Continuous Variable Quantum Photonics

Zachary Vernon

Photonics for Quantum Workshop
January 24, 2019
Rochester, NY

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Outline

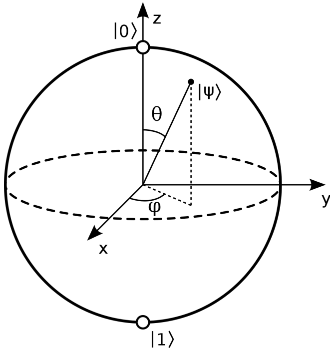
- ➢ Why (and what is) continuous variable (CV) quantum optics?
- ➢ *Integrated* CV quantum photonics: progress to date
- ➢ Nanophotonic squeezing
- ➢ (Advertisement!) A bit about Xanadu

Background & Motivation

Encoding quantum information in continuous degrees of freedom like "intensity and phase" or field quadratures

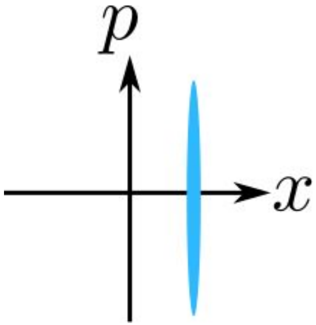
Rather than ….

$$\{|0\rangle, |1\rangle\}$$



Use instead …

$$\{|x\rangle\} \text{ or } \{|p\rangle\}$$



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Background & Motivation

CV quantum toolkit can implement universal quantum computation!

VOLUME 82, NUMBER 8 PHYSICAL REVIEW LETTERS 22 FEBRUARY 1999

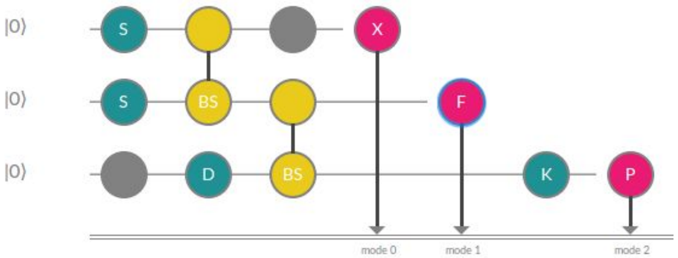
Quantum Computation over Continuous Variables

Seth Lloyd
MIT Department of Mechanical Engineering, MIT 3-160, Cambridge, Massachusetts 02139

Samuel L. Braunstein
SEECS, University of Wales, Bangor LL57 1UT, United Kingdom
(Received 27 October 1998)

This paper provides necessary and sufficient conditions for constructing a universal quantum computer over continuous variables. As an example, it is shown how a universal quantum computer for the amplitudes of the electromagnetic field might be constructed using simple linear devices such as beam splitters and phase shifters, together with squeezers and nonlinear devices such as Kerr-effect fibers and atoms in optical cavities. Such a device could in principle perform "quantum floating point" computations. Problems involving noise, finite precision, and error correction are discussed. [S0031-9007(99)08418-5]

PACS numbers: 03.67.Lx, 46.05.+b



Thesis: interesting sampling problems make CV a powerful encoding for realistic & useful quantum technologies in the near term

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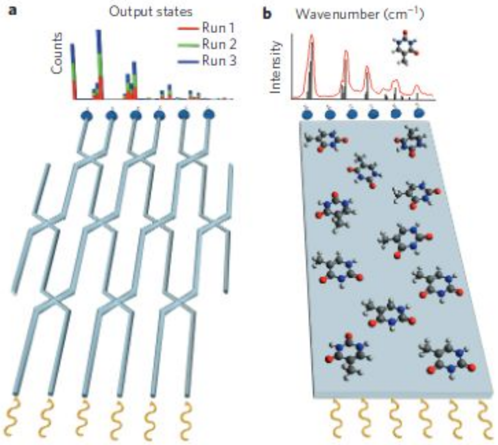
Gaussian Boson Sampling

nature photonics | ARTICLES
PUBLISHED ONLINE: 24 AUGUST 2015 | DOI: 10.1038/NPHOTON.2015.153

Gaussian

Boson sampling for molecular vibronic spectra

Joonsuk Huh*, Gian Giacomo Guerreschi, Borja Peropadre, Jarrod R. McClean and Alán Aspuru-Guzik*

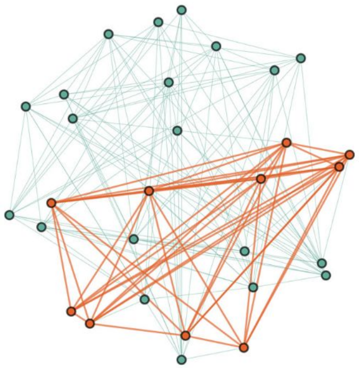


PHYSICAL REVIEW LETTERS **121,** 030503 (2018)

Using Gaussian Boson Sampling to Find Dense Subgraphs

Juan Miguel Arrazola* and Thomas R. Bromley†
Xanadu, 372 Richmond Street W, Toronto, Ontario M5V 1X6, Canada

(Received 5 April 2018; revised manuscript received 14 May 2018; published 19 July 2018)



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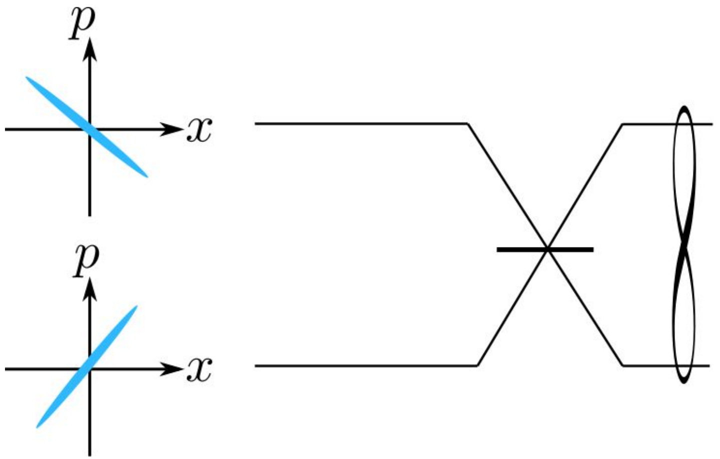
Why integrate CV quantum devices?

- Passive phase stability
- Scalability
- Power efficiency
- Microresonators
- Ease of mode engineering



Deterministic generation of CV entanglement: two mode squeezing

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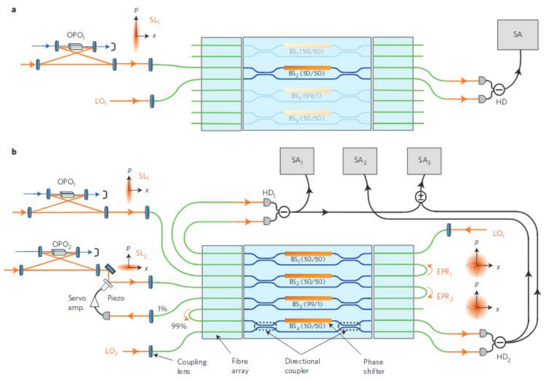
CV operations on chip

nature photonics LETTERS
PUBLISHED ONLINE: 30 MARCH 2015 | DOI: 10.1038/NPHOTON.2015.42

Continuous-variable entanglement on a chip

Genta Masada[1,2], Kazunori Miyata[1], Alberto Politi[3], Toshikazu Hashimoto[4], Jeremy L. O'Brien[5] and Akira Furusawa[1]*



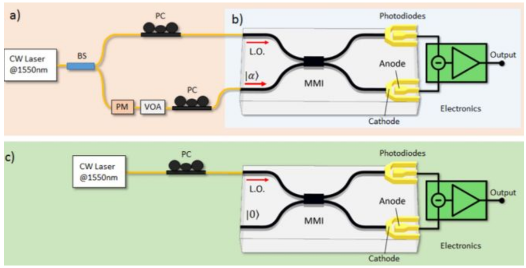
Quantum Sci. Technol. 3 (2018) 025003 https://doi.org/10.1088/2058-9565/aaa38f

Quantum Science and Technology

PAPER

A homodyne detector integrated onto a photonic chip for measuring quantum states and generating random numbers

Francesco Raffaelli, Giacomo Ferranti, Dylan H Mahler, Philip Sibson, Jake E Kennard, Alberto Santamato, Gary Sinclair, Damien Bonneau, Mark G Thompson and Jonathan C F Matthews
Quantum Engineering Technology Labs, H. H. Wills Physics Laboratory and Department of Electrical & Electronic Engineering, University of Bristol, BS8 1FD, United Kingdom



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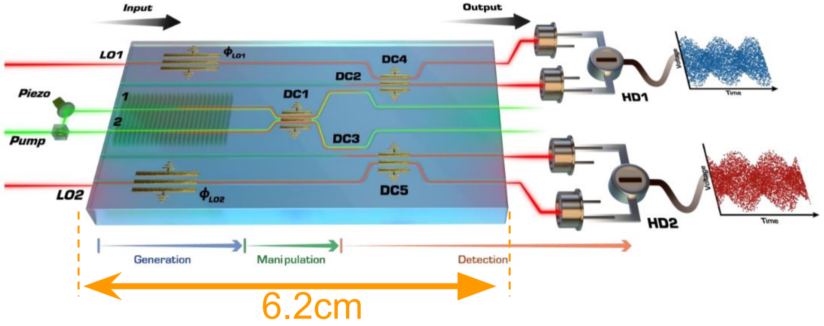
Integrated squeezing: existing work

Integrated photonic platform for quantum information with continuous variables

Francesco Lenzini[1,2], Jiri Janousek[3,4], Oliver Thearle[3,4], Matteo Villa[1], Ben Haylock[1], Sachin Kasture[1], Liang Cui[5], Hoang-Phuong Phan[6,7], Dzung Viet Dao[6,7], Hidehiro Yonezawa[8], Ping Koy Lam[4], Elanor H. Huntington[3], and Mirko Lobino[1,6,*]



- Low confinement LiNb waveguides
- 2xPPLN squeezers integrated
- Entanglement and local oscillator mixing on chip
- 1.4dB squeezing at end

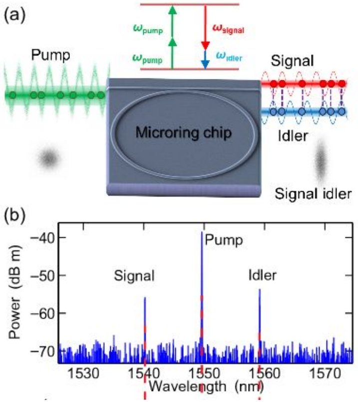
PHYSICAL REVIEW APPLIED **3**, 044005 (2015)

On-Chip Optical Squeezing

Avik Dutt,[1,*] Kevin Luke,[1] Sasikanth Manipatruni,[2] Alexander L. Gaeta,[3,4] Paulo Nussenzveig,[1,5] and Michal Lipson[1,4]

[1]*School of Electrical and Computer Engineering, Cornell University, Ithaca, New York 14853, USA*
[2]*Exploratory Integrated Circuits, Intel Components Research, Intel Corporation, Hillsboro, Oregon 97124, USA*
[3]*School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853, USA*
[4]*Kavli Institute at Cornell for Nanoscale Science, Cornell University, Ithaca, New York 14853, USA*
[5]*Instituto de Física, Universidade de São Paulo, P.O. Box 66318, 05315-970 São Paulo, Brazil*

(Received 20 April 2014; revised manuscript received 3 March 2015; published 13 April 2015)



- OPO above threshold in SiN microring resonator
- Intensity difference squeezing: bright twin beams
- 1.7dB measured
- First *nanophotonic* squeezing demonstration

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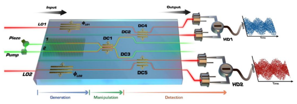
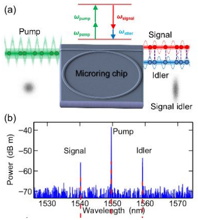
Integrated squeezing: what’s missing?

Wish list for integrated squeezing platform & device

	Low confinement PPLN	SiN OPOs above threshold	
Nanophotonic system	X	✓	
Quadrature squeezing	✓	X	
Photon counting compatible	✓	X	
Single temporal mode	?	X	





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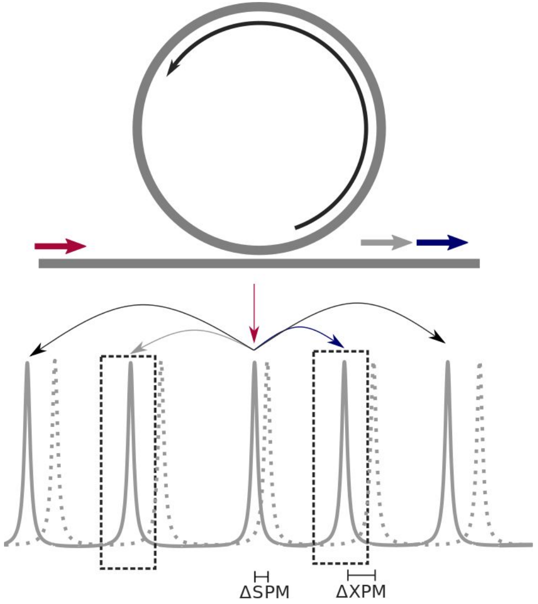
New! Nanophotonic quadrature squeezing

- Silicon nitride microring resonator (~100um radius, 800x1000nm cross section) with microheater
- Loaded Q ~ 200,000 overcoupled to 75% escape efficiency
- Pumped CW below threshold, 0-100mW
- Track SPM frequency shift by tuning laser
- Measure squeezing in composite signal/idler mode using bichromatic homodyne



$$H_{\mathrm{NL}} = -\hbar\Lambda(b_P b_P b_S^\dagger b_I^\dagger + \tfrac{1}{2} b_P^\dagger b_P b_P^\dagger b_P + 2 b_P^\dagger b_P (b_S^\dagger b_S + b_I^\dagger b_I))$$

SFWM **SPM** **XPM**

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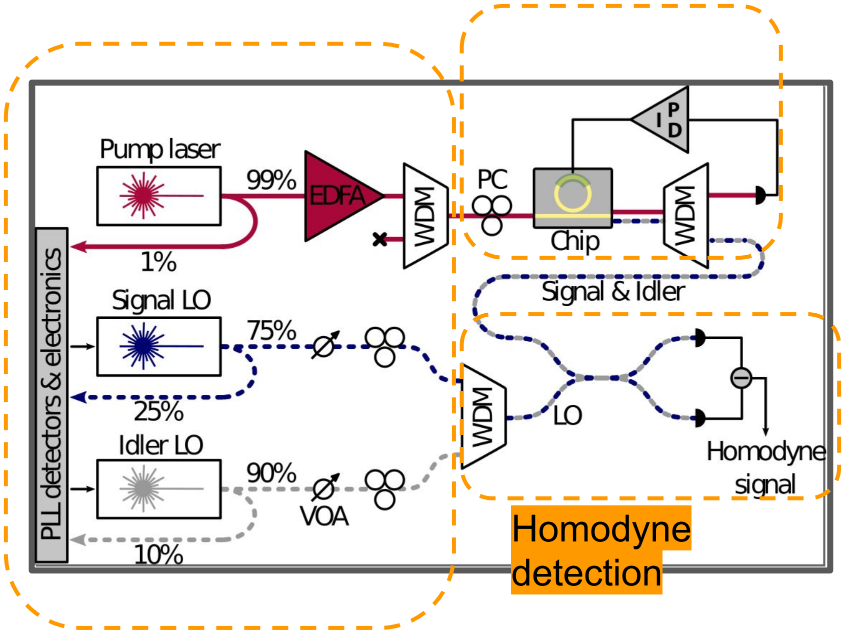
New! Nanophotonic quadrature squeezing

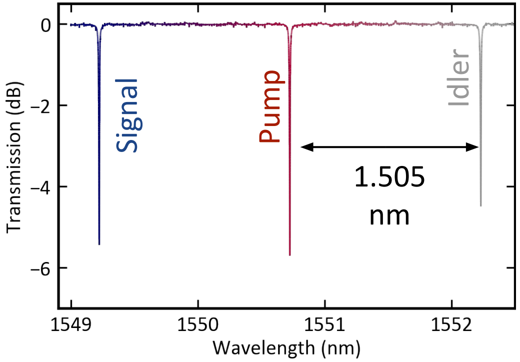
Generate squeezing

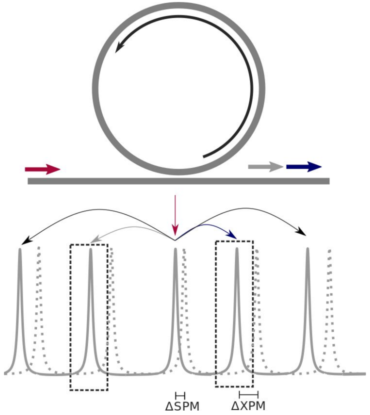


Homodyne detection

Prepare phase-locked pump & bichromatic local oscillator

Microring spectrum

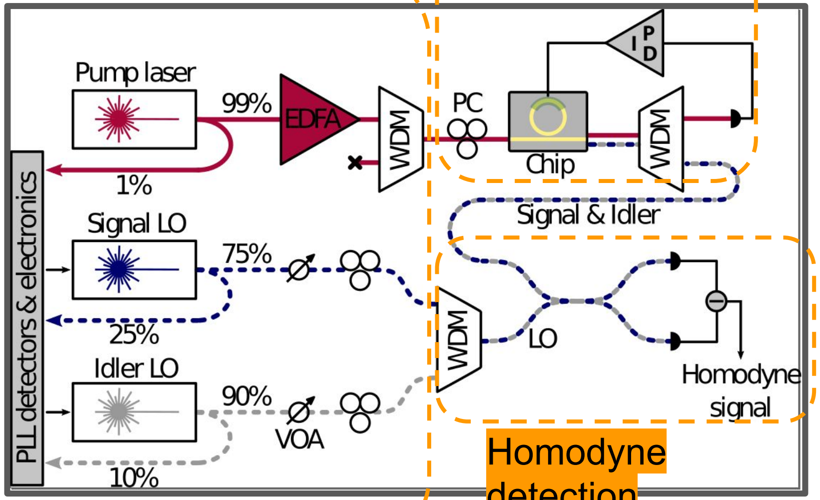




"Nondegenerate" (two-mode) squeezing between signal and idler ⟺ Squeezed mode has frequency support at both signal and idler

New! Nanophotonic quadrature squeezing

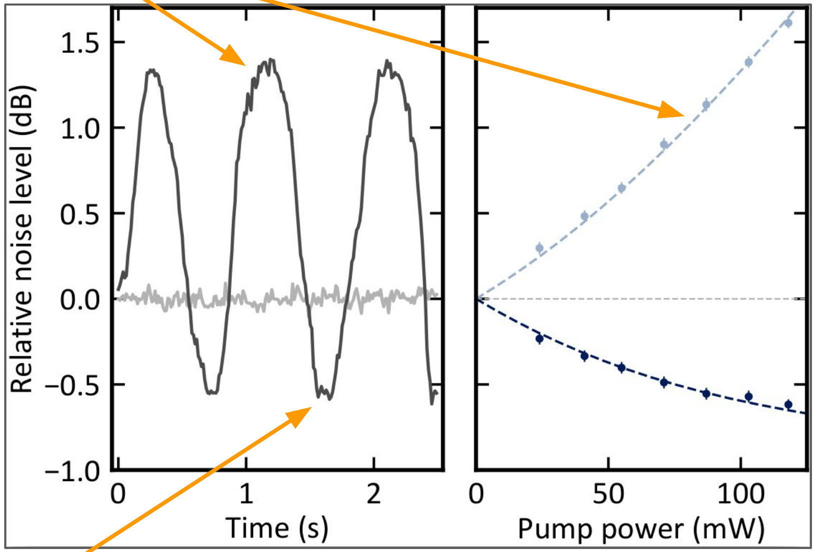
Generate squeezing



Homodyne detection

Prepare phase-locked pump & bichromatic local oscillator

Excess anti-squeezing consistent with loss



0.6 dB squeezing (87% of vacuum variance) -- infer ~1.5dB on chip

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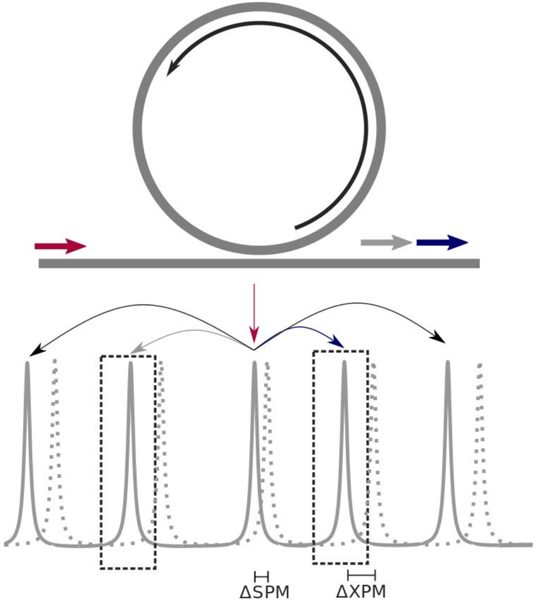
Photon number difference squeezing

- Same microring device as for quadrature squeezing
- Chopped CW pump to avoid detector saturation
- Measure photon statistics using photon number resolving transition-edge sensors (TES)
- Expect number difference variance suppressed (sub-Poissonian), limited by loss/noise



$$V_{\Delta n} = (1-\eta) n_{\mathrm{tot}}$$

Variance of the per-pulse signal-idler photon number difference

Loss

Mean signal+idler photon number

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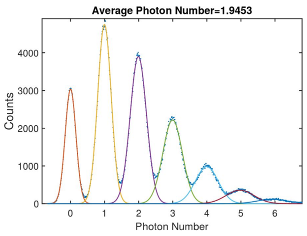
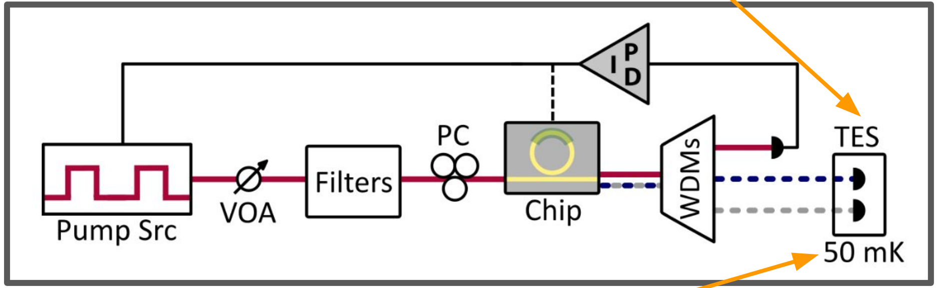
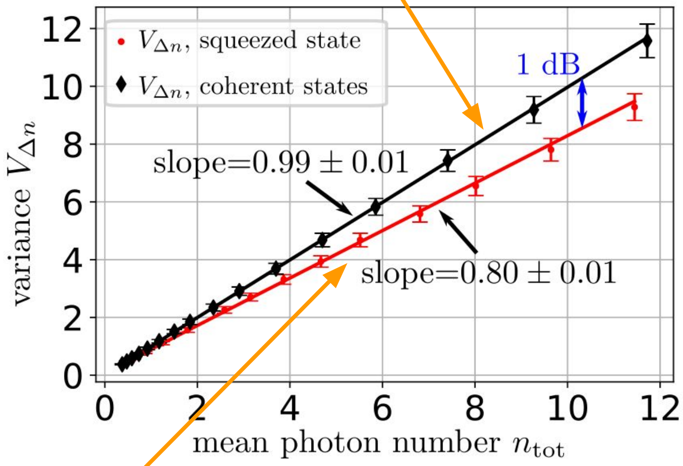
Photon number difference squeezing





Transition edge sensors
(provided by NIST team: S.W. Nam, T. Gerrits, A. Lita)
Measure >10-fold coincidences
With 100s Hz rates!

Slope 0.99 (coherent state calibration)



Slope 0.8 (~1dB of difference squeezing -- infer about 6dB on chip)

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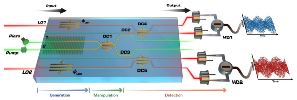
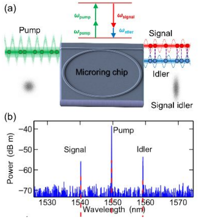
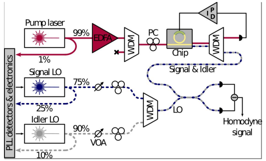
Integrated squeezing: what’s missing?

Wish list for integrated squeezing platform & device

	Low confinement PPLN	SiN OPOs above threshold	SFWM below threshold
Nanophotonic system	X	✓	✓
Quadrature squeezing	✓	X	✓
Photon counting compatible	✓	X	✓
Single temporal mode	?	X	*In progress - theory says yes!*







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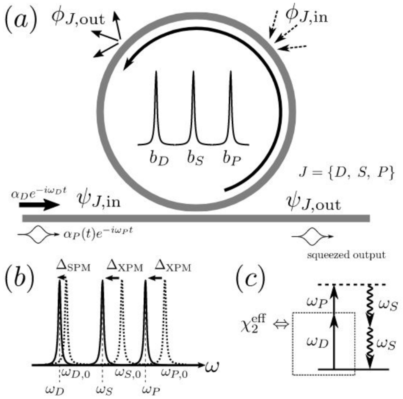
Next steps: dual pump for degenerate squeezing



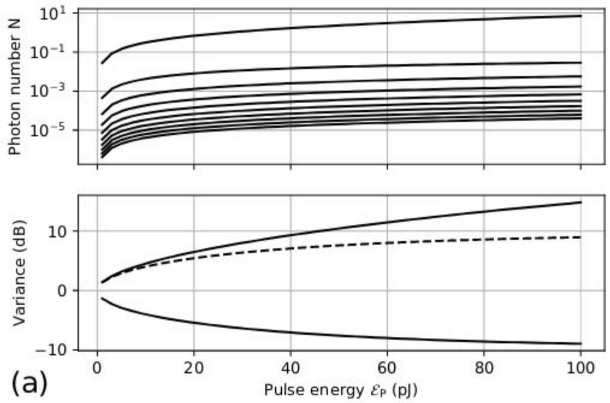
Scalable squeezed light source for continuous variable quantum sampling

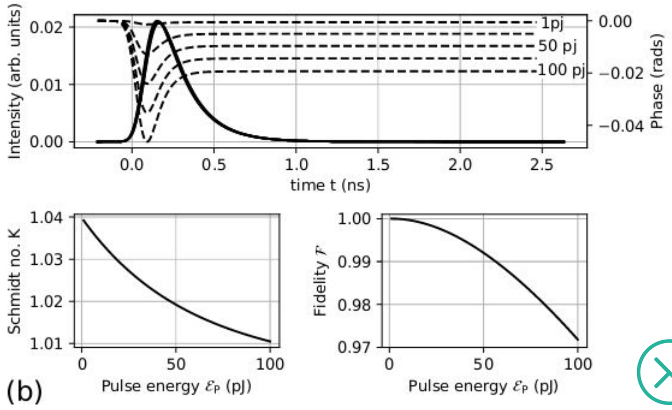
Z. Vernon,[1,*] N. Quesada,[1] M. Liscidini,[2,3] B. Morrison,[1] M. Menotti,[1] K. Tan,[1] and J.E. Sipe[4]

[1] *Xanadu, 372 Richmond St. W, Toronto, ON, M5V 1X6, Canada*
[2] *Dipartimento di Fisica, Università degli studi di Pavia, Via Bassi 6, 27100 Pavia, Italy*
[3] *Impact Centre, University of Toronto, 411-112 College St., Toronto, ON, M5G 1L6, Canada*
[4] *Department of Physics, University of Toronto, 60 St. George St., Toronto, ON, M5S 1A7, Canada*

(Dated: July 3, 2018)

arXiv: 1807.00044v1





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About Xanadu

- ★ ~35 employees full time in Toronto (32 PhDs)
- ★ Teams focused on hardware, software, business, and applications (theory & algorithm development)
- ★ Cutting-edge photonics lab
- ★ Hardware: 11 full time (and growing!)

<u>NIST Collaborators</u>
Sae Woo Nam
Thomas Gerrits
Adriana Lita

<u>ORNL</u>
Raphael Pooser

Matthew Collins
Luke Helt
Jonathan Lavoie
Dylan Mahler
Matteo Menotti
Blair Morrison
Nicolas Quesada
Alain Repingon
Reihaneh Shahrokhshahi
Kang Tan
Varun Vaidya
Zachary Vernon
John Sipe (adv)
Marco Liscidini (adv)

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About Xanadu

*We are a **full-stack** quantum computing startup*

PENNYLANE

Introducing the first dedicated machine learning platform for quantum computers

Follow the Gradient

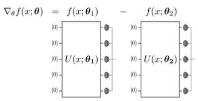
The TensorFlow of quantum computing: built-in automatic differentiation of quantum circuits.

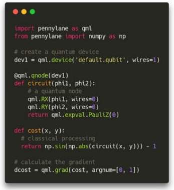
Best of Both Worlds

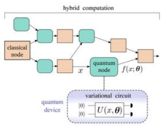
Support for hybrid quantum and classical models, with built-in optimization and machine learning tools.

Device Independent

Install plugins to run your computational circuits on more devices, including Strawberry Fields and ProjectQ.

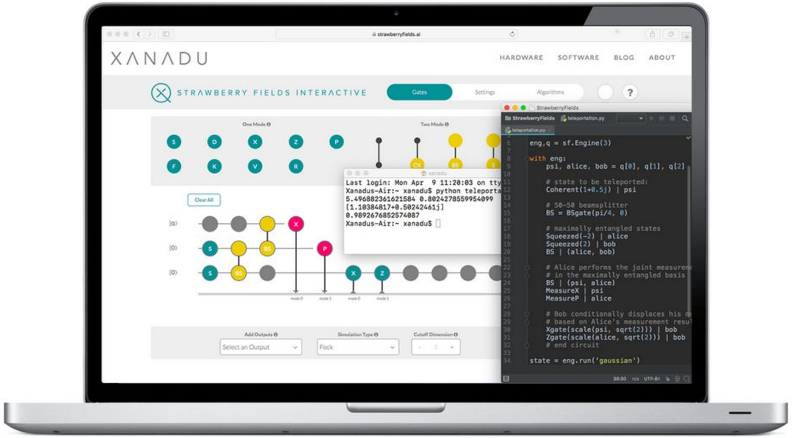






STRAWBERRY FIELDS

Open-source software for photonic quantum computing



We're hiring -- contact zach@xanadu.ai

www.xanadu.ai

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