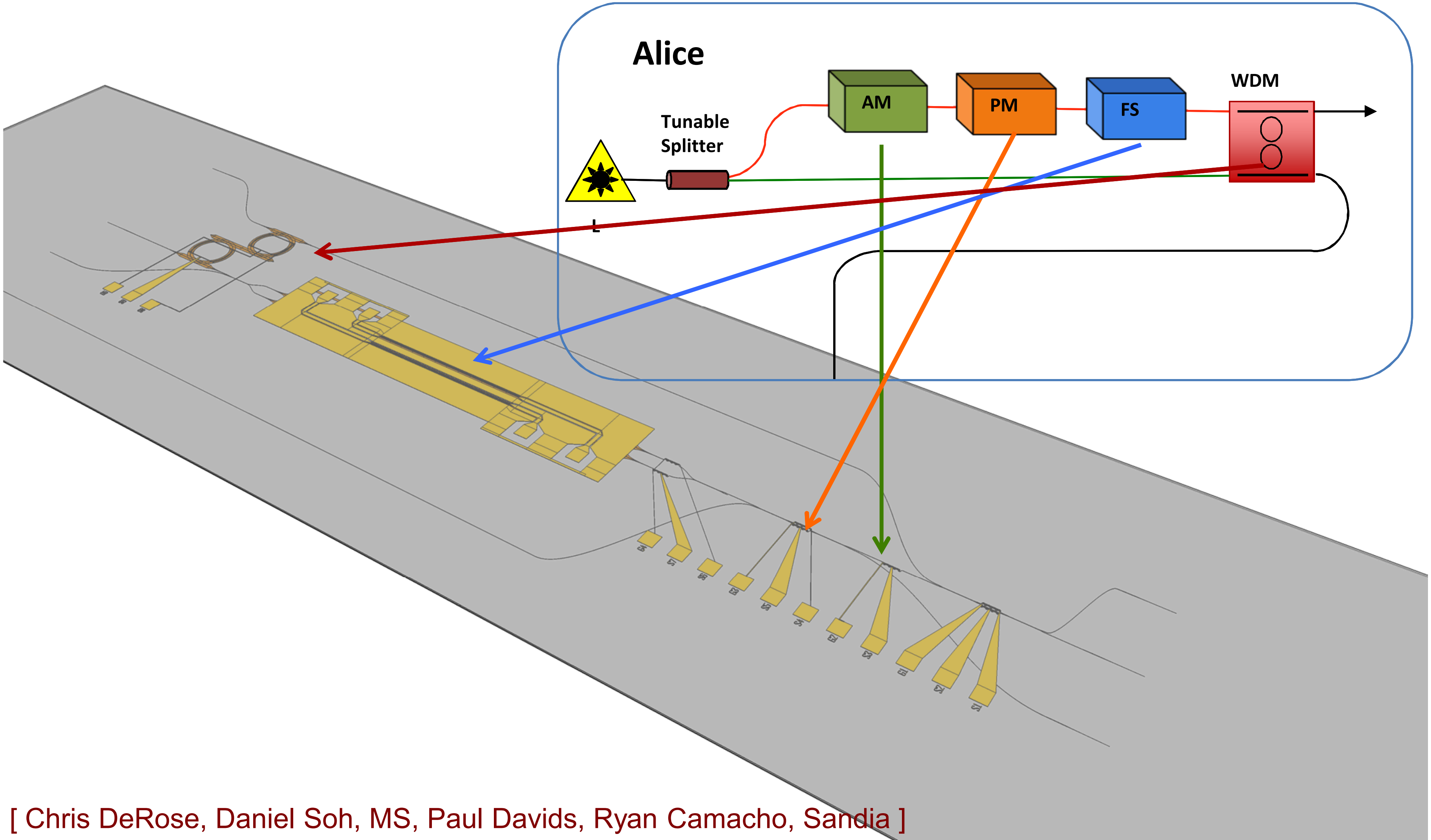
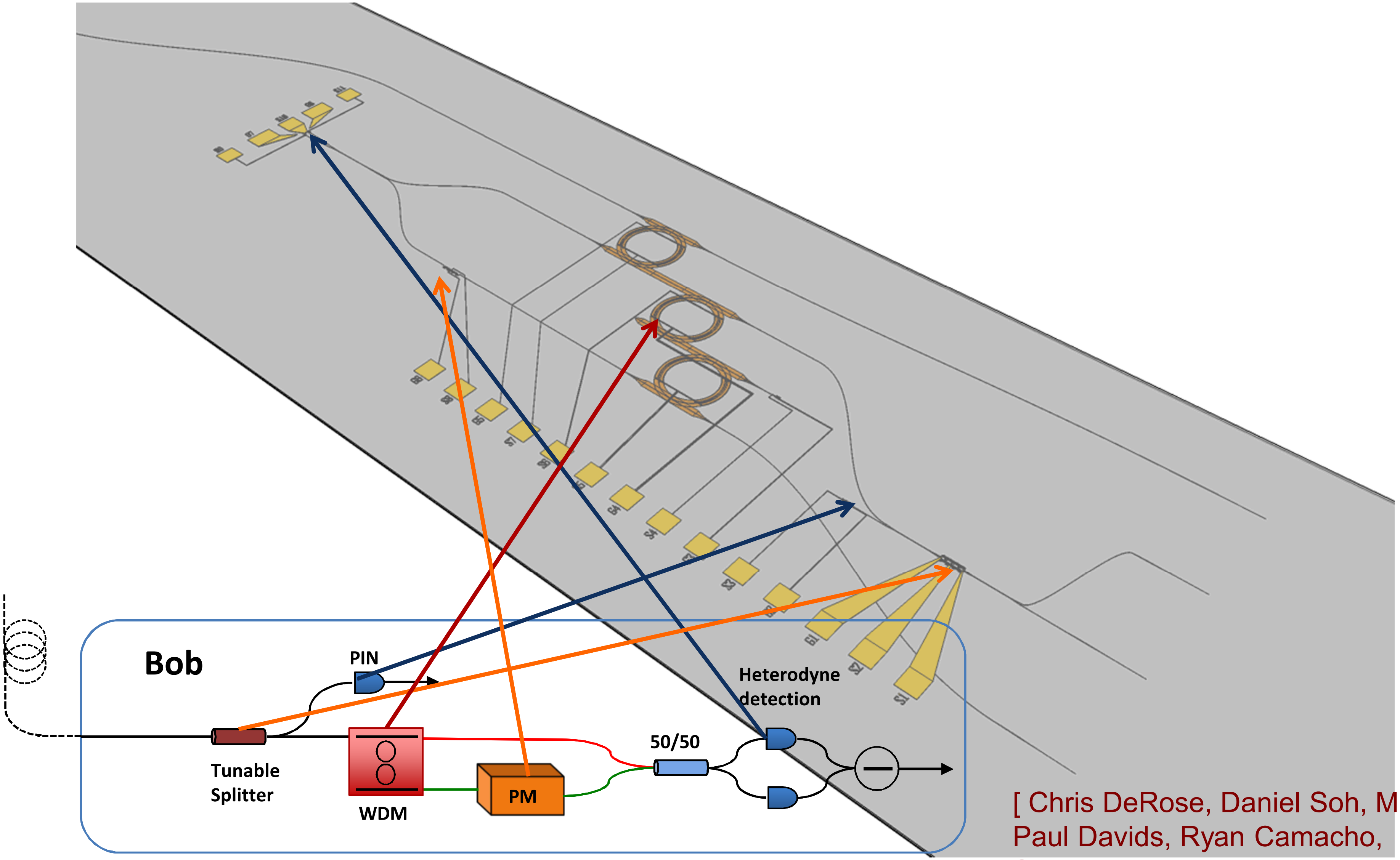


[Chris DeRose, Daniel Soh, MS, Paul Davids, Ryan Camacho, Sandia]

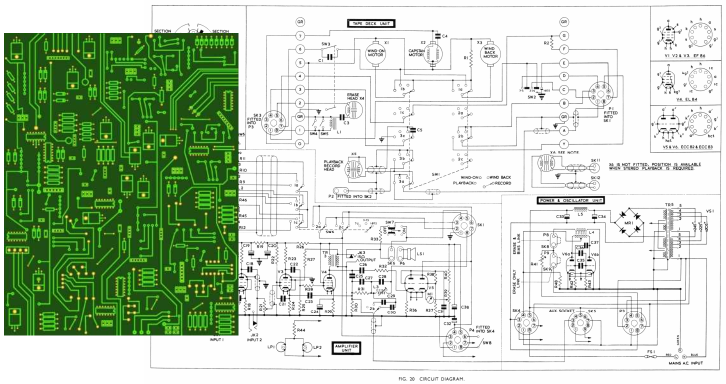
On-Chip CV-QKD Receiver (Bob)



[Chris DeRose, Daniel Soh, MS, Paul Davids, Ryan Camacho, Sandia]

CQFC and integrated optics

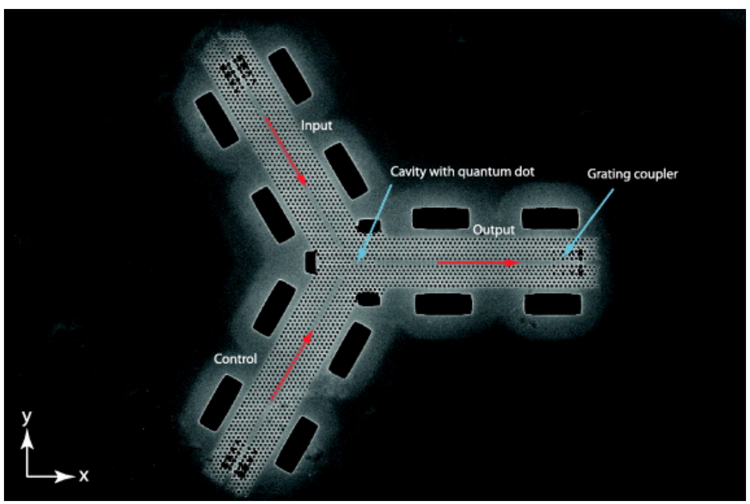
CQFC = lumped element circuit analysis for quantum optics



Electrical circuits

Basic elements: capacitors, inductors, resistors, op-amps, etc.

Tools: VHDL, SPICE, Electronics Workbench



[Vuckovic group, Stanford]

Optical circuits in low power or quantum regimes

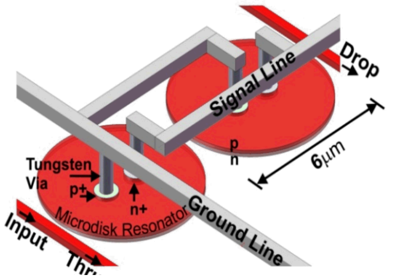
Basic elements: beam splitters, cavities, waveplates, mirrors, etc.

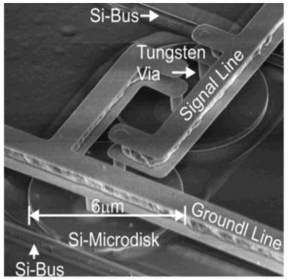
Tools: QHDL, SLH formalism

Applications:
- Low power all-optical switching
- Producing engineered states of light
- Optical signal processing

Silicon Photonics

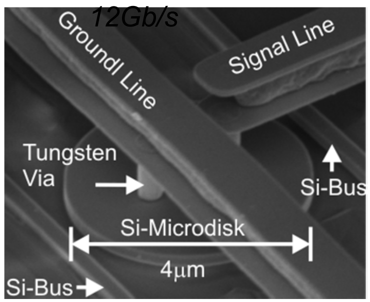
Free-carrier Effect (high-speed)

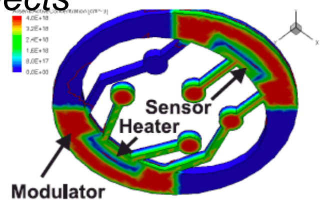


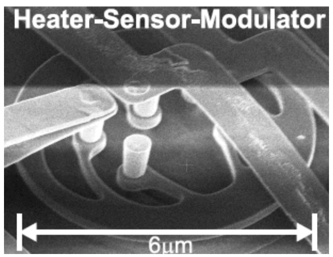


Fast Reconfigurable Interconnects

3.2fJ/bit at 12Gb/s



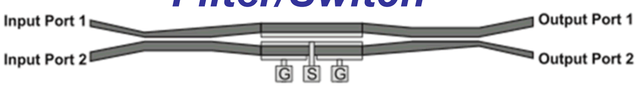




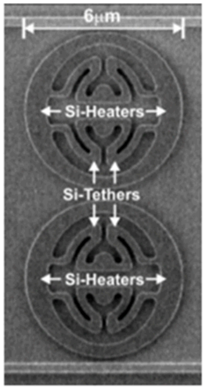
Resonant Optical Modulator/Filter

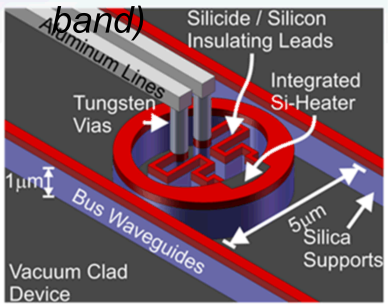
Thermally stabilized modulator

Broadband Mach-Zehnder Filter/Switch < 1V-cm at 10 Gb/s

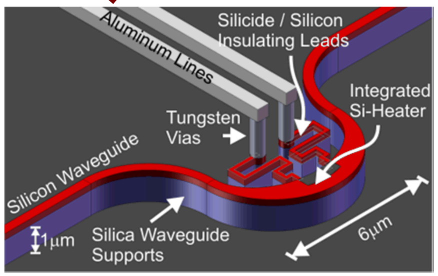


Thermal Optic Effect (wide-band)



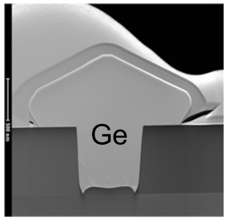


Tunable Resonant Filter

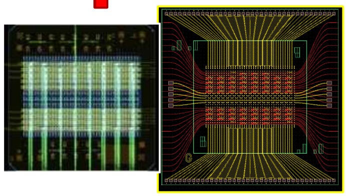


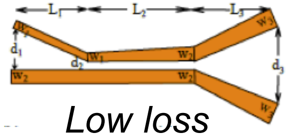
Thermo-optic Phase Shifter

High-speed Ge Detector in

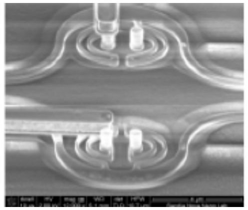


Si Photonics-CMOS Integration

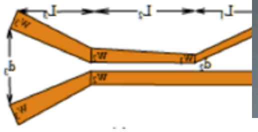


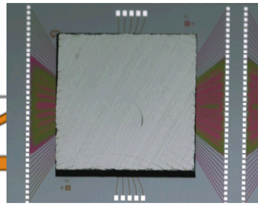


Low loss optical coupler



Switch Arrays



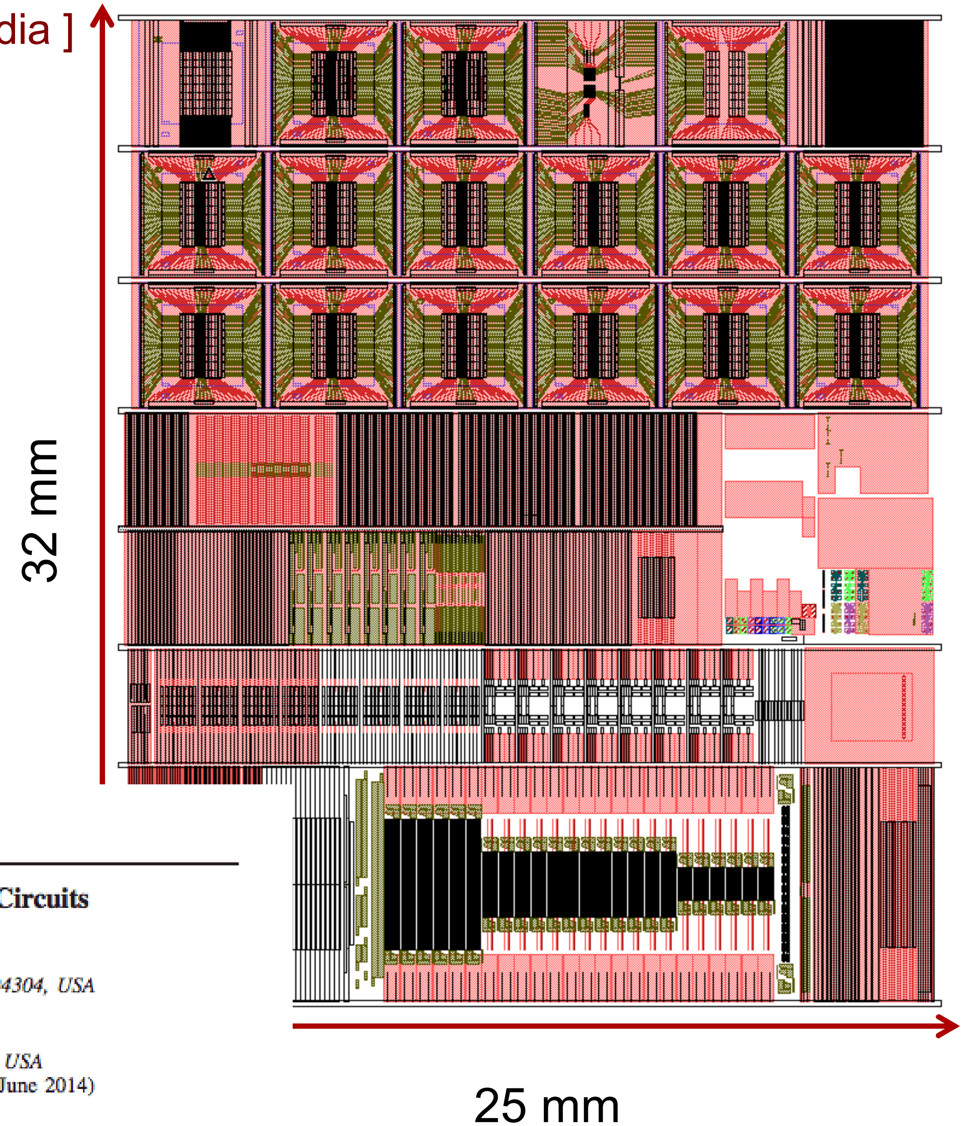


[Paul Davids, Sandia]

Integration enables large scale CQFC

Optical Transceiver for Exascale

[Paul Davids, Sandia]



PHYSICAL REVIEW APPLIED **1,** 054005 (2014)

Quantum Noise in Large-Scale Coherent Nonlinear Photonic Circuits

Charles Santori,* Jason S. Pelc, and Raymond G. Beausoleil
Hewlett-Packard Laboratories, 1501 Page Mill Road, MS1123, Palo Alto, California 94304, USA

Nikolas Tezak, Ryan Hamerly, and Hideo Mabuchi
Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA
(Received 24 February 2014; revised manuscript received 24 May 2014; published 26 June 2014)

Guiding light in silicon

- Dispersion
- Linear loss
  - Surface scattering
  - Raman/Brillouin scattering
- Nonlinearities ($\chi^{(3)}$ mainly)
- Two-photon absorption
- Free carrier generation, heating

At low power/intensity most of these do not matter.
But field concentration can be significant in certain integrated structures.

Guiding light in silicon

- Dispersion
- Linear loss
  - Surface scattering
  - Raman/Brillouin scattering

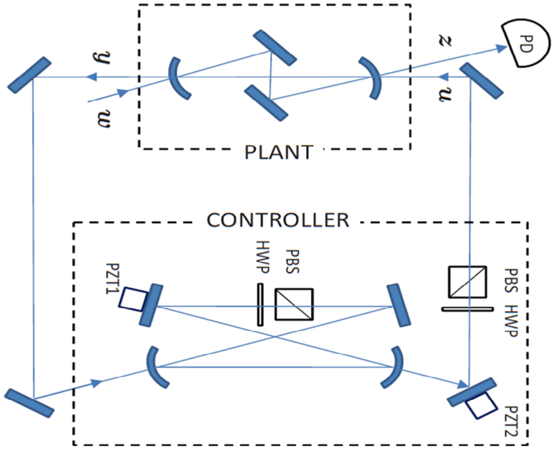
} Does not impact SLH, Hudson-Parthasarathy treatment

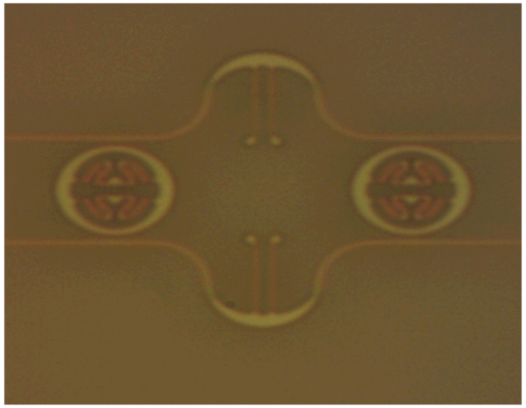
- Nonlinearities ($\chi^{(3)}$ mainly)
- Two-photon absorption
- Free carrier generation, heating

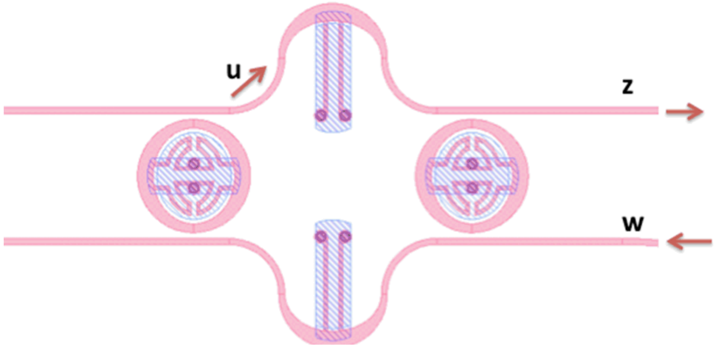
Possible solutions:
(1) Nonlinear input-output theory
(2) Model nonlinearities as sequence of SLH elements

A simple example

- Explore simple quantum coherent quantum feedback control circuit.
  - H. Mabuchi. Coherent-feedback quantum control with a dynamic compensator. Physical Review A, 78(3):032323, 2008.







[Jonathan Cox, Paul Davids, Sandia]

Outline

- Example project: next-generation QKD hardware
  - Integrated photonics and coherent quantum feedback control
- Looking ahead: a couple of problems of interest
  - **Quantum computing**: Fault detection in medium-to-large scale quantum systems
  - **Quantum simulation**: When is a quantum simulation robust?

Fault detection in quantum systems

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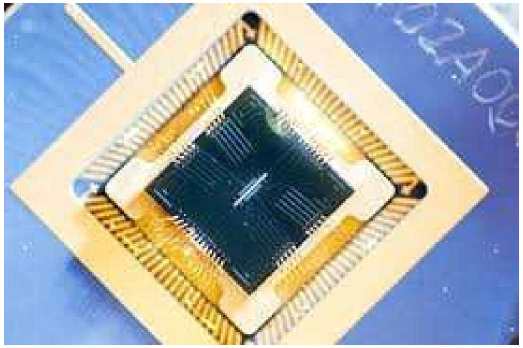
Building quantum computing platforms to scale



Sandia on-chip ion trap

Assembling well characterized qubits and applying well characterized one and two-qubit gates.

Fault tolerance theorem should be sufficient to guarantee correct operation of device.

BUT…

Fault detection in quantum systems

- Things that could violate the usual error models:

  1. Cross talk in control lines
  2. Unintentional effects of control fields
  3. Persistent faults – dead qubits or links due to fabrication imperfection
  4. …

“Emergent faults” that arise due to connectivity and scale of system

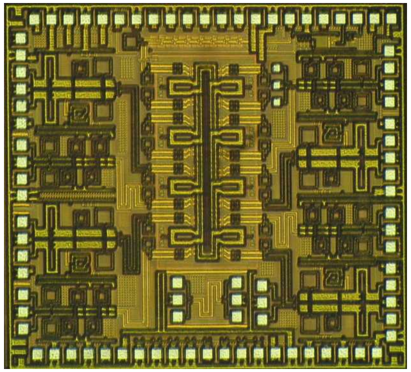
- Tomography would reveal these, but unfeasible at medium-to-large scale

- Randomized benchmarking scales, but does not yield the fine grained information necessary to identify faults

- Especially problematic for near-term implementations where error in each element will be close to threshold

Fault detection in quantum systems

- **Some ideas**
  - Use information from error correction cycles to diagnose device in "online"
    - 1405.0964
  - Statistical inference based on calibration sequences
  - Adapt techniques from classical fault detection and isolation



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Robust quantum simulation

- When can we trust a ground state preparation device?

$$\hat{H}_0 = \sum_i \hat{h}_i$$

$$\hat{H}_{\rm real} = \sum_i \hat{h}_i + \sum_i \delta\hat{h}_i$$

- The actual ground state $|\Psi_0\rangle$ is NOT robust in general
  - Quantum phase transitions and ground state fidelity [Zanardi et al.]
  - Anderson orthogonality catastrophe
- But how robust are the observables we might care about?

Robust quantum simulation

- Given an ideal Hamiltonian and perturbation/error model:

$$\hat{H}_0 = \sum_i \hat{h}_i$$

$$\hat{H}_{\text{real}} = \sum_i \hat{h}_i + \sum_i \delta\hat{h}_i$$

- What are the robust observables?
  - At T=0 and T≠0.

Conclusion

- Many interesting problems *en route* to scaling and maturing quantum information technologies

- Many of these problems have similarities to problems faced when scaling classical technologies