SAND2014-18551PE

SECANT QKD Grand Challenge

Sandia Enabled Communications and Authentication Network using Quantum Key Distribution

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LORD

CV-QKD and on-chip coherent quantum feedback

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U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

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Moving optical networks on-chip

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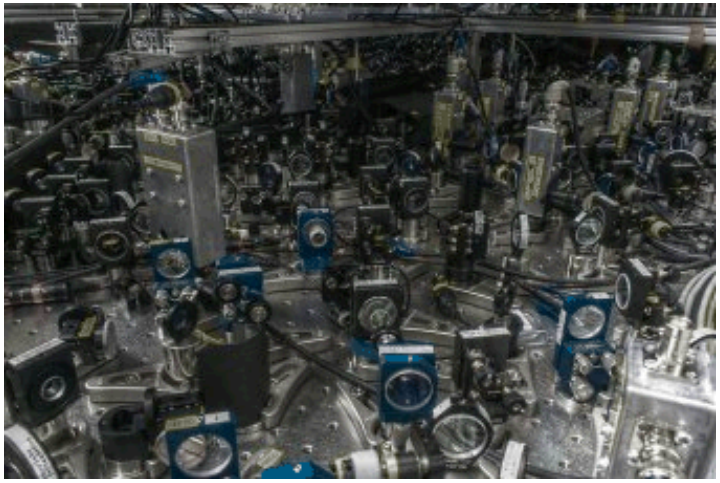

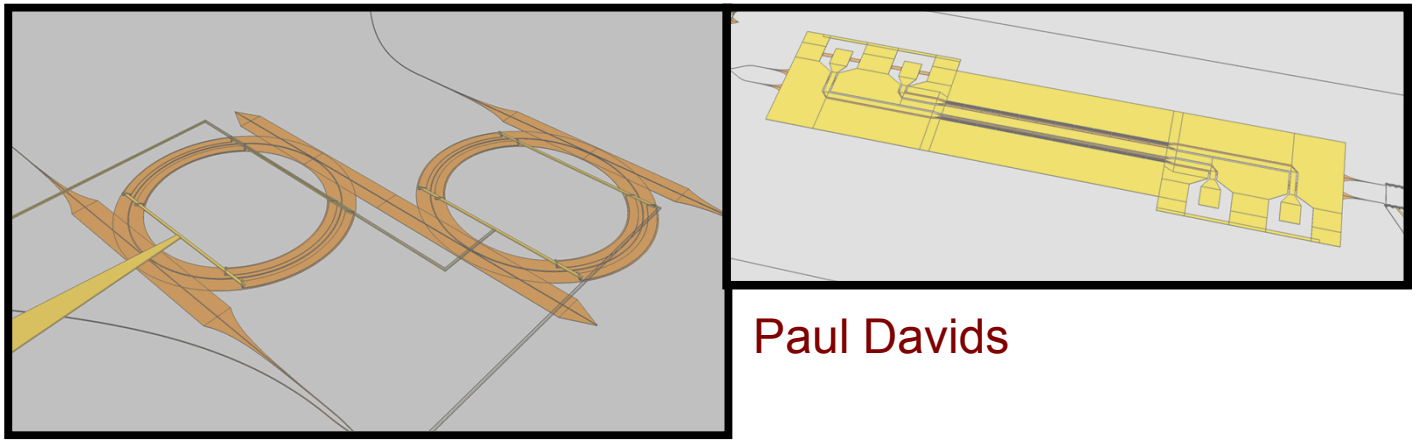

Paul Davids

SNL Photonics Fabrication

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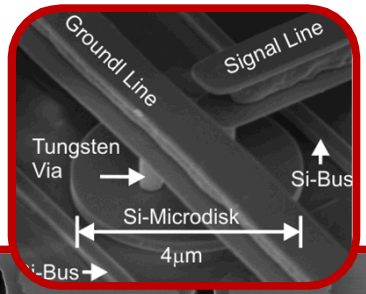
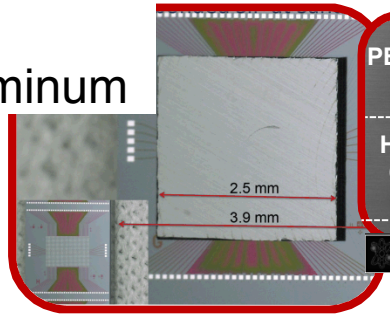
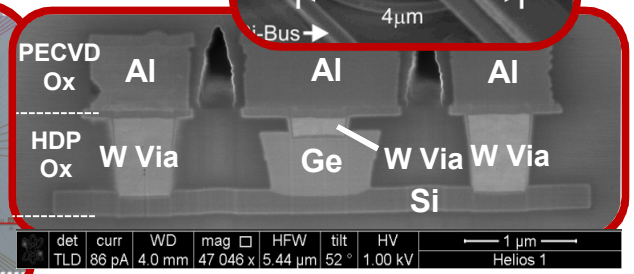
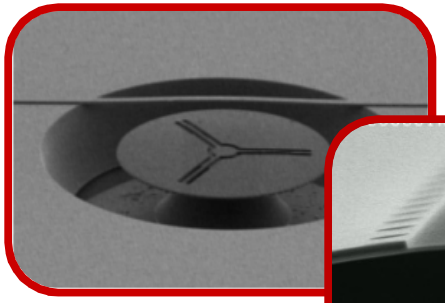
- Low-energy modulators[1], detectors[2], low-loss waveguides, SiN edge couplers, travelling wave Mach-Zehnder modulators, grating couplers, advanced CMOS flip-chip / direct CMOS integration

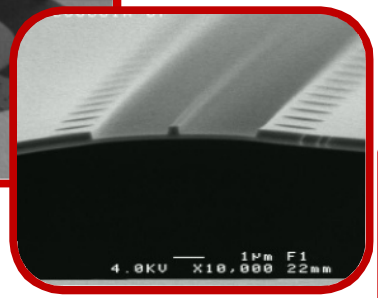


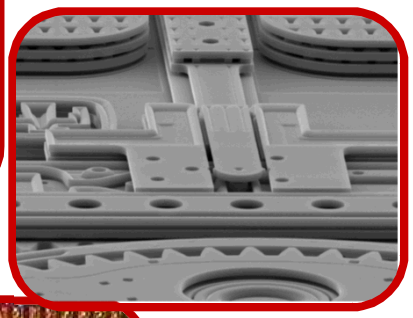
- Suspended Si/SiN resonators phononic/photonic crystals[3], aluminum nitride resonators and transducers.



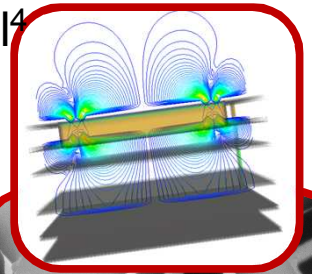




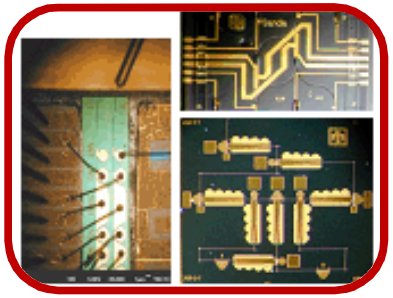


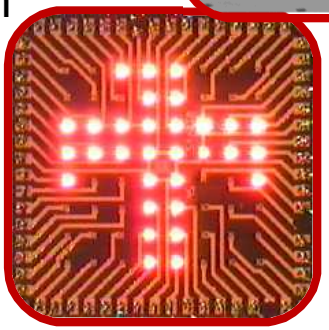


- Near to long-wave IR plasmonics and metamaterial[4] based devices.

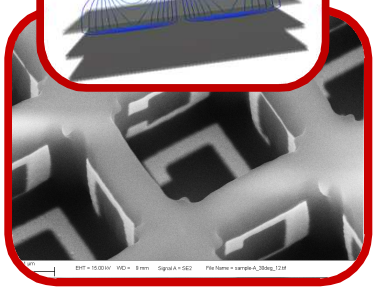


- Compound semiconductor devices and fabrication





- MEMS processing



[1]M.R. Watts, et al. OPEX **19** 21989 (2011)
[2]C.T. DeRose, et al. OPEX **19** 24897 (2011)
[3]P.T. Rakich, et al. Nature Comm. **4** 1 (2013)
[4]D.B. Burckel, et al. Advanced Mat. **22** 5053 (2010)

Core Silicon Photonics

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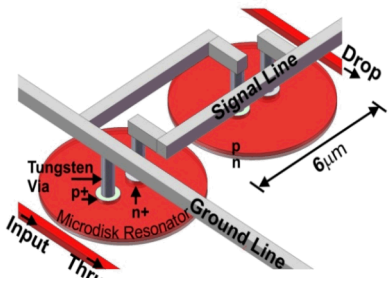
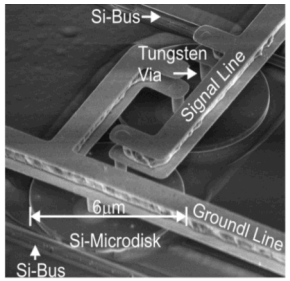
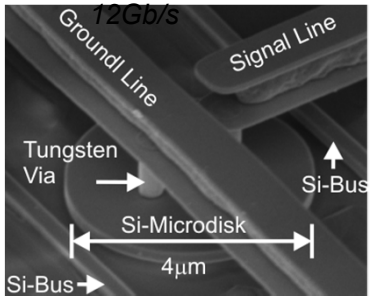
Free-carrier Effect (high-speed)

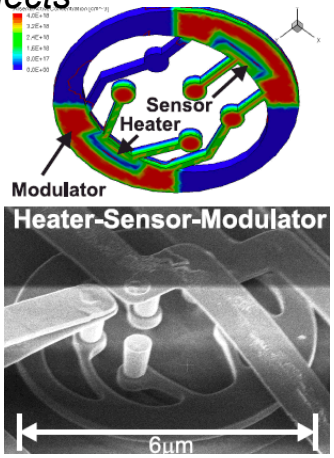




Fast Reconfigurable Interconnects

3.2fJ/bit at 12Gb/s



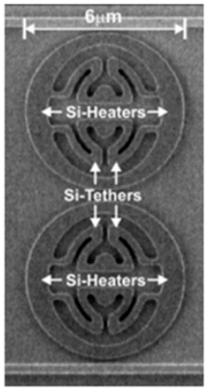


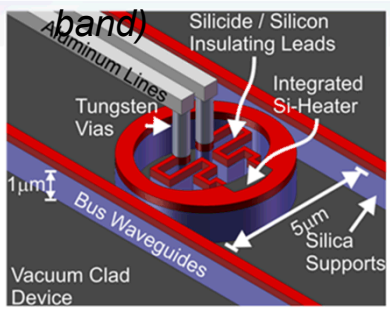
Resonant Optical Modulator/Filter

Thermally stabilized modulator

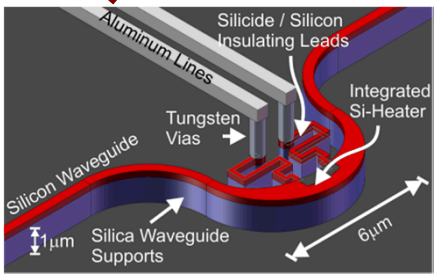
Broadband Mach-Zehnder Filter/Switch < 1V-cm at 10 Gb/s

Thermal Optic Effect (wide-band)

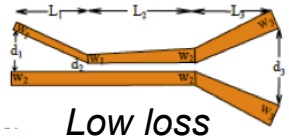




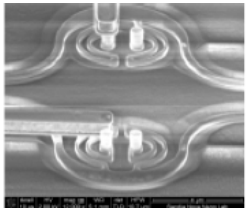
Tunable Resonant Filt



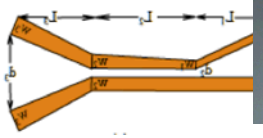
Thermo-optic Phase Shifter

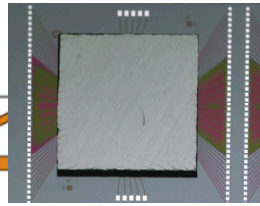


Low loss optical coupler

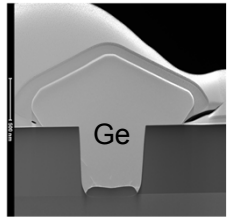


Switch Arrays

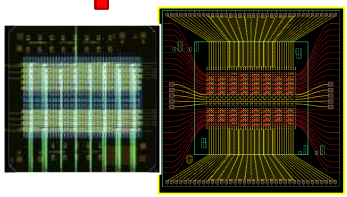




High-speed Ge Detector in



Si Photonics-CMOS Integration



Electronic-Photonics Integration

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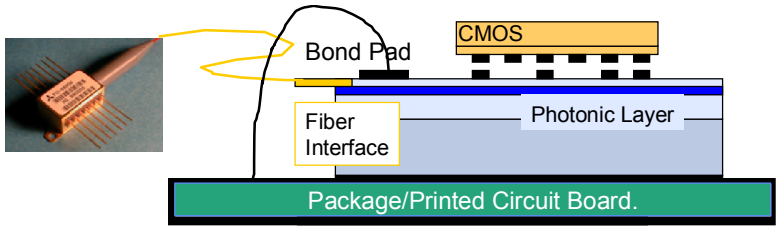
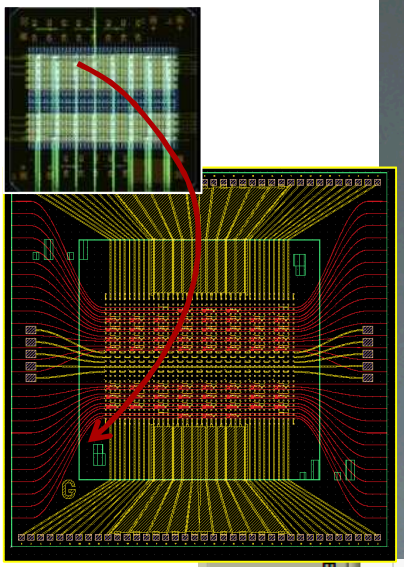
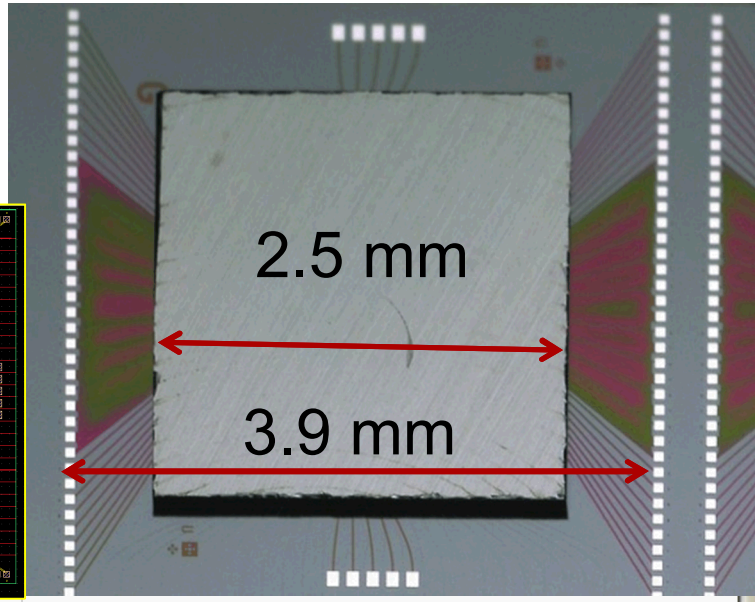
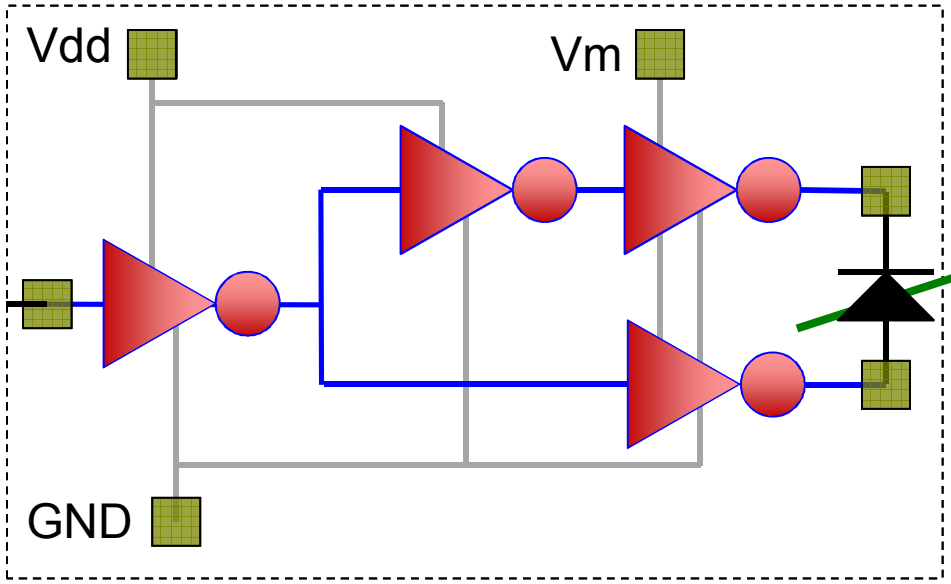
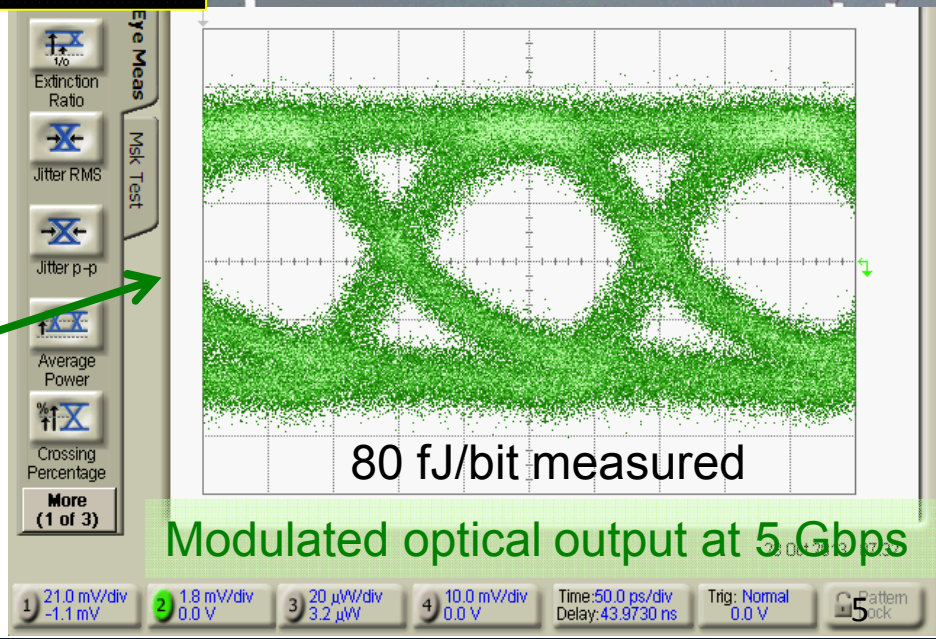






- Heterogeneous integration
  - Independent optimization of electronics & photonics
  - Challenge: Need high yields and small bond size

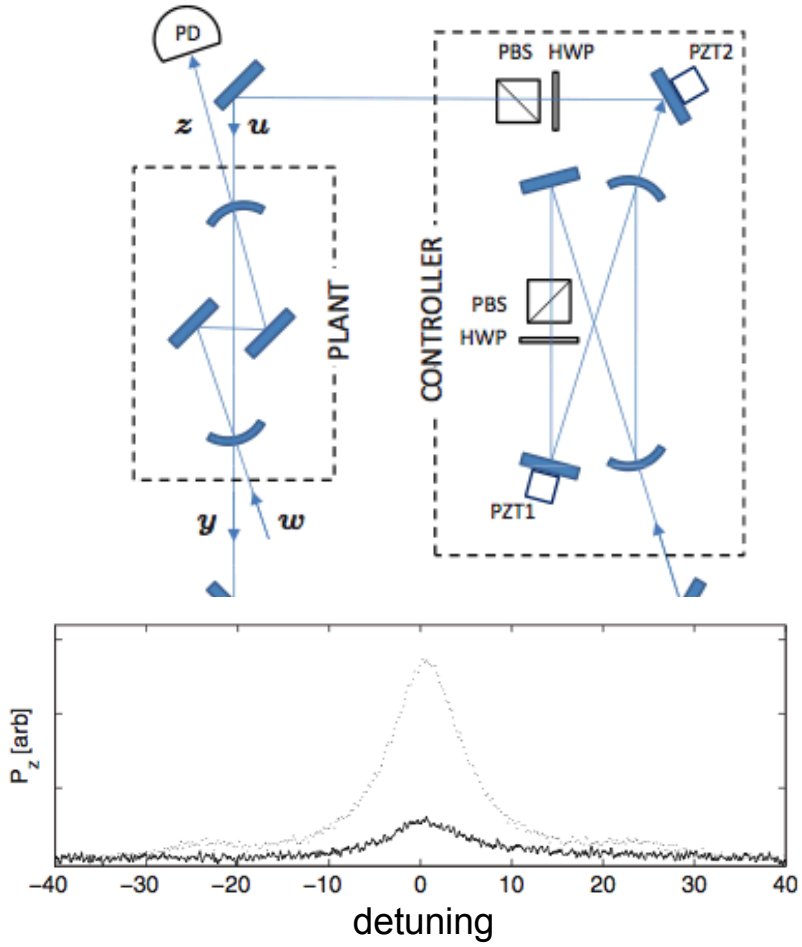




Coherent quantum feedback

Example: disturbance rejection

Example: disturbance rejection by dynamic compensation



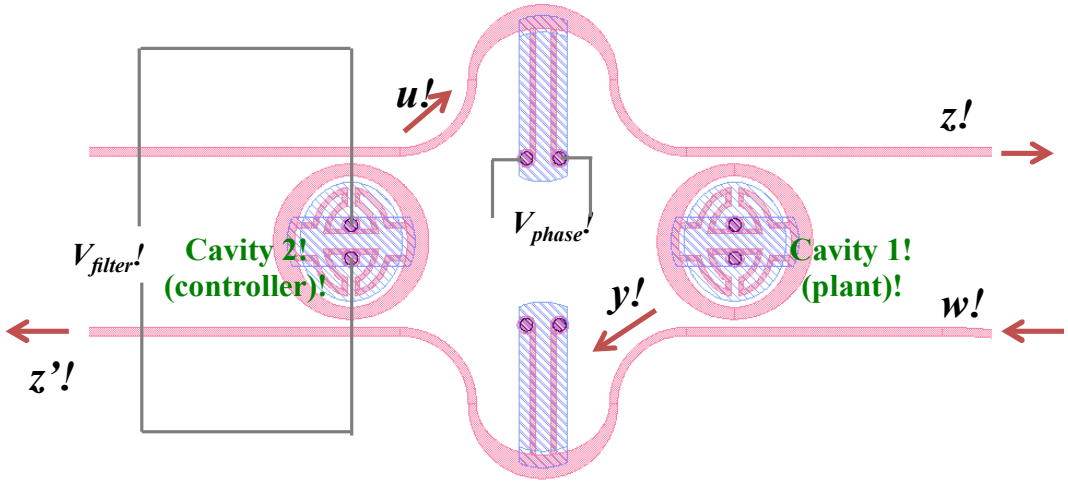
Goal: maintain z(t)=0 in the presence of w(t)

Feedback: use cavity output y(t) and actuate with u(t)

Mabuchi, H. *Phys. Rev. A*, *78*, 032323 (2008).

James, M. R., Nurdin, H. I., & Petersen, I. R. *IEEE Transactions on Automatic Control*, *53*, 1787 (2008).

On-chip CQFC



Paul Davids
Jonathan Cox

Free parameters in device (in linear mode)

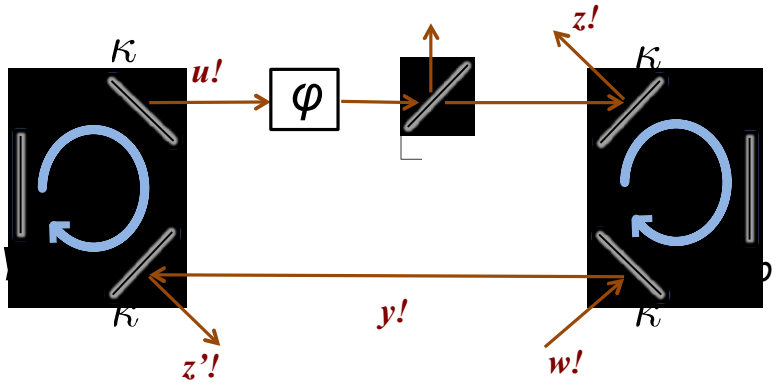
Resonance frequencies of two cavities (ω_p, ω_c)

Cavity-waveguide coupling κ

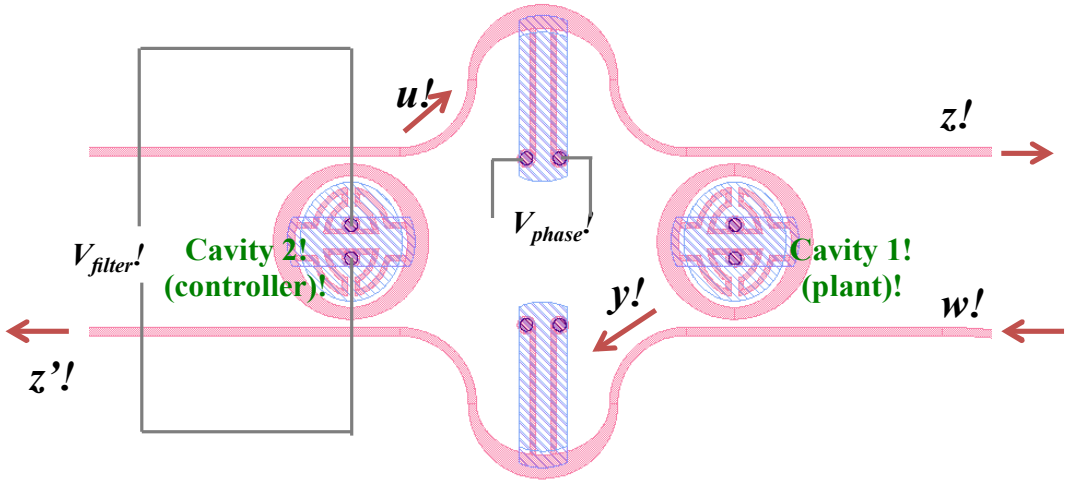
Intrinsic cavity losses (γ_p, γ_c)

Feedback phase ϕ

Losses in waveguide coupling η



On-chip CQFC

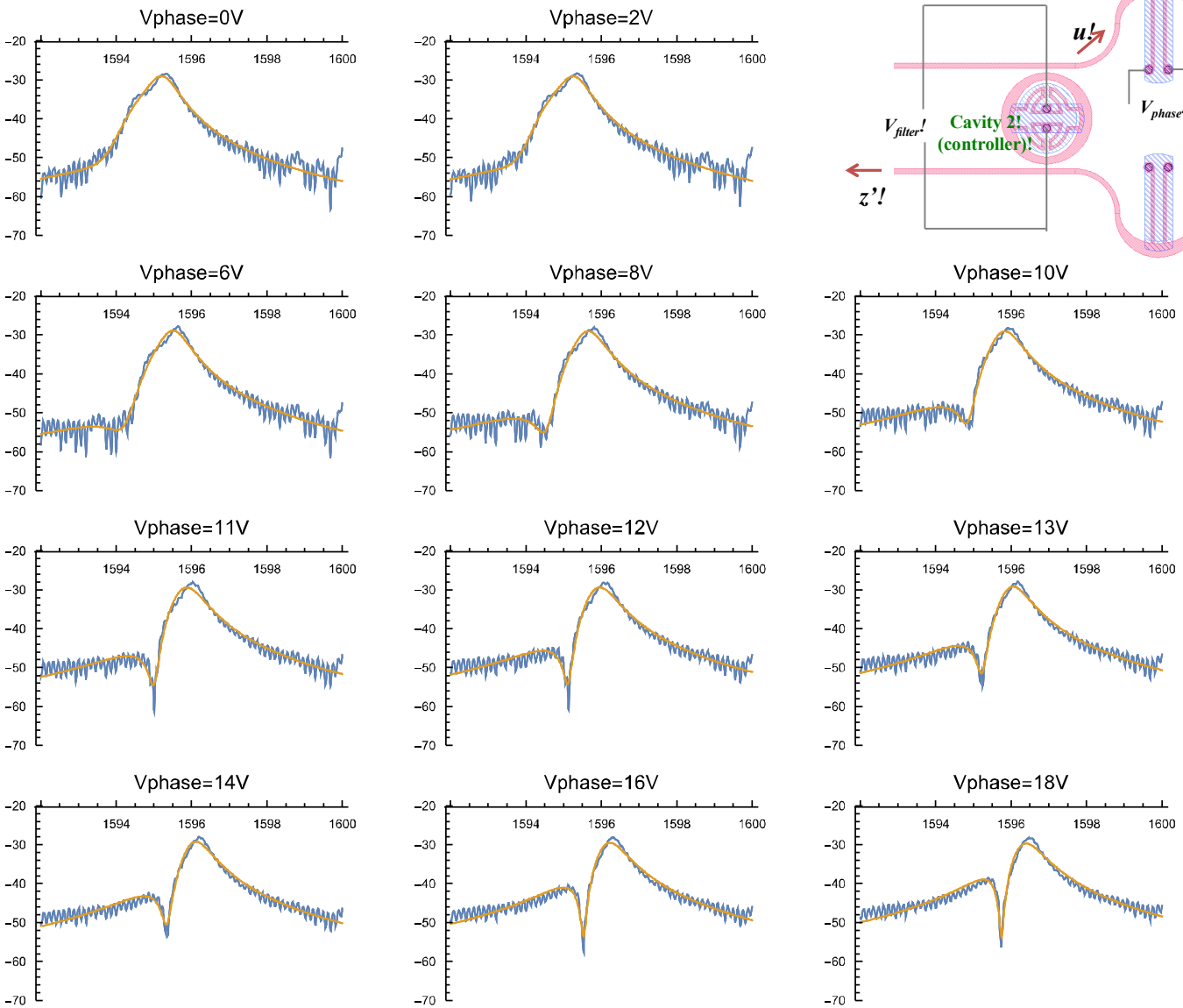


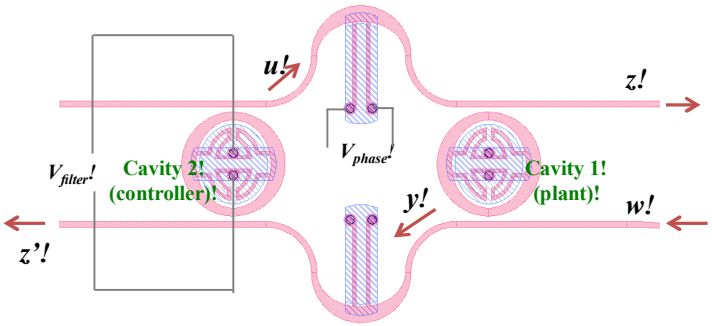
Built SLH model for this device.

Weak probe power => all components in their linear regime

Equivalent to the transfer function approach used by Mabuchi
[Mabuchi, H. *Phys. Rev. A*, *78*, 032323 (2008)].

Transmission spectra

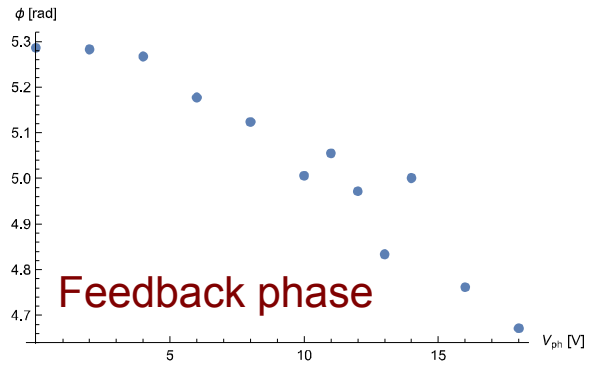


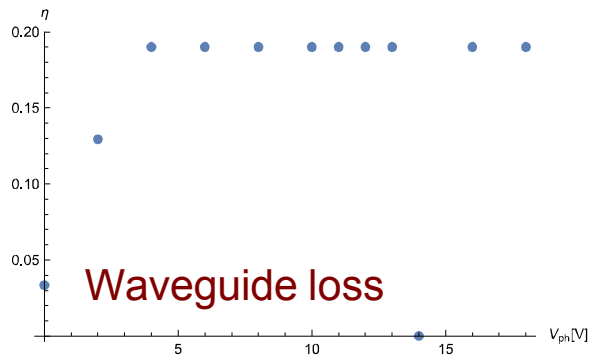


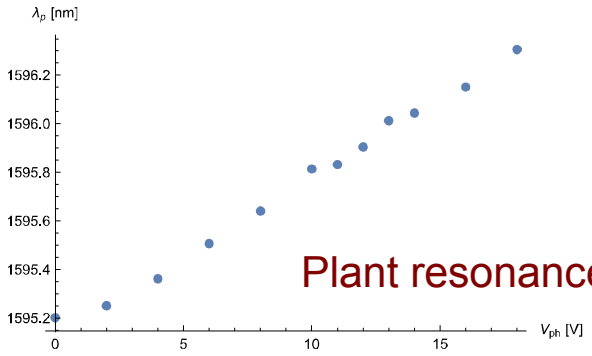
Experiment

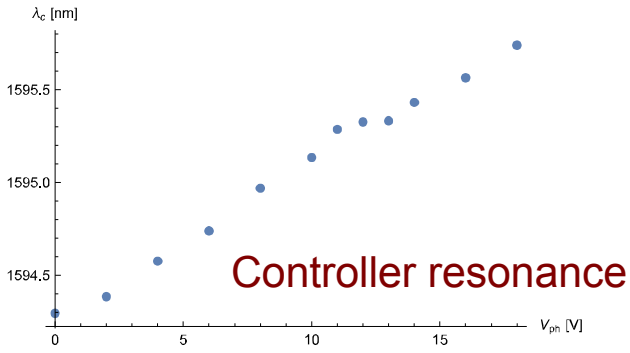
Theory

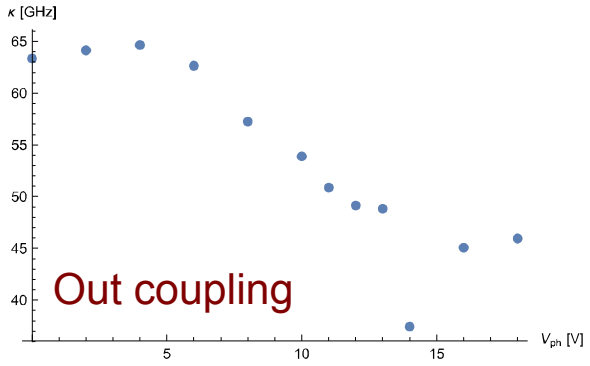
Theoretical fit to experiment











Thermal effect induced by thermo-optic phase shifter is not localized

No independent control over parameters

Integrated optics implementation of CQFC: issues

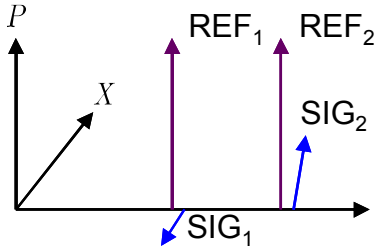
Sandia National Laboratories

- *Experimental challenges:*
  - In-situ control must be well localized and thermal effects contained
  - High quality nonlinear elements (e.g. OPO) necessary

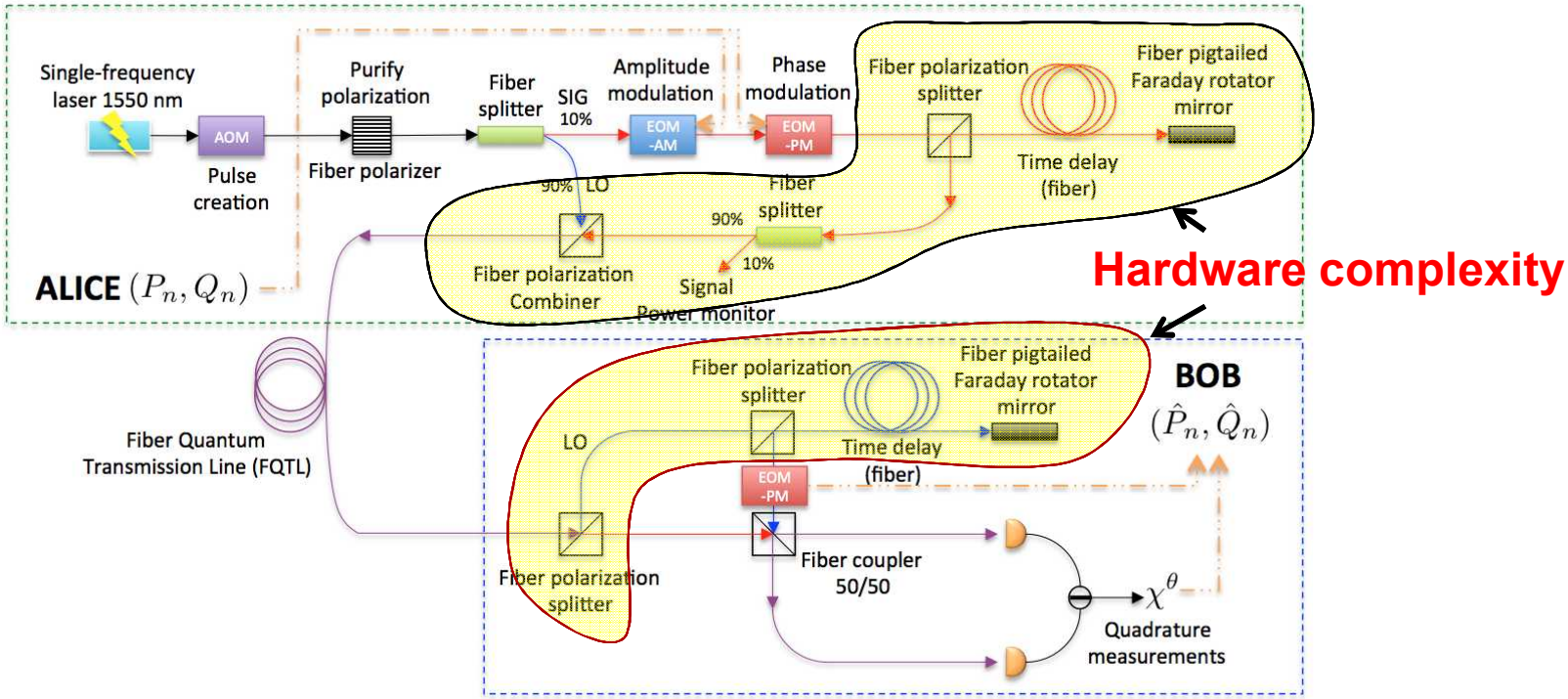
- *Theory challenges*:
  - Nonlinear effects (losses, Raman/Brillouin scattering) must be taken into account in resonant structures (if Q factor is large or probe power is large)
  - Two-photon absorption: can cause dynamical parameter changes (due to carrier concentration change, heating)
  - Thermal shifts of material properties

Year 1 research highlights

- Single OPO squeezed light apparatus almost complete
- Analysis and optimization of coupled OPO CQF network
- Implementation and analysis of on-chip optical feedback device
- New CV-QKD protocol without local oscillator transmission



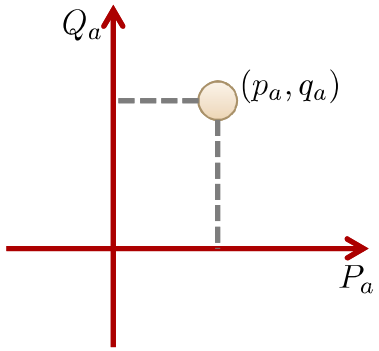
Sending a LO is expensive



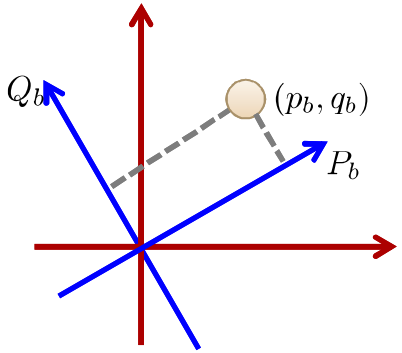
- Must multiplex SIG and LO
  - Strong LO added onto tiny SIG (50 dB power difference)
  - Multiple, simultaneous separation through – Time, Polarization, and Frequency (heterodyne)
- Complex phase tracking & control algorithm is needed for dynamic compensation of phase drift

LO = reference frame alignment

- Alice's encoding



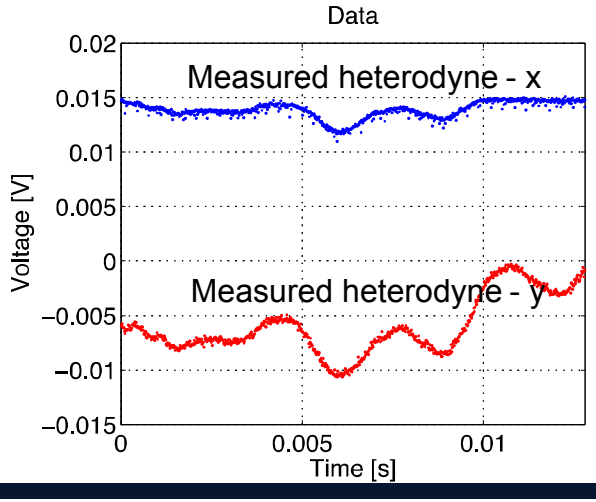
- Bob's decoding (homodyne)



$$(p_b, q_b) \neq (p_a, q_a)$$

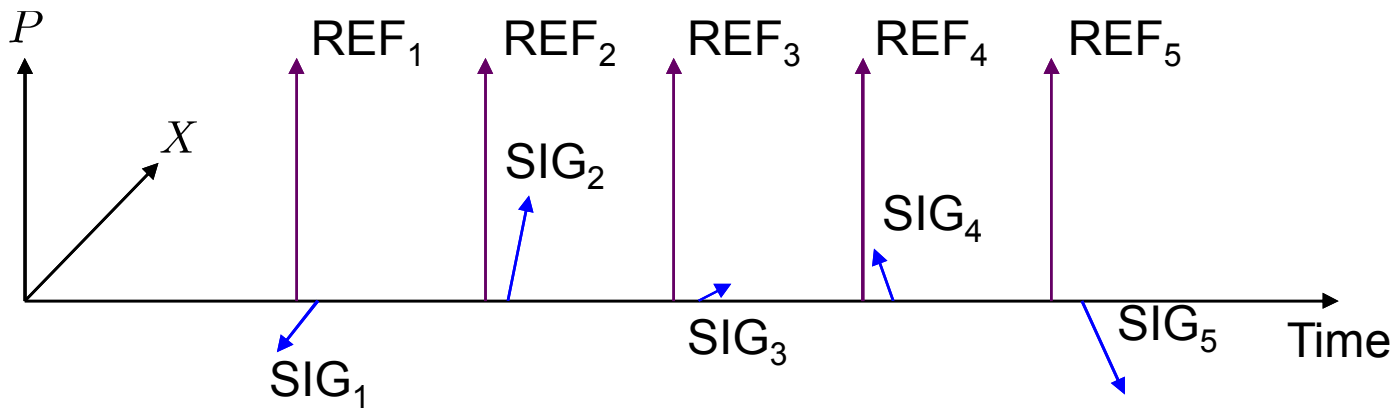
- Aligning Bob's quadrature angle with Alice's is important.
  - Quadrature angle is defined by phase difference between LO and SIG
  - If there is path-length difference between LO and SIG, Alice's angle may be different from Bob's angle.

Example: Alice transmits constant signal, signal measured by Bob:



Our solution: real-time referencing

- Every signal pulse accompanied by a reference pulse
- Replaces LO phase reference



Our solution: real-time referencing

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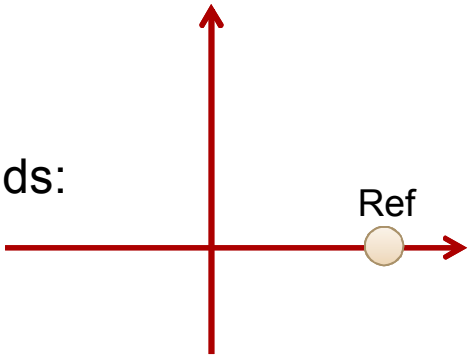
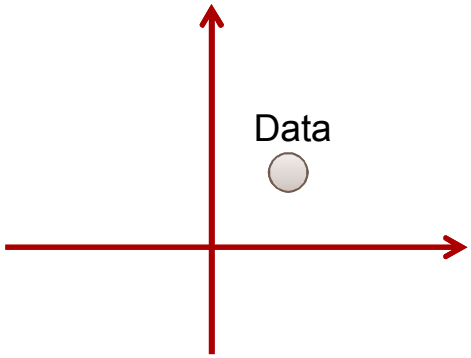
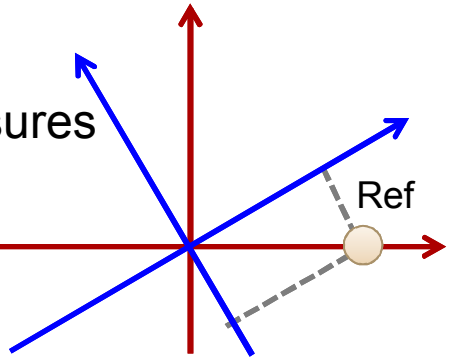
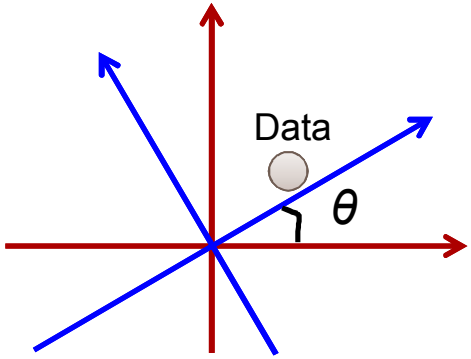
Alice sends:





Bob measures





Using the Ref measurements, Bob computes rotation angle θ that relates original Data value to measured Data value

Then Bob corrects the measured Data value or transmits measurement angle to Alice

Phase drift compensation in action

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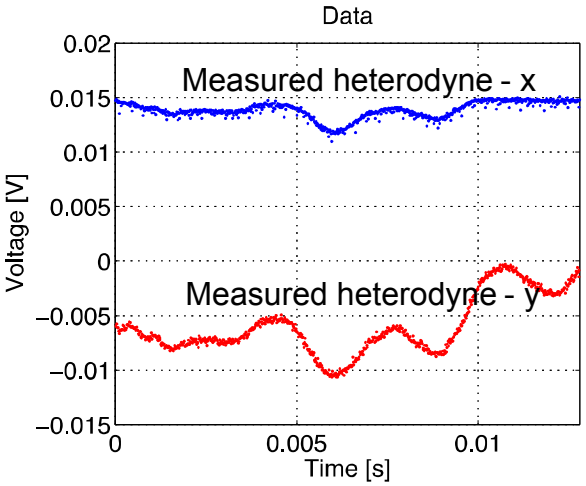
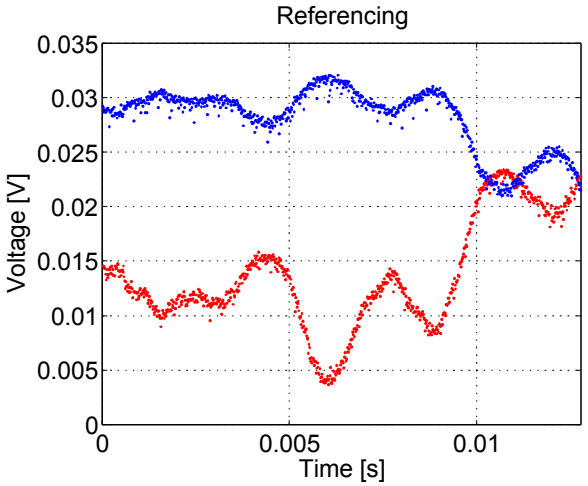
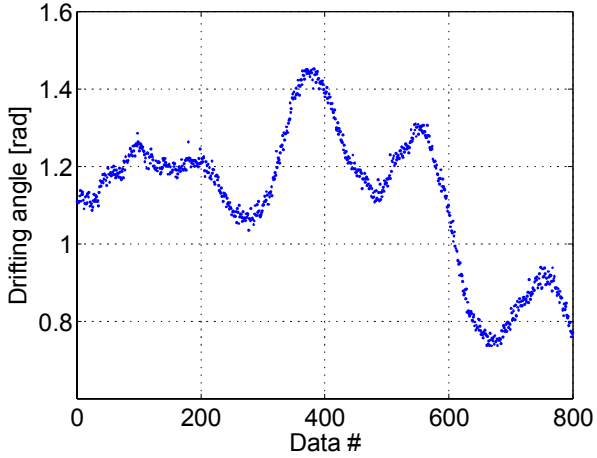
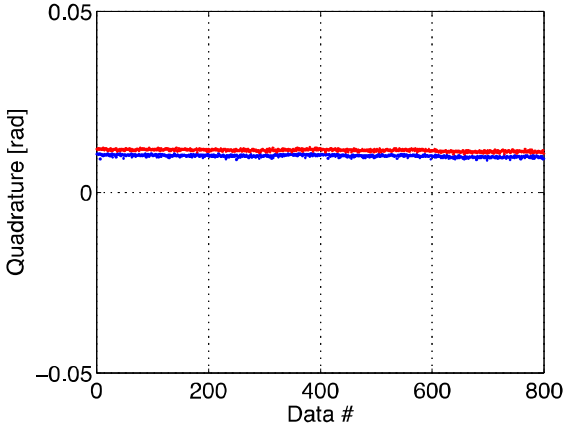
Alice transmits constant signal



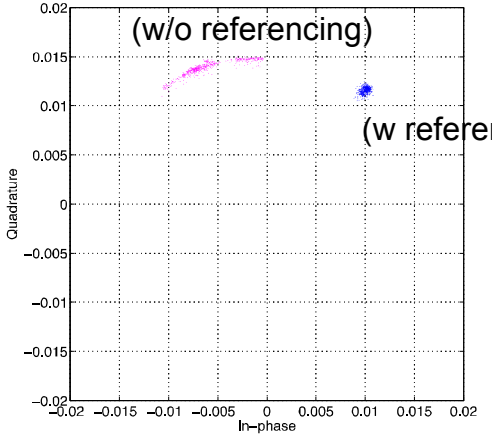




(Phase drift compensation)

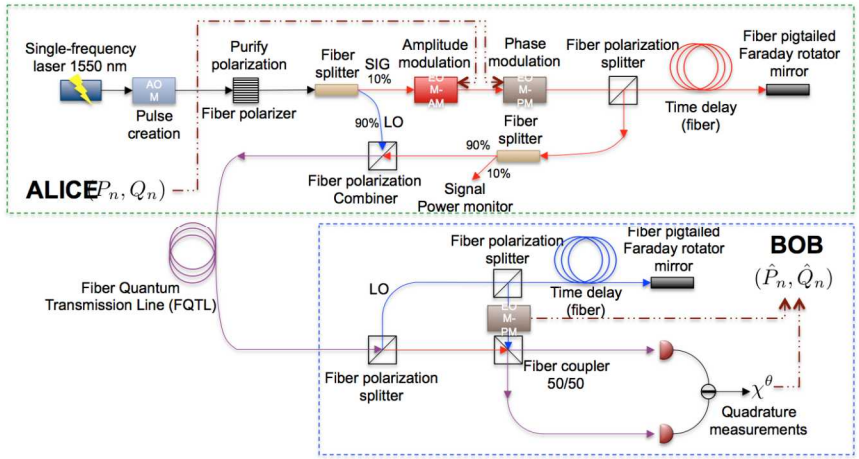


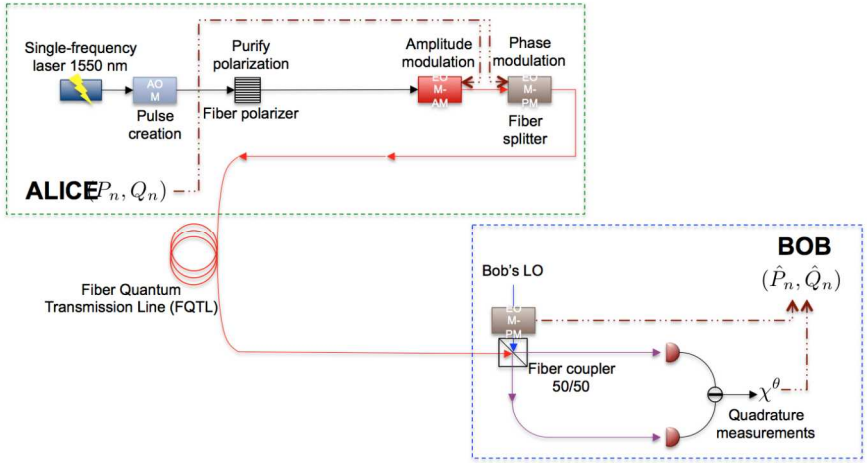
(Phase plane)



Benefits of new method

- Transmitting local oscillator no longer necessary
- Simplification of hardware
  - A real advantage for on-chip implementation





- No sacrifice in bandwidth
  - Real-time phase tracking & control also requires bandwidth for tracking and control sessions.
- REF pulses can be used for additional real-time calibration
  - e.g. time stamping, channel analysis, frequency locking

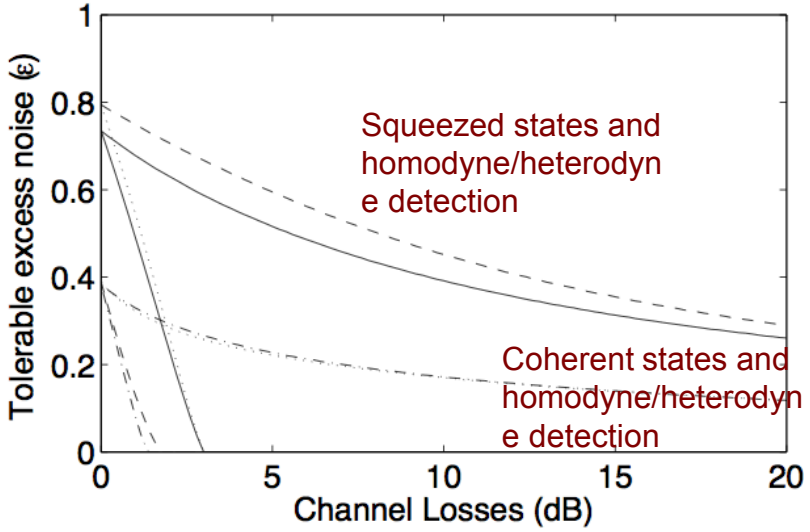
Security analysis

- Currently under way
- Similar information leakage as LO transmission
- Noise induced by imperfect phase compensation will impact key rate, especially in high loss channels

Task Objectives

To mature CV-QKD technology and protocols

1. Produce a stable source of squeezed light suitable for CV-QKD deployment
   - Demonstrate advantages of squeezed light for CV-QKD: Tolerance to excess noise



[Raul Garcia-Patron, Ph.D thesis, 2008]

2. On-chip realization of CV-QKD hardware

   (with CSI team, Paul Davids)

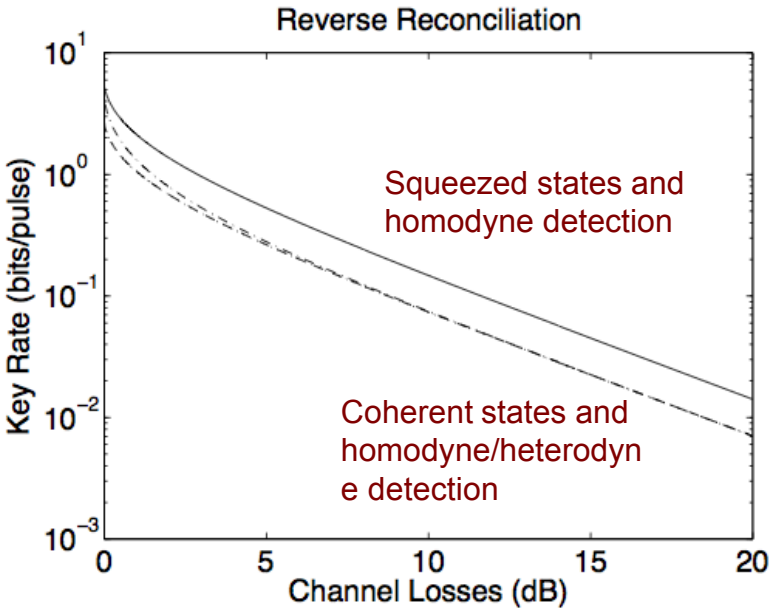
3. New protocols for CV-QKD

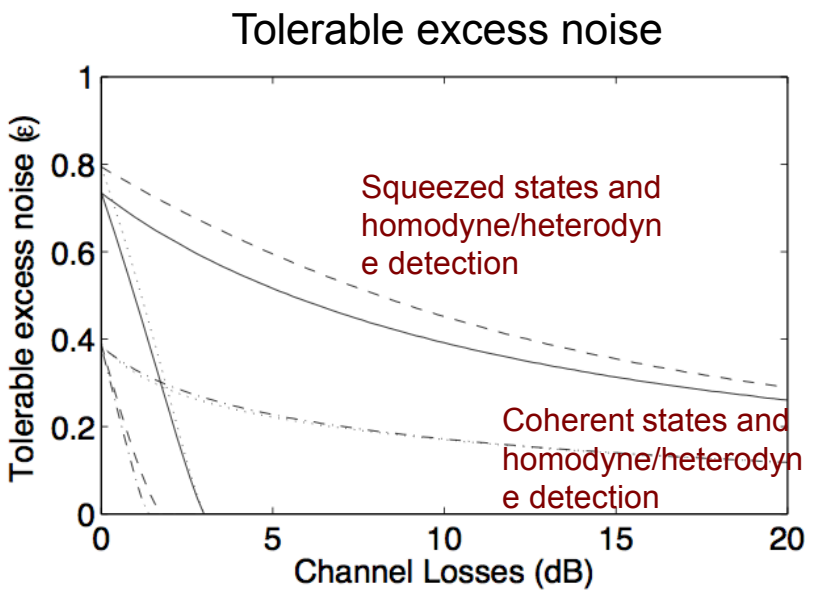
   (with QTL team, Junji Urayama)

Backup slides

Advantages of squeezed light encoding

- Squeezed light encoding can enable higher key rate/longer distance CV-QKD, and be more robust against excess noise





[Raul Garcia-Patron, Ph.D thesis, 2008]

- Possible to generate squeezed light with high degree of squeezing, high bandwidth, in a portable package?

CV-QKD with squeezed light encoding

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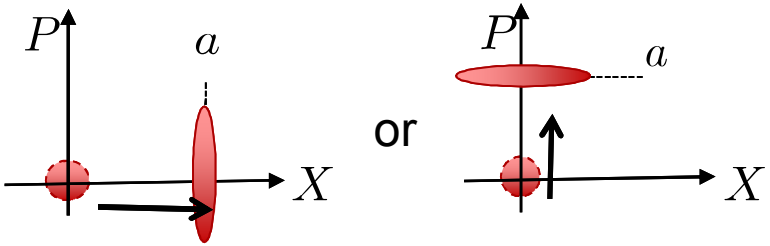
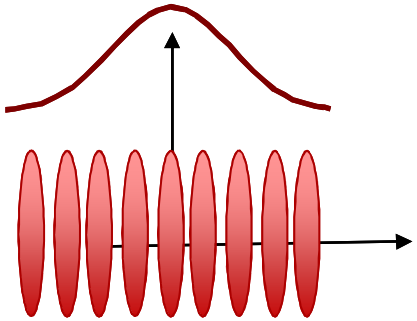
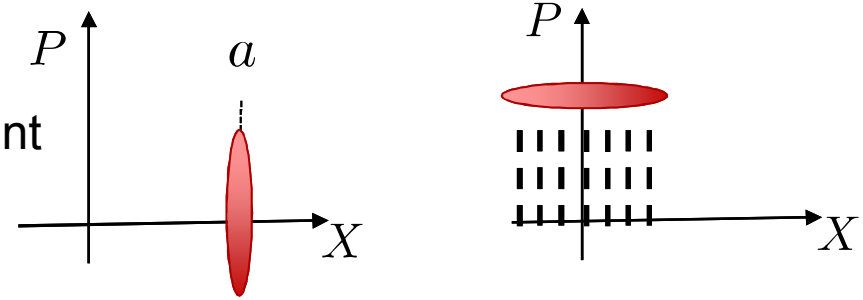
1) Alice generates a random real number (a) from a Gaussian distribution of variance V_A and a random bit (b) from a binary distribution. Bob generates a random bit (b′).
2) Depending on the value of the random bit (b) Alice sends a x-squeezed state with first moment d = (a, 0) or a p-squeezed state with first moment d = (0, a), where the squeezing r satisfies $V_A = 2 \sinh 2r$.





3) Bob, depending on his random bit (b′), measures either X or P.

Suppose an X measurement



4) Sifting: Alice discloses for each pulse the value of b (whether she displaced X or P). Bob keeps only the cases where he measured the right quadrature (b = b′).
5) Channel identification, **key discretization**, error correction, privacy amplification.