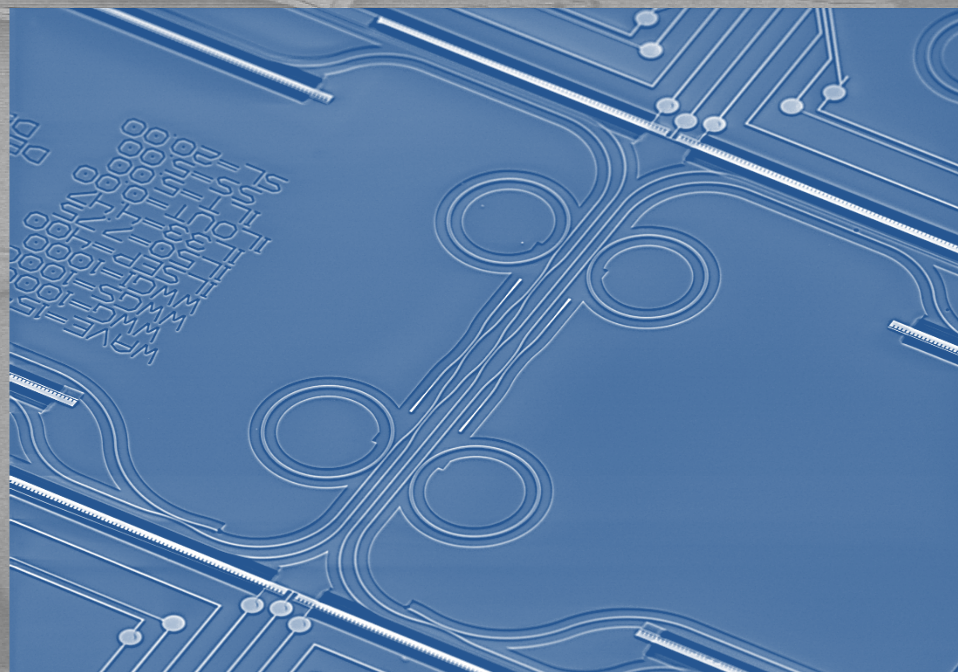
Integrated optomechanics and linear optics quantum circuits



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Erice, Italy
August 4, 2016

Outline

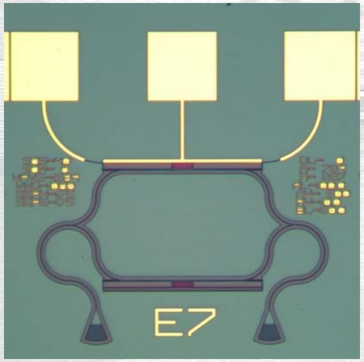
Opto- & electromechanics with the “H-resonator”

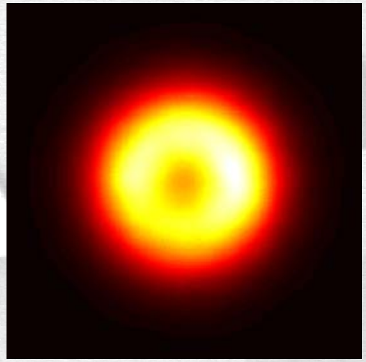
- Application: broadband phase shifting
- Optomechanics
  - Electrostatic spring effect and tunable nonlinearities
  - 15 dB of squeezing using Y-feedback
  - Towards the quantum regime

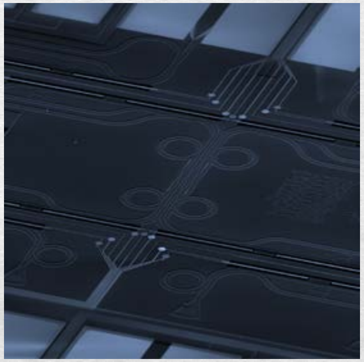
Linear optics quantum circuits

- Photons as qubits, circuits as operations
- Towards a fully scalable integrated CNOT gate
  - Directional couplers, SSPDs, phase determination

Outlook and conclusions

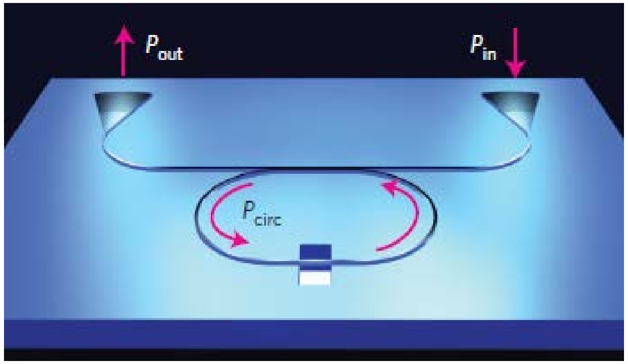






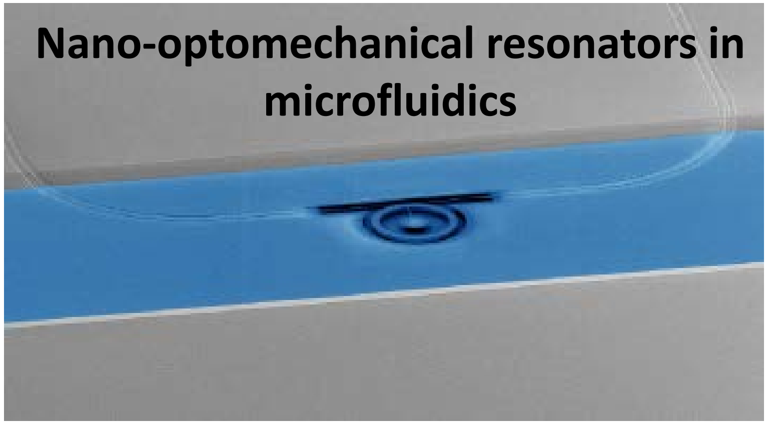
On-chip optomechanics at Yale

Large-amplitude motion and optomechanical memories



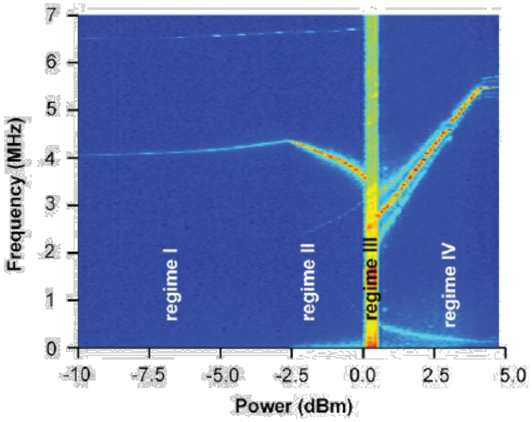
Bagheri, Poot *et al.*, Nature Nanotech. 2011
Poot, Bagheri *et al.*, Phys Rev. A. 2012

Nano-optomechanical resonators in microfluidics



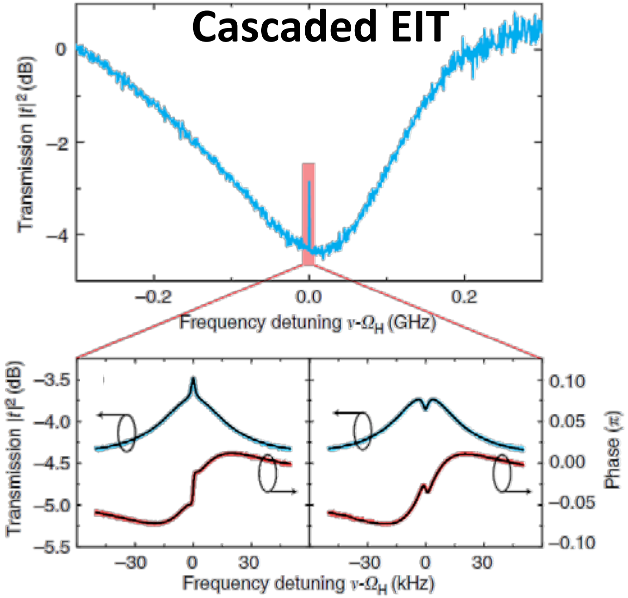
Fong, Poot, and Tang, Nano Lett., 2015

Synchronization between remote optomechanical oscillators



Bagheri*, Poot* *et al.*, Phys. Rev. Lett. 2013

Cascaded EIT

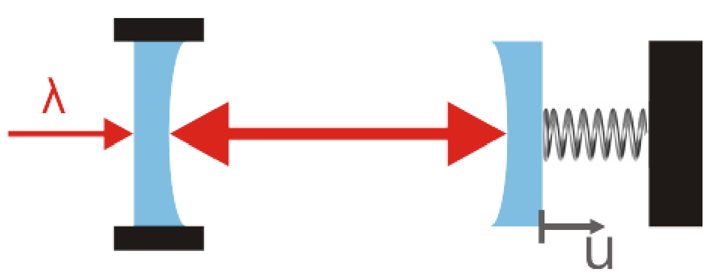


Fan, Fong, Poot, Tang, Nature Comm. 2015

Opto-electromechanics

Optomechanics

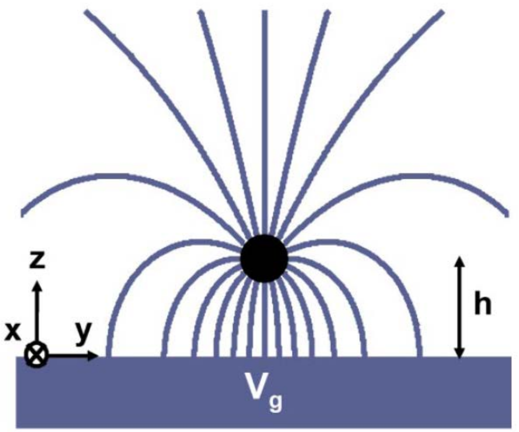
- Very good sensitivity
  - Quantum-limited lasers
  - Low-noise detectors
- Photons interact only very weakly with the resonator
  - Momentum: $p = h/\lambda = 4.3 \times 10^{-28}$ kg m/s



Phys. Rev. A **86** 053826 (2012)

Nanoelectromechanics

- Sensitivity "low" without special mesoscopic devices
- Strong electrostatic forces
  - Inversely proportional to the gap → make small



Phys. Stat. Sol. B **244** 4253 (2007)

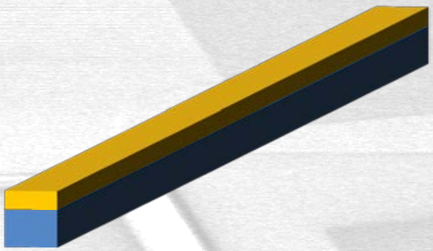
For a review of all the different optomechanical and NEMS devices that are used see e.g. "Mechanical Systems in the Quantum Regime" Phys. Rep. ***511*** *273–335 (2012)*

Device design

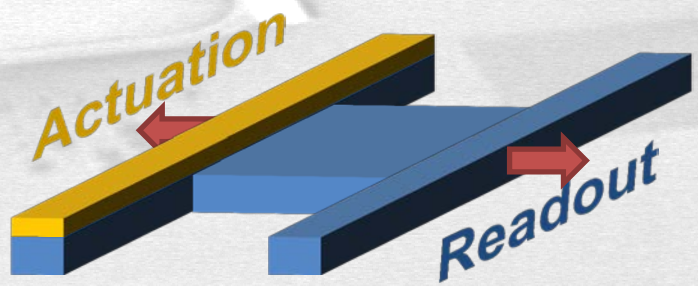
- What we want:
  - Sensitive optical readout
    Use an on-chip Mach-Zehnder interferometer
  - Strong forces
    Electrostatic interactions between nearby electrodes
  - High quality factor mechanics
    Many oscillations before relaxing

- Make integrated photonic circuits out of high-stress SiN with metal electrodes

- Problem: metal absorbs light
  - Separate actuation and readout parts



Beam



“H-resonator”

Device design

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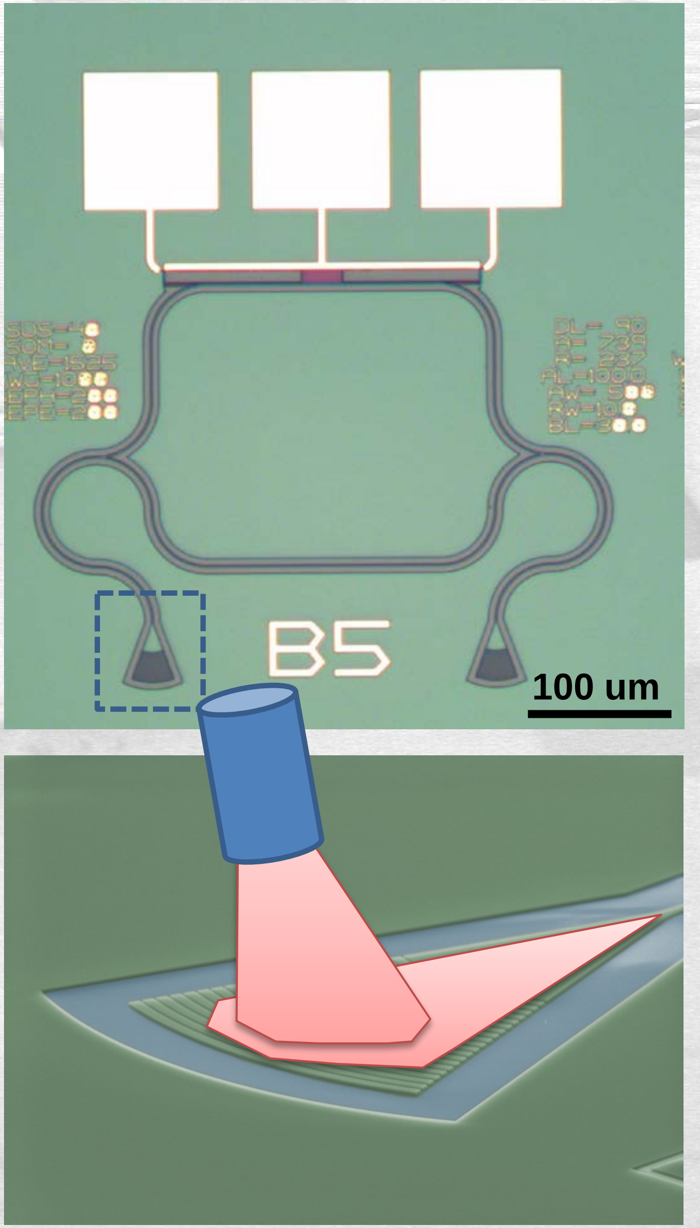

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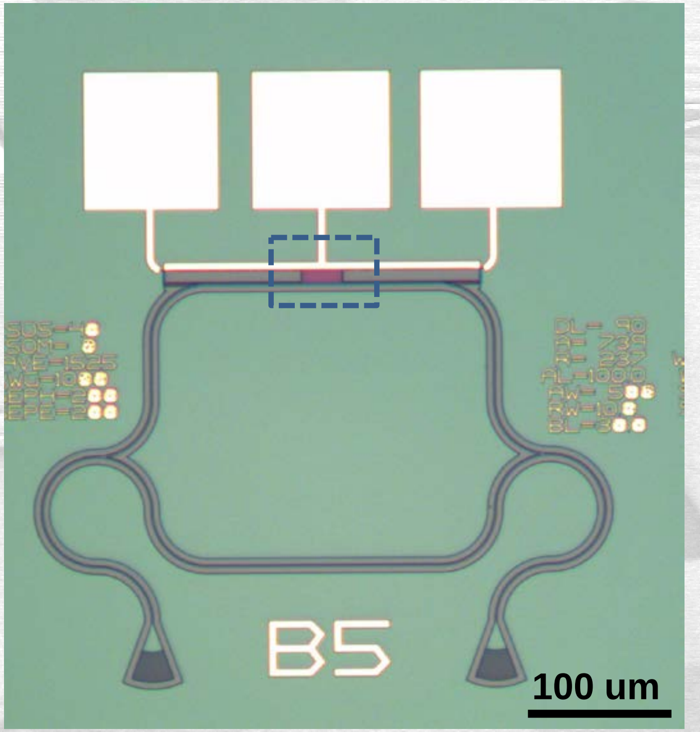

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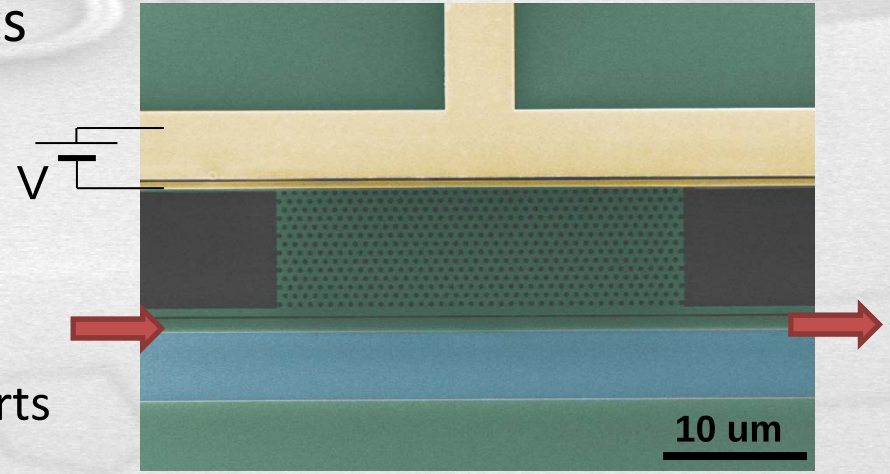
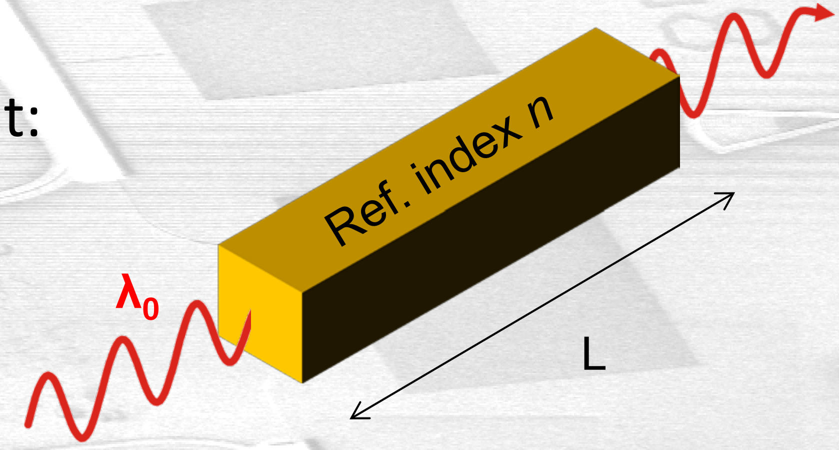
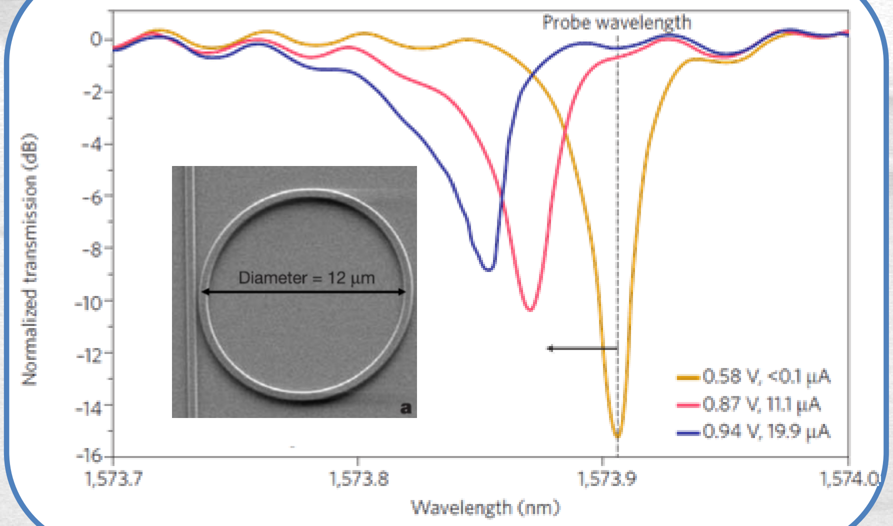


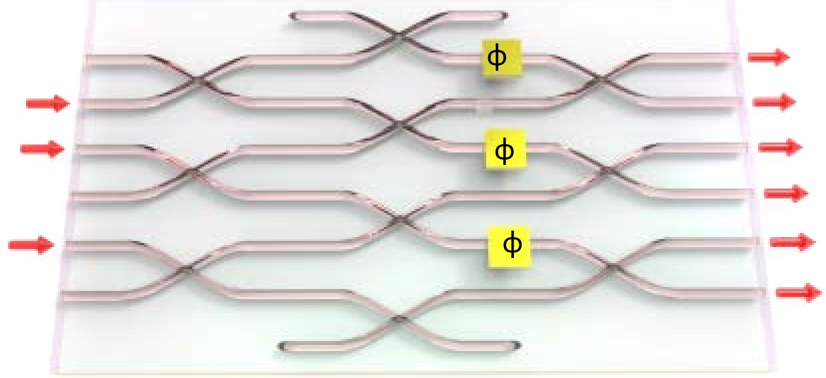
- Problem: metal absorbs light
  - Separate actuation and readout parts

Application: phase shifting

- Very important optical component:
  - Power modulators
  - Tunable filters
  - Quantum algorithms
- Phase acquired when light travels through a material: $\phi = 2\pi \boxed{n} L/\lambda_0$



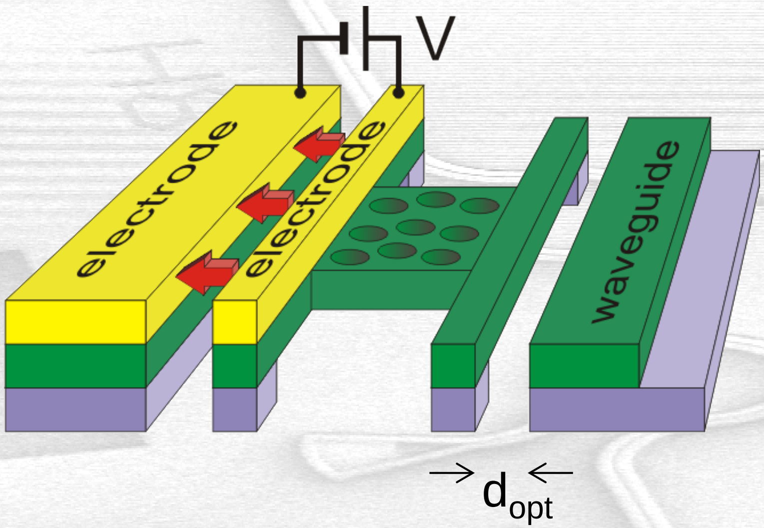


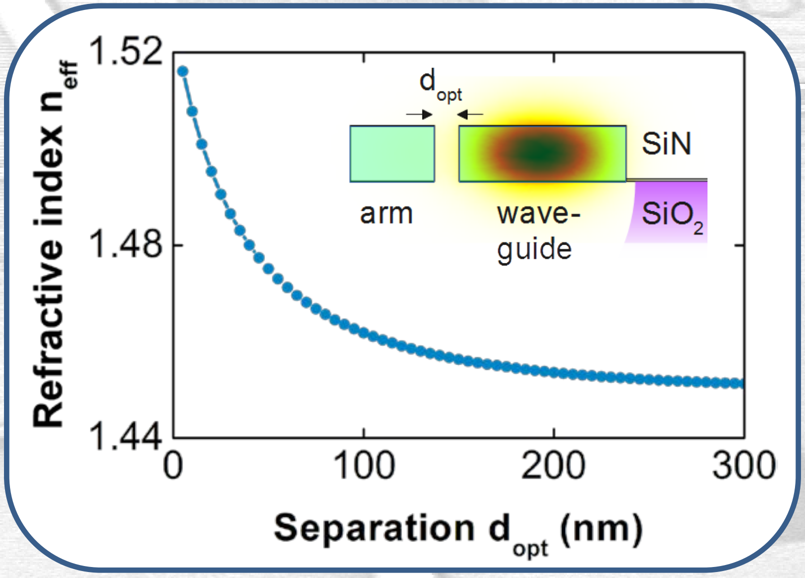


Xu, Schmidth, Pradhan, and Lipson, Nature **435** 325 (2005)
G. T. Reed *et al.*, Nat Phot, **4** 518 (2010)

source: http://www2.physics.ox.ac.uk/

The “H” optomechanical phase shifter





Voltage → displacement → refr. index → phase

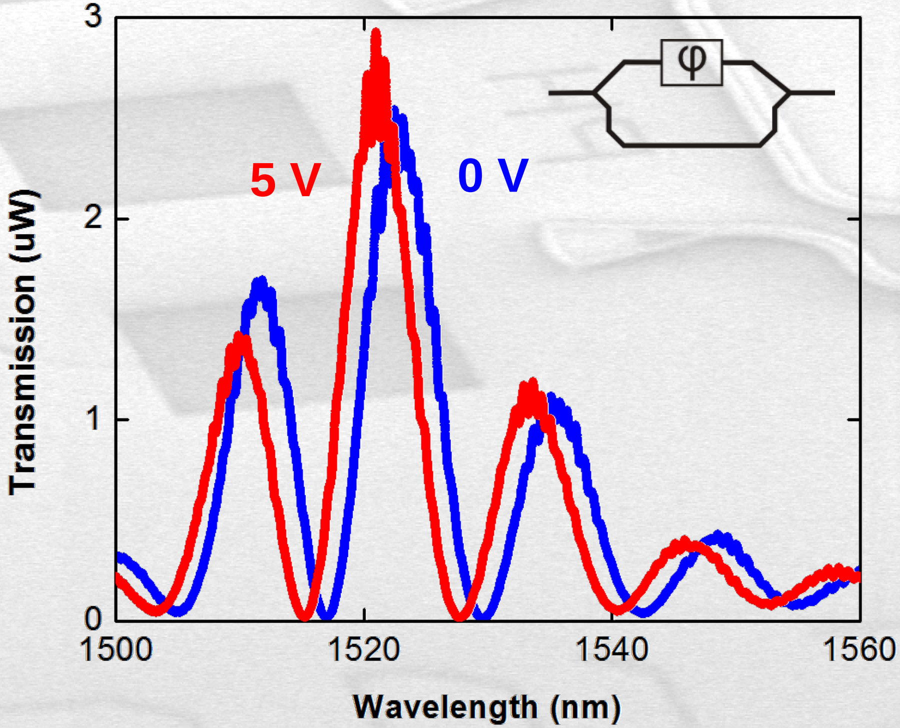
- Electrostatic: no power dissipated
  - ✓ No thermal crosstalk
  - ✓ Ideal for cryogenic operation
- Does not rely on a cavity
  works for a large wavelength range
- Small optical forces
  large power range possible: from single photon to Watt
- SiN = high-stress material = high eigenfrequency
  broadband operation

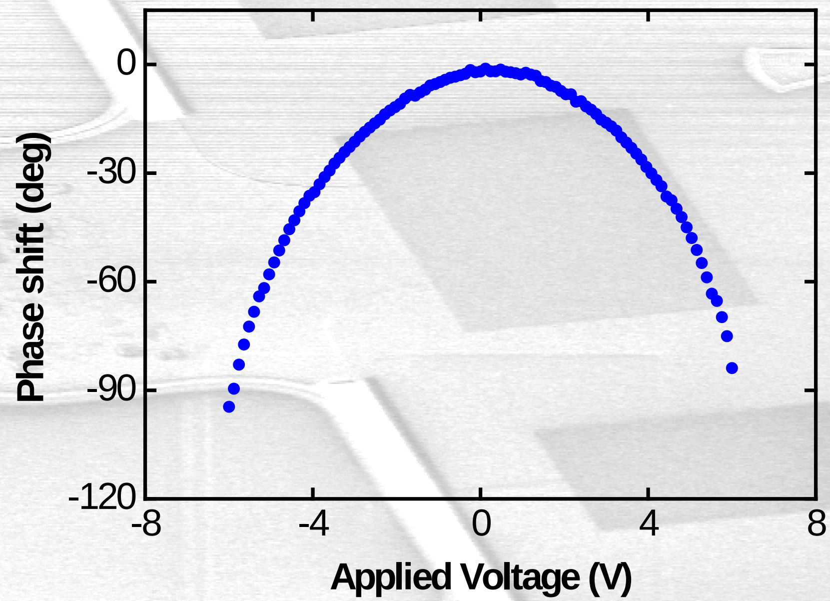
M. Poot and H. Tang, Appl. Phys. Lett. 104, 061101 (2014)

Opto-electromechanical phase shifting

- Measure transmission of the device: MZI fringes
- Apply voltage:

  Shift in the fringe position = phase shift

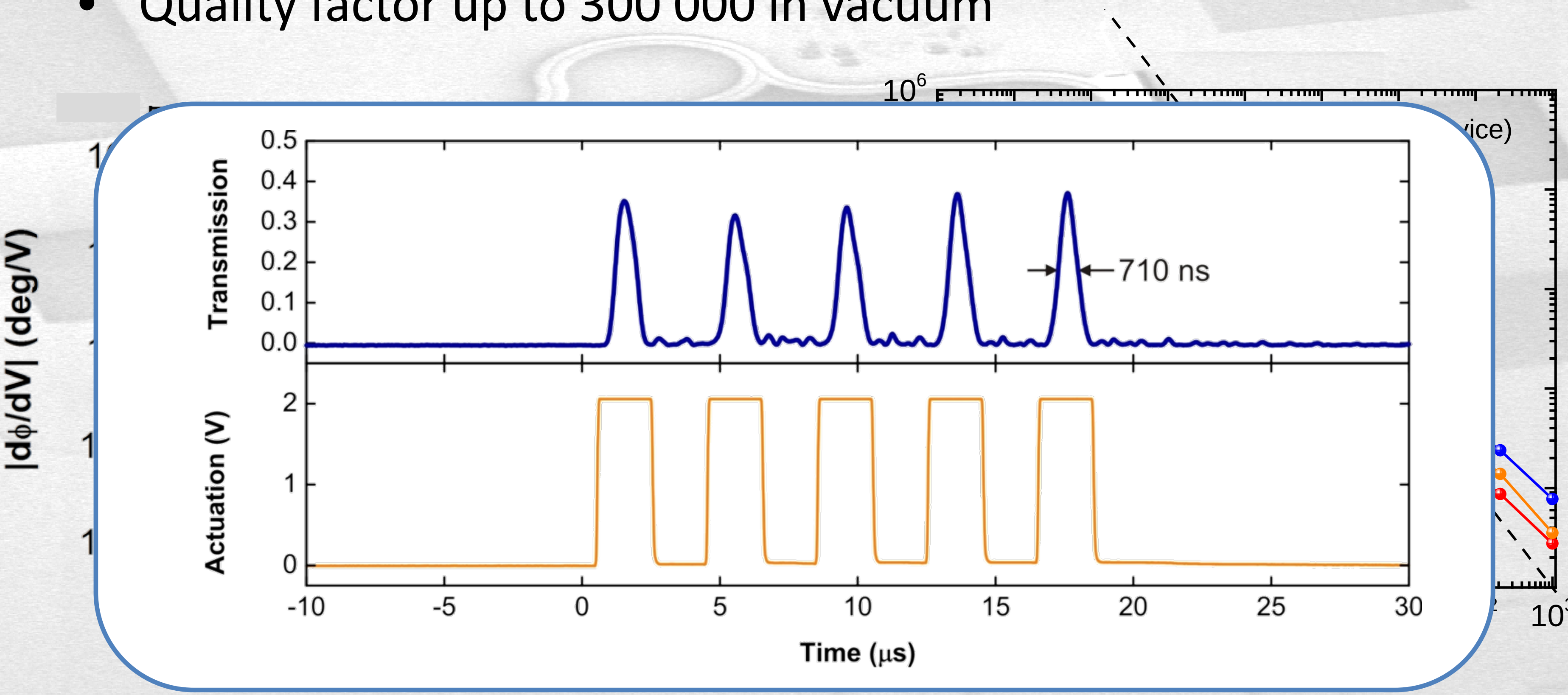




- Quadratic phase shift with V (electrostatic force ∝ V^2)
- π/2 phase shifts for the first generation of devices

Dynamic performance – frequency domain

- Operates up to a few MHz; 3 dB point at 1 MHz
- Peaks due to the mechanical modes
- Quality factor ~ 10 in air
- Quality factor up to 300 000 in vacuum



M. Poot and H. Tang, Appl. Phys. Lett. 104, 061101 (2014)
M. Poot *et al.*, High-quality opto-electromechanical resonators, in preparation

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- Application: broadband phase shifting
- **Optomechanics**
  - **Electrostatic spring effect and tunable nonlinearities**
  - **15 dB of squeezing using Y-feedback**
  - **Towards the quantum regime**

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- Towards a fully scalable integrated CNOT gate
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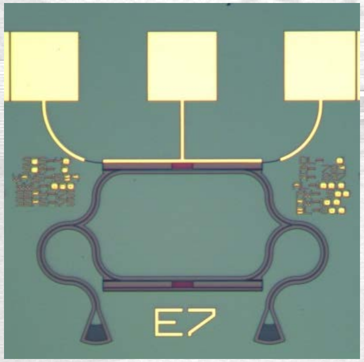
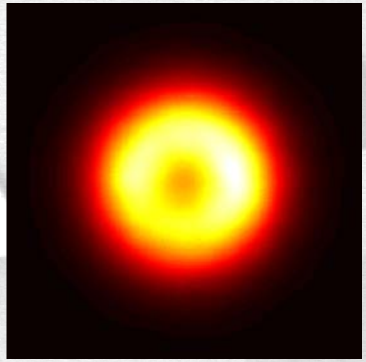
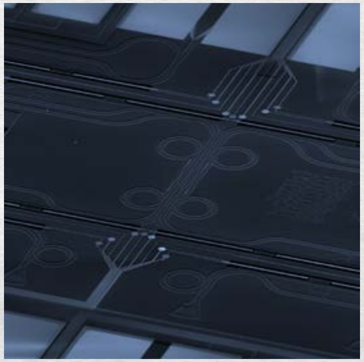






Electromechanics with H-resonators

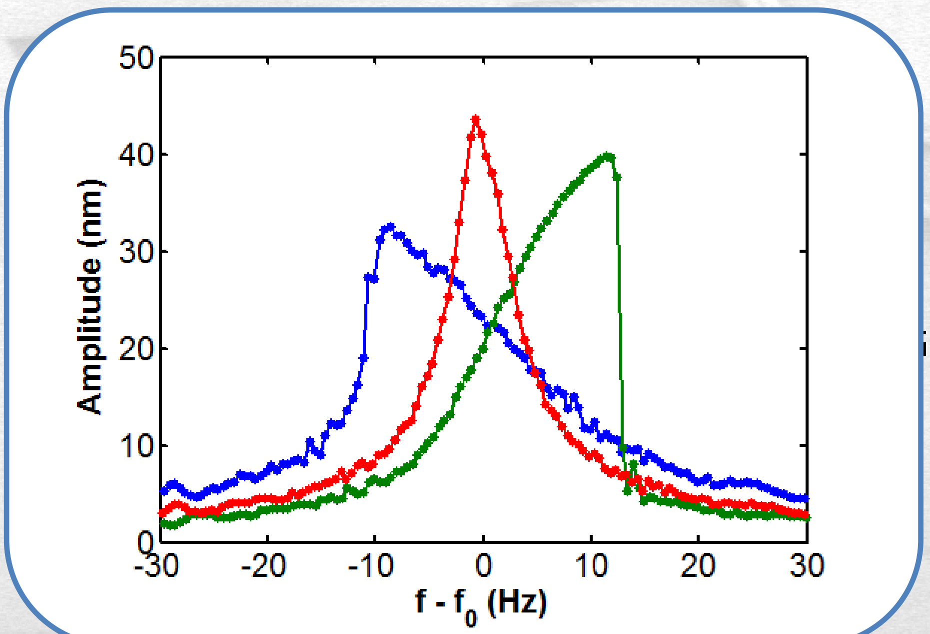
Electrostatic spring effect

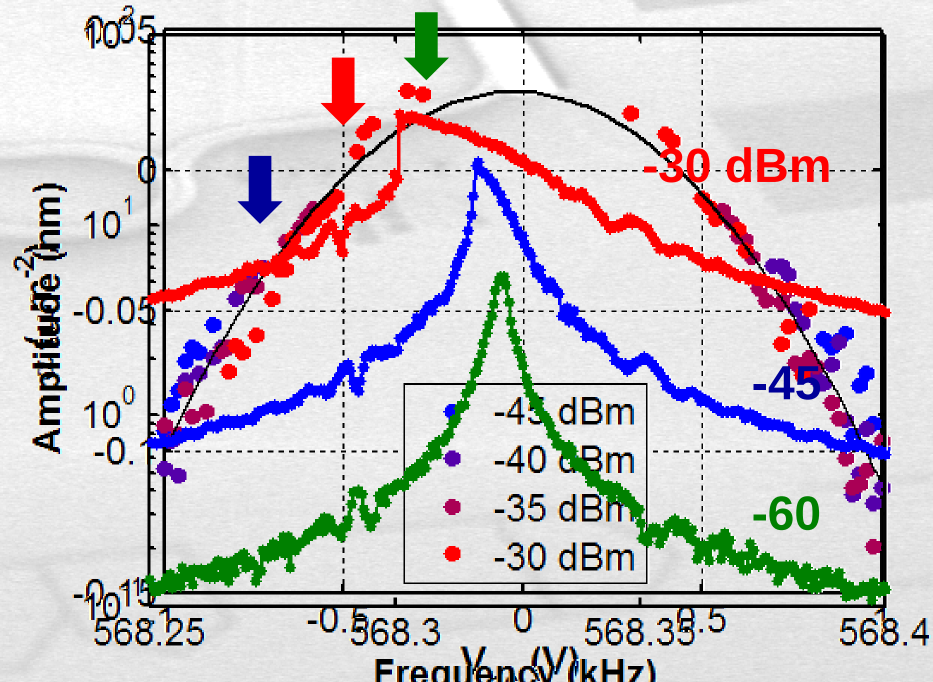
An extremely strong electrostatic tuning of the resonance frequency is observed

Tunable nonlinearity

The Duffing parameter α is completely determined by the strong electrostatic effects

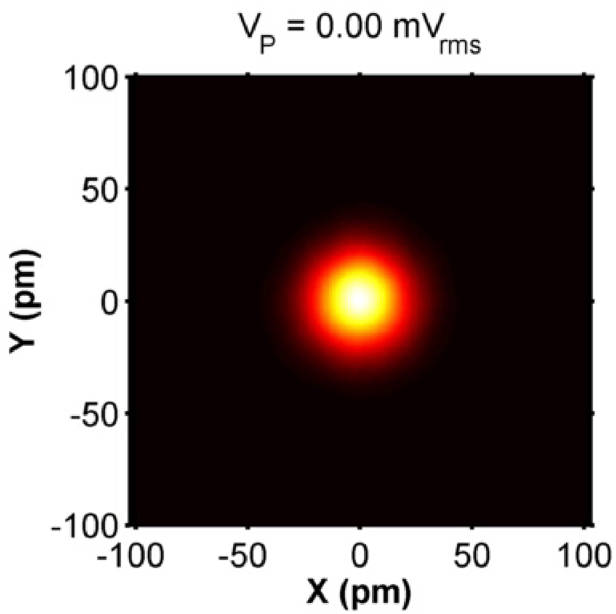
CNT: Hüttel, Nano Lett. 2009, Häkkinen, Nano Lett. 2015

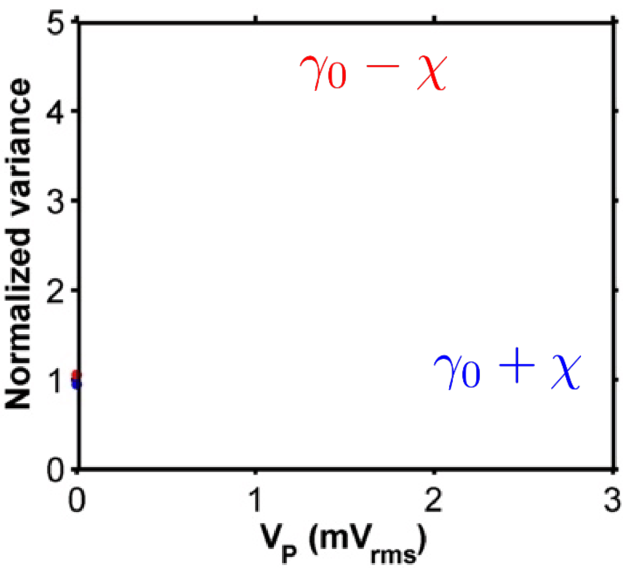




Optomechanics with H-resonators

- Small objects perform Brownian motion: Gaussian and equal quadratures
- Modulation of the resonance frequency f_0 at $2f_0$: $\chi = \partial f_0 / \partial V_{\mathrm{dc}} \cdot V_P$
- Noise squeezed in the X quadrature – limited to 3 dB





(note: actual data)

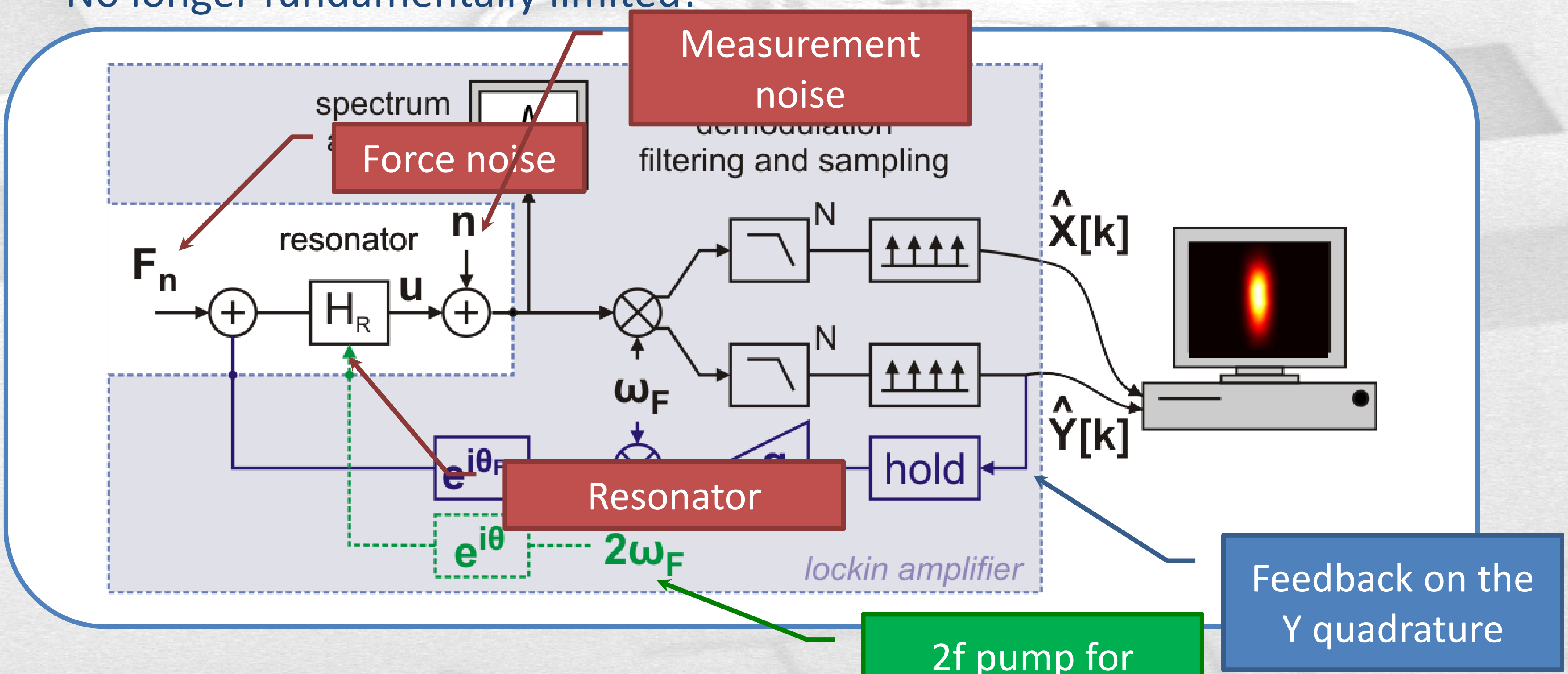
$$X = \langle x(t)\cos(\omega_F t)\rangle_{\omega_F}$$

$$Y = \langle x(t)\sin(\omega_F t)\rangle_{\omega_F}$$

M. Poot, K.Fong, and H.Tang, Phys.Rev. A **90** 063809 (2014)

Optomechanics with H-resonators

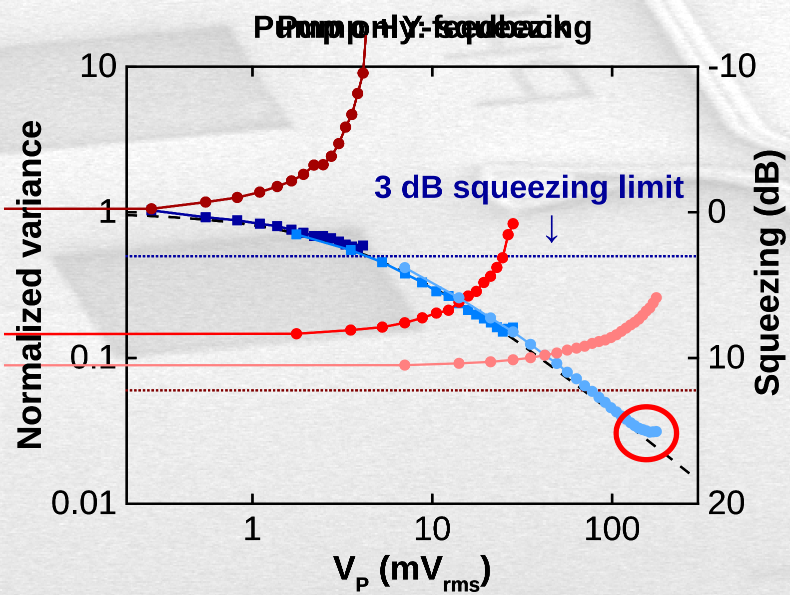
- Parametric squeezing reduces noise in one quadrature (X) $\gamma_0 + \chi$
  Limited to 3 dB due to instability in other quadrature (Y) $\gamma_0 - \chi + g$
- Feedback cooling can reduce thermal noise. Limited by SNR
- Use squeezing to reduce noise and feedback to prevent instabilities
- No longer fundamentally limited!

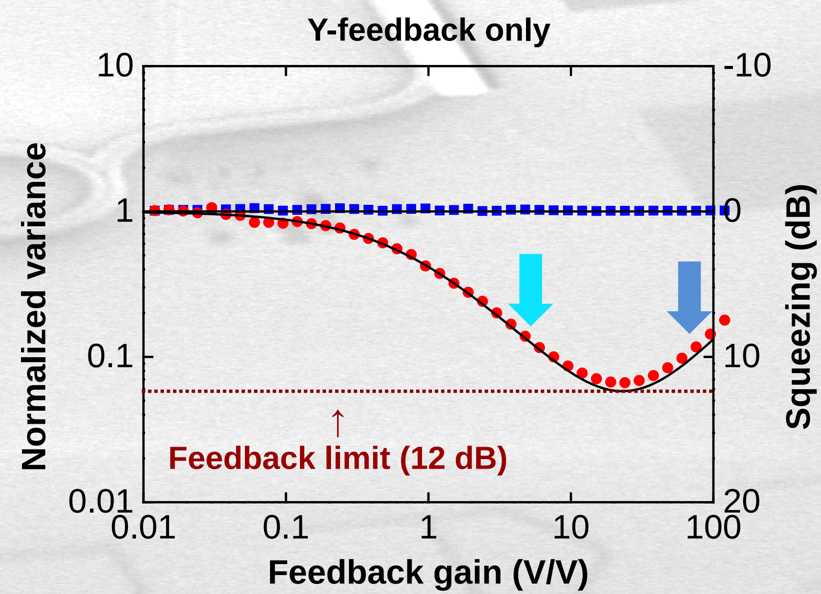


M. Poot, K.Y. Fong, and H.X. Tang, New J. Phys. **17** 043056 (2015)
Pioneering work: A. Vinante and P. Falferi, Phys. Rev. Lett. **111** 207203 (201

Optomechanics with H-resonators

- Parametric squeezing reduces noise in one quadrature (X, blue hues)
  Limited to 3 dB due to instability in other quadrature (Y, red hues)
- Feedback cooling can reduce thermal noise. Limited by SNR
- Use squeezing to reduce noise and feedback to prevent instabilities
  No longer fundamentally limited!
- 15 dB of squeezing achieved:
  far beyond the 3 dB limit and even surpasses the FB cooling limit





M. Poot, K.Y. Fong, and H.X. Tang, New J. Phys. **17** 043056 (2015)

Towards quantum squeezing

- So far these experiments were done with thermal motion
- How about the quantum regime?

Resonance frequency	Temperature	Thermal occupation	Required squeezing
500 kHz	300 K	1.3×10^7	74 dB
1 GHz	4 K	83	22 dB
1 GHz	20 mK	0.1	0.8 dB

- Low temperature and high frequency are the way to go
  Need for faster electronics/alternative feedback schemes
  e.g. Poot et al., APL **99**, 013113 (2011)
- What is actually limiting the squeezing?

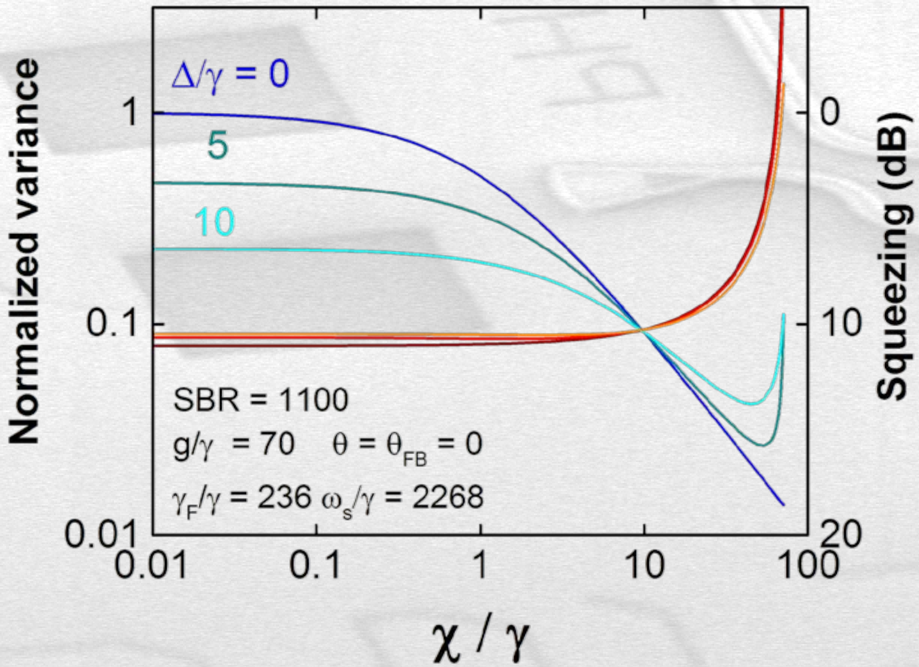
$$\bar{n} = \left\{ \exp\left(\frac{hf}{k_B T} \right) - 1 \right\}^{-1}$$

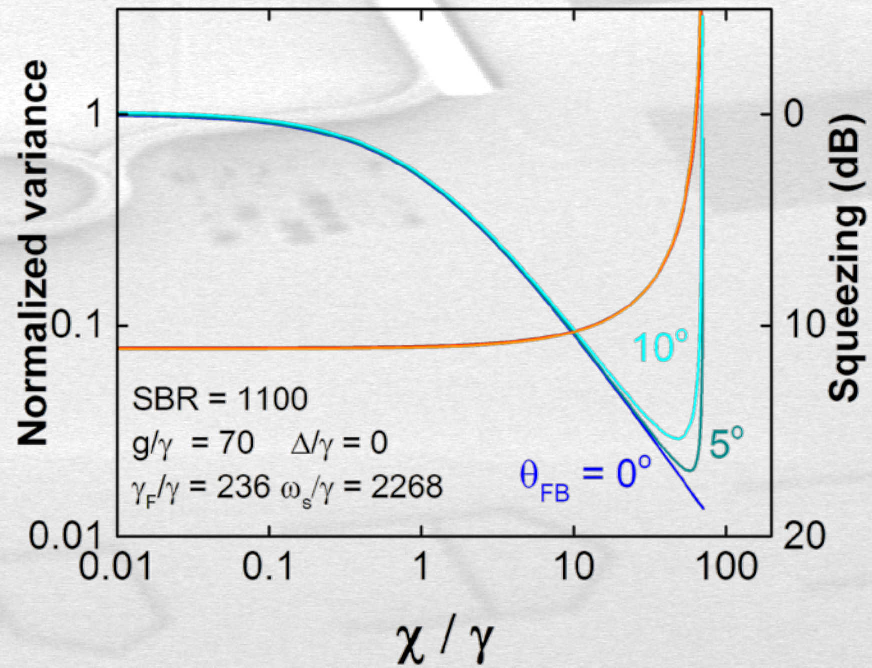
$$\frac{\langle u^2 \rangle}{u_{\mathrm{zpm}}^2} = 2\bar{n} + 1$$

Recent work on quantum squeezing using BAE:
Wollman, Schwab *et al.*, *Science*, **349**, 952 (2015)
Lecocq, Teufel *et al.*, *PRX*, **5**, 041037 (2015)

Towards quantum squeezing

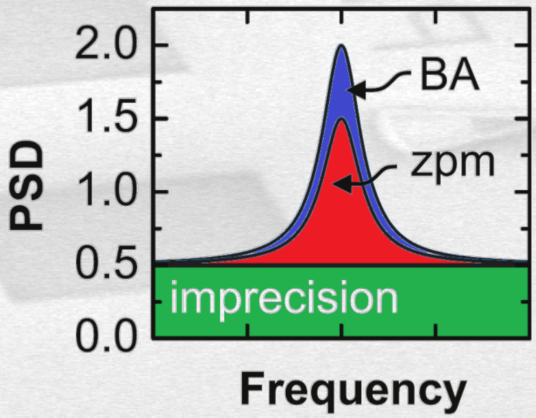
- Calculate the amount of squeezing for nonideal parameters
- The maximum squeezing degrades when the not exactly on resonance → frequency drift
- Similar effect for finite phases θ, θ_{FB}

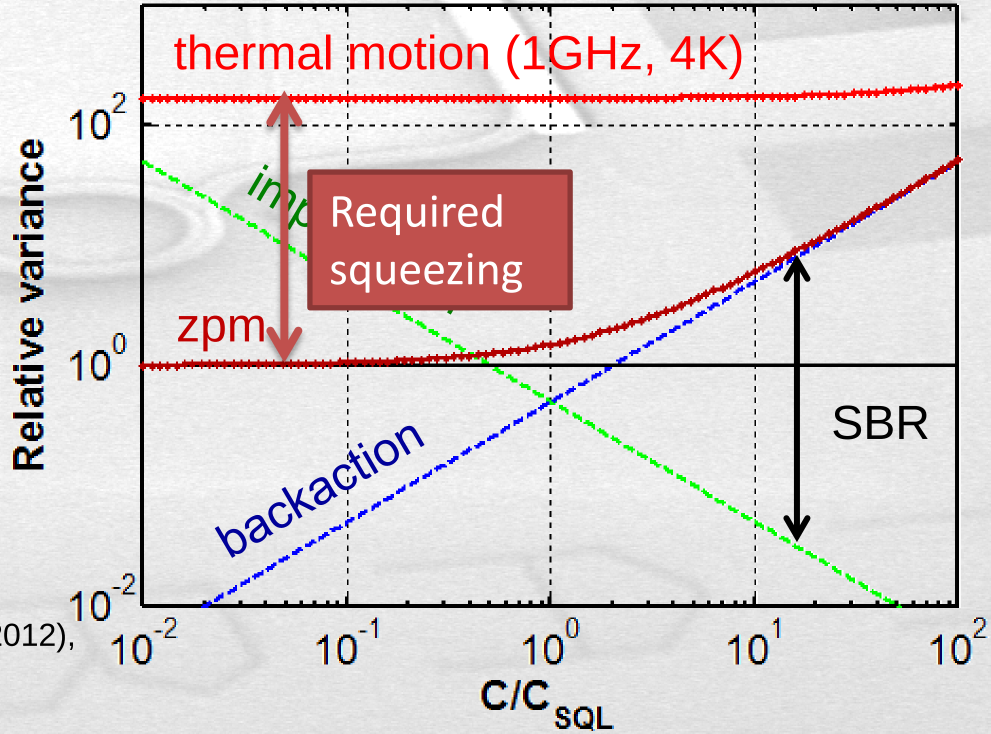




Towards quantum squeezing

- What about the signal-to-background ratio (SBR)?
  - A weak measurement ($C \ll C_{SQL}$) gives a noisy signal
  - A strong measurement ($C \gg C_{SQL}$) gives a clearer signal, but backaction heats the resonator
- For a quantum resonator the SBR is small near the SQL; for higher temperature SBR is larger

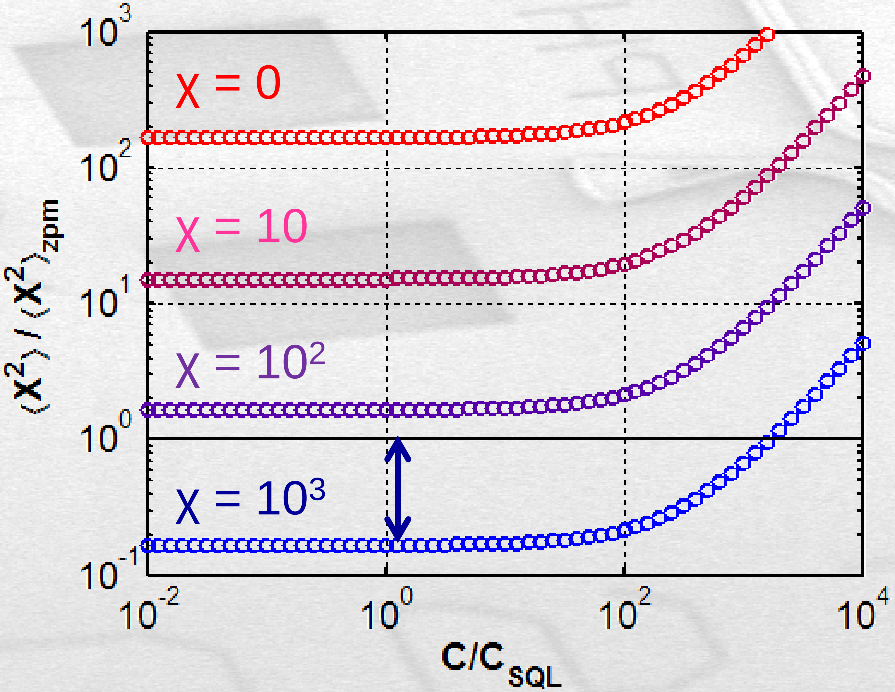


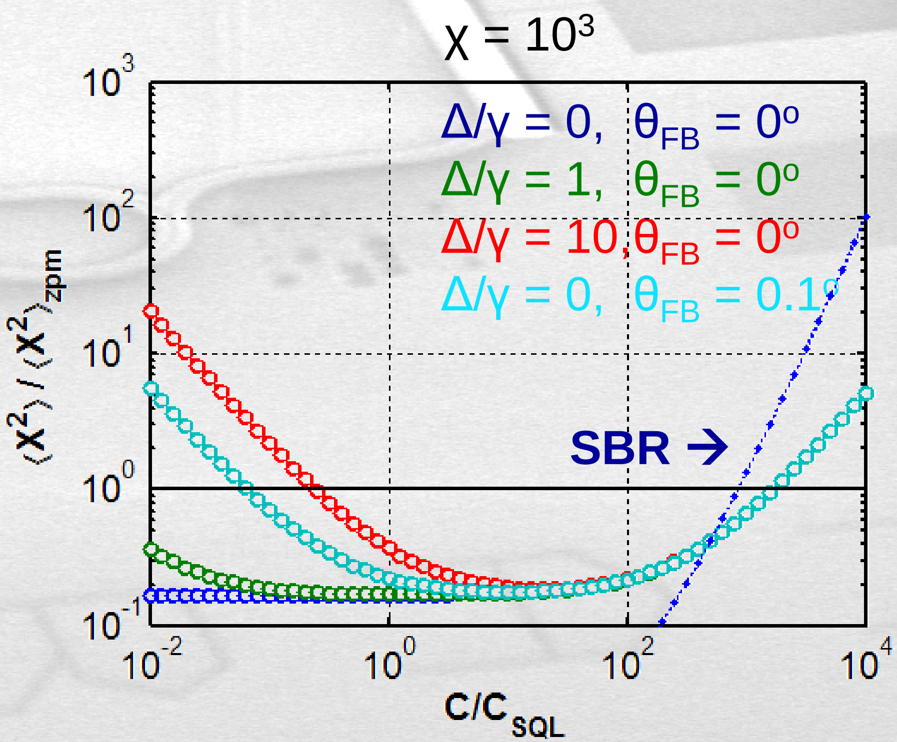


e.g. M. Poot and H.S.J van der Zant, *Phys. Rep.* **511** 273–335 (2012), or Aspelmeyer *et al.*, *Rev. Mod. Phys.* **86** 1391 (2014)
See also Wilson, Kippenberg *et al.*, *Nature* **524** 325 (2016)

Towards quantum squeezing

- Turn up the parametric pump (and stabilizing feedback) to increase squeezing
- 8 dB of quantum squeezing for $\chi = 10^3$
- How robust is it?
- Can one see it?





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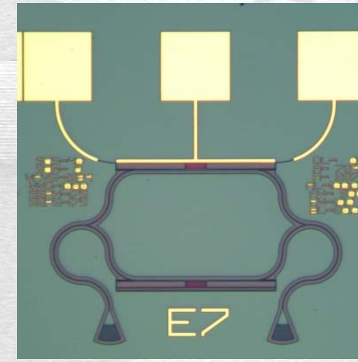
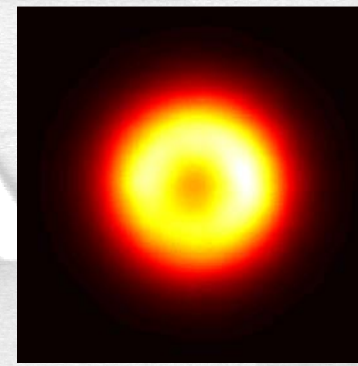
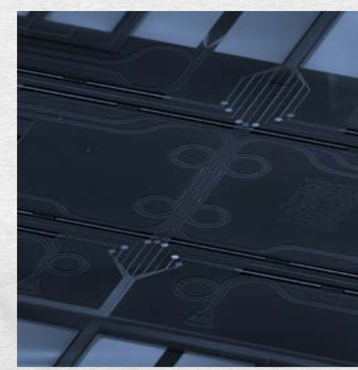
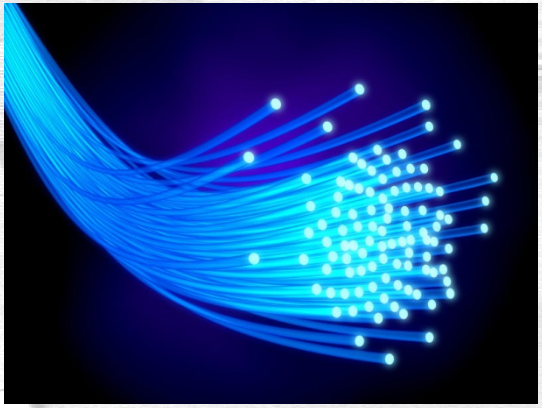


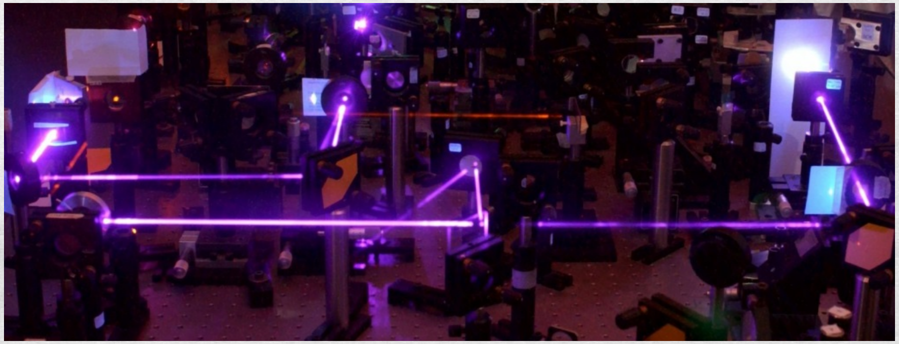




Linear optical quantum computation

- Optical photons are ideal qubits: they hardly interact with their environment
  - Easily transferred over large distances
  - Coherence is well preserved
- Problems:
  - Photons hardly interact with each other: Difficult to make 2 qubit gates
    Solution: measurement-induced nonlinearity (KLM scheme)
  - Not very scalable in free-space optics
    Measured in “number of optical tables”
    Use integrated optics:
    - Many small devices on a chip
    - Phase stability

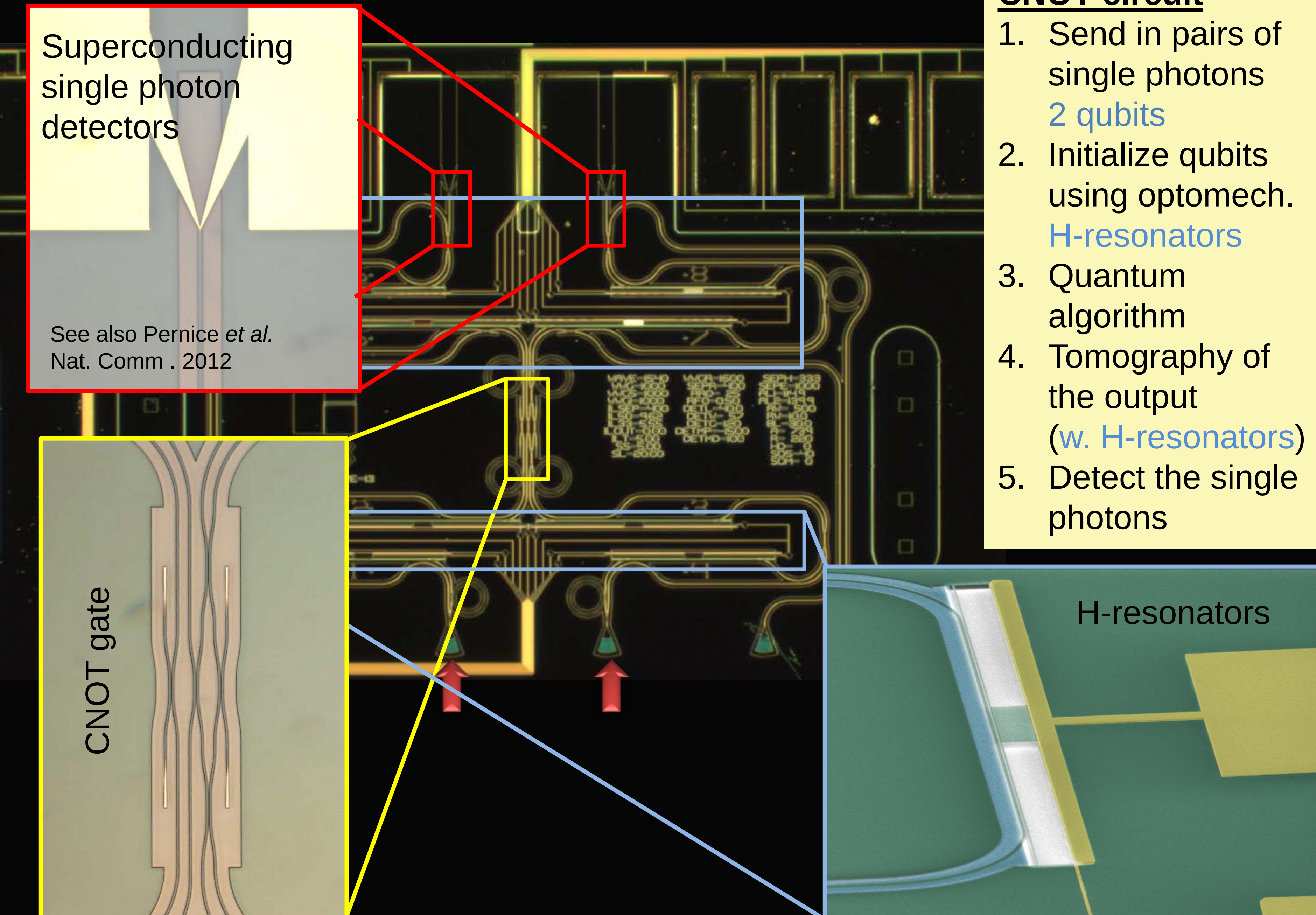




http://www.wiretechworld.com/files/2015/07/Optical-Fibers.jpg
http://www.fisi.polimi.it/sites/default/files/allegati/images/LabLaserA1.JPG

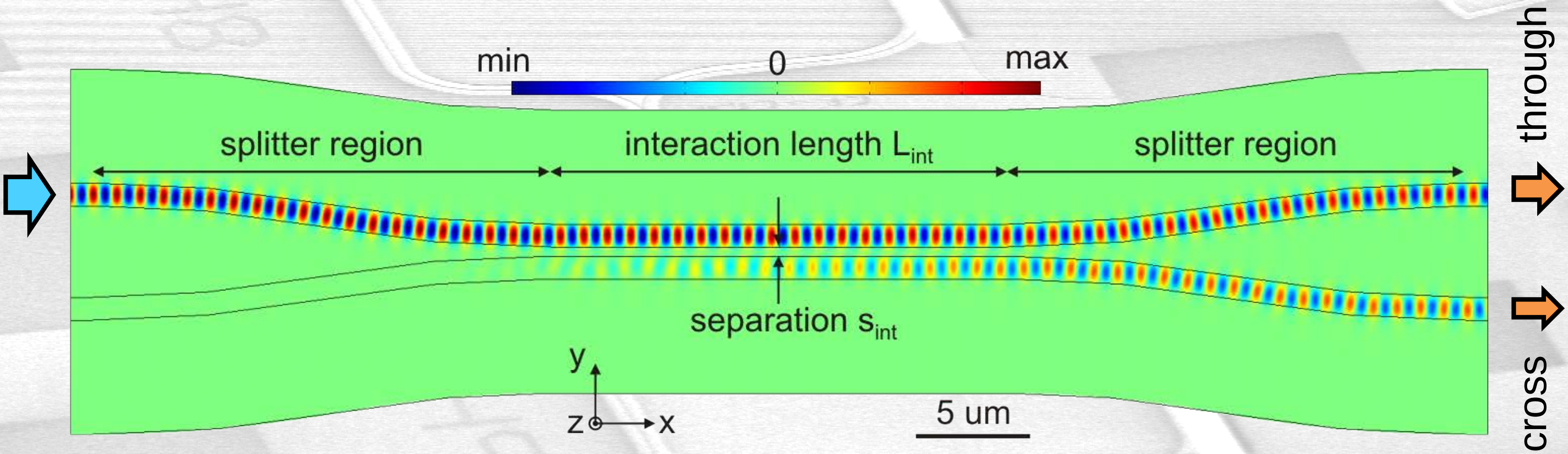
CNOT circuit

1. Send in pairs of single photons
   2 qubits
2. Initialize qubits using optomech.
   H-resonators
3. Quantum algorithm
4. Tomography of the output
   (w. H-resonators)
5. Detect the single photons

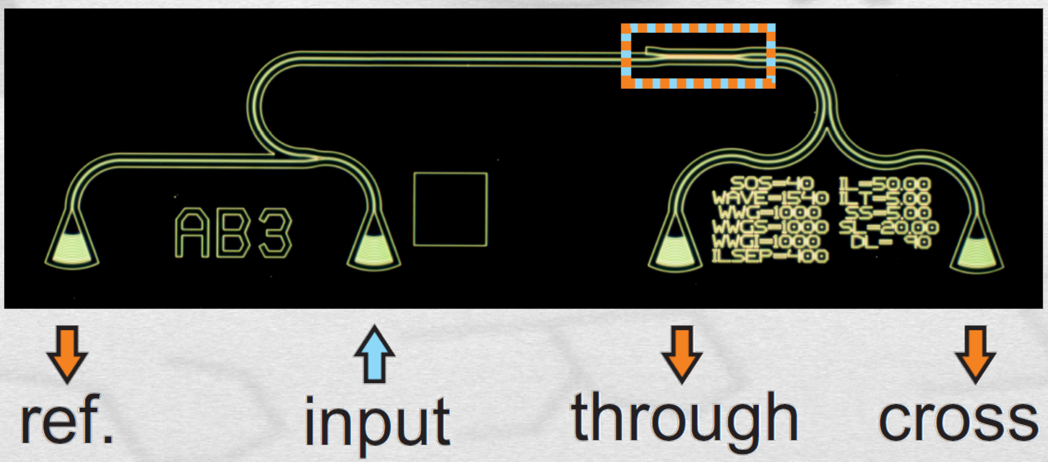


M. Poot et al, Integrated quantum optics circuits with superconducting detectors and optomechanical phase shifters, in preparation

Directional coupler

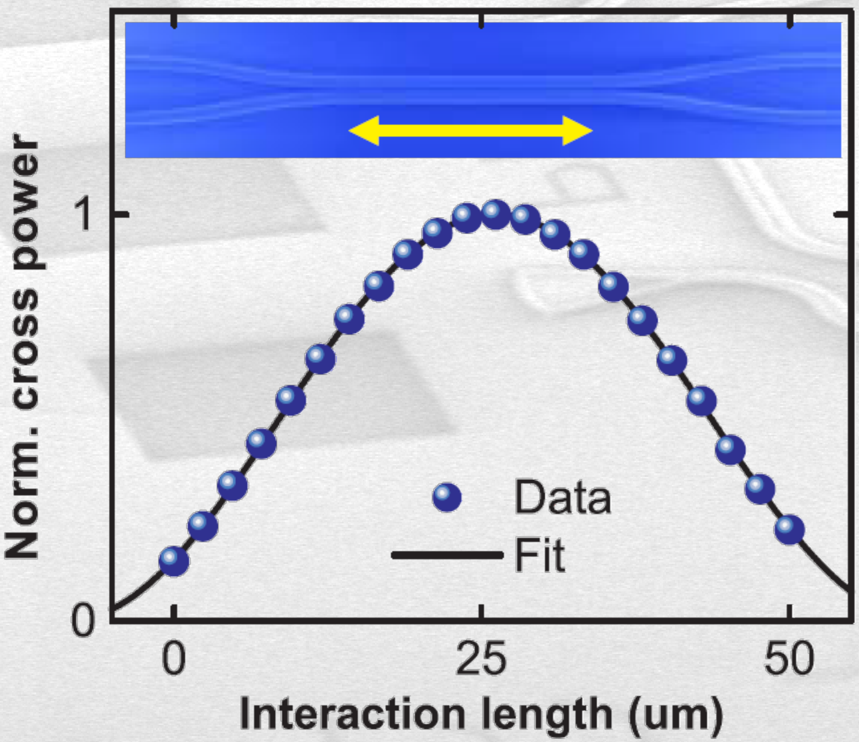


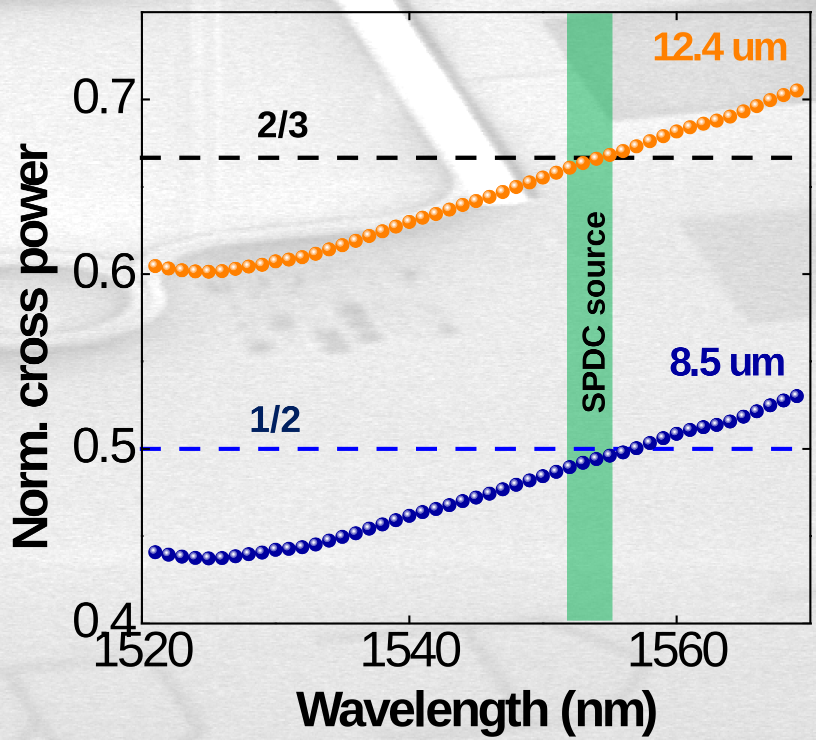
How large should the interaction length be for a given splitting ratio *C*?



Directional coupler

- Measure transmission for different interaction lengths L_{int}
- Fit: $C = \sin^2\left(\frac{\pi}{2}\frac{L_{\mathrm{int}}+\ell_0}{\ell_c}\right)$
- With ℓ_0, ℓ_c determine L_{int} for new chip
- Very close to target values of 1/2 and 2/3





M. Poot *et al.*, Op. Ex. **24** 6843 (2016)

A more complex circuit: a CNOT gate

- Need to confirm that the network works as designed
- Classical scattering matrix determines the quantum behavior
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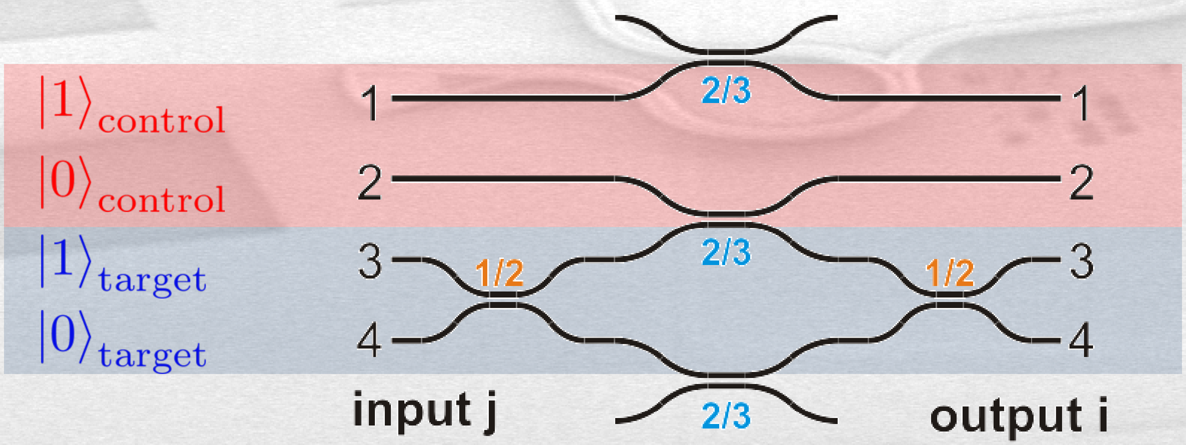
- How to find the scattering matrix?



M. Poot *et al.*, Op. Ex. **24** 6843 (2016)

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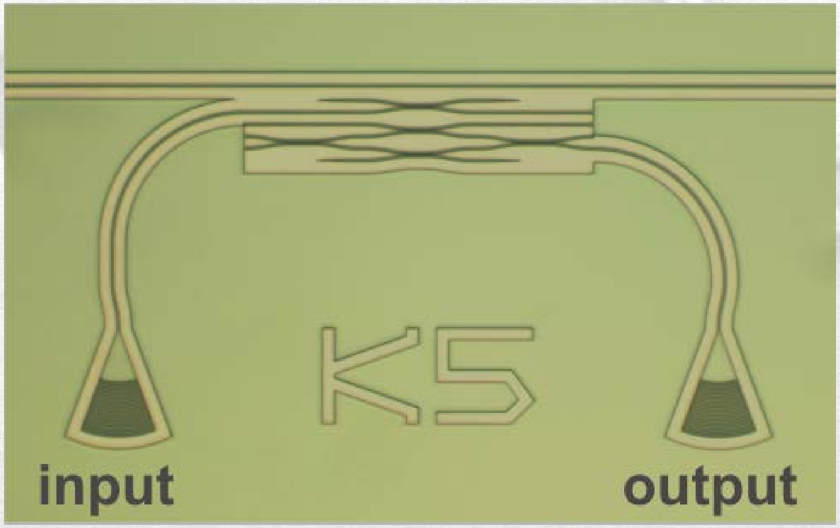

- Make identical CNOT devices with different combinations of input and outputs connected
- Example: input=1, output=4
- Transmission determines $|S_{41}|^2$
- Do this for all 16 combinations

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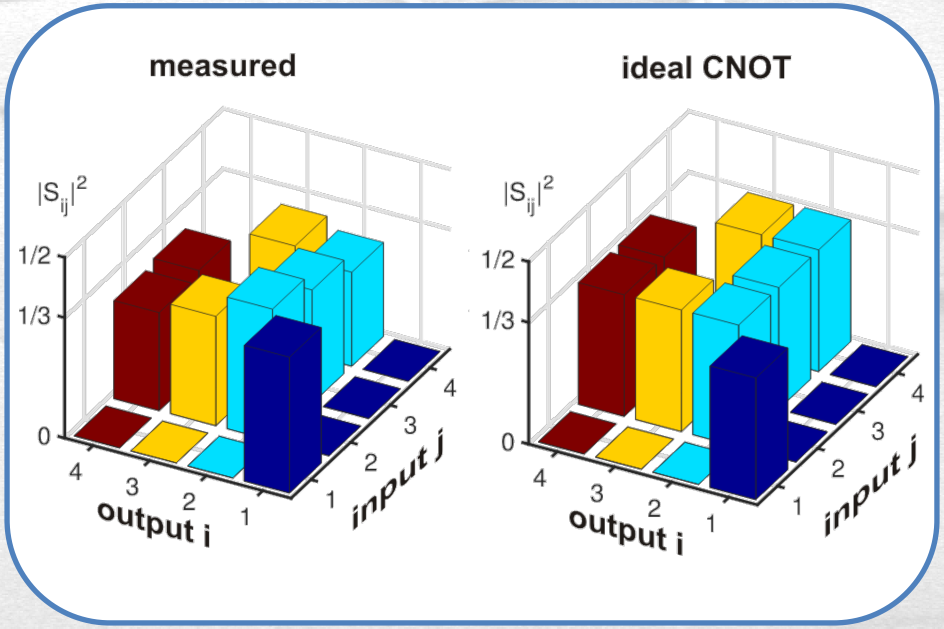

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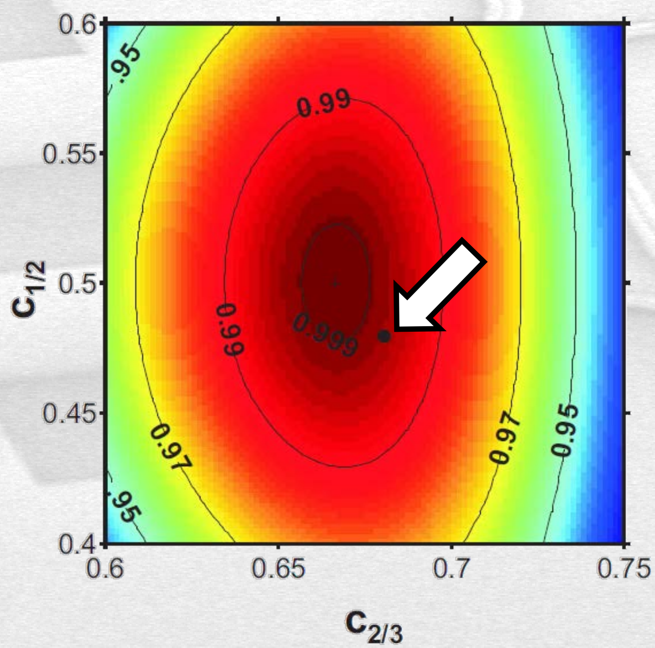
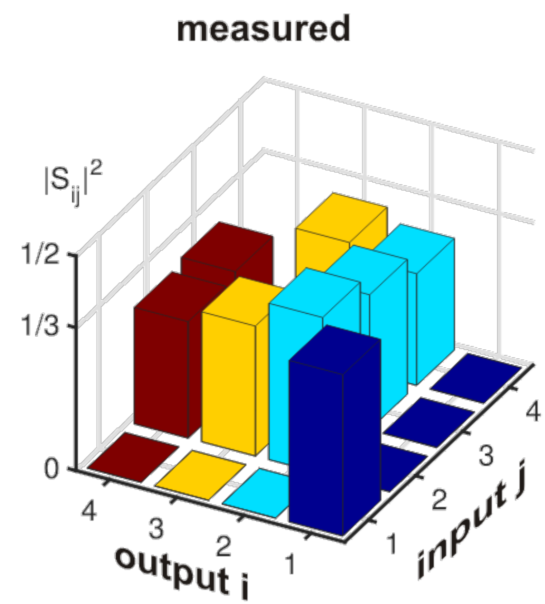
M. Poot *et al.*, Op. Ex. **24** 6843 (2016)

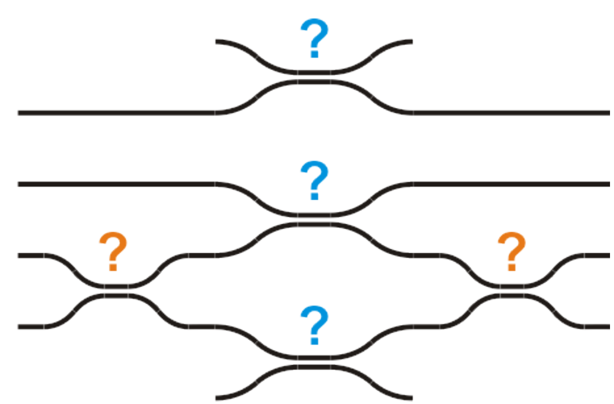
Characterizing the CNOT

- Transmissions determined by the model of the CNOT gate
- From least-squares fit: $C_{50} = 0.477$ and $C_{67} = 0.676$
- Values close to ideal



- Simulation: correct result 99.8% of the time → high fidelity operation

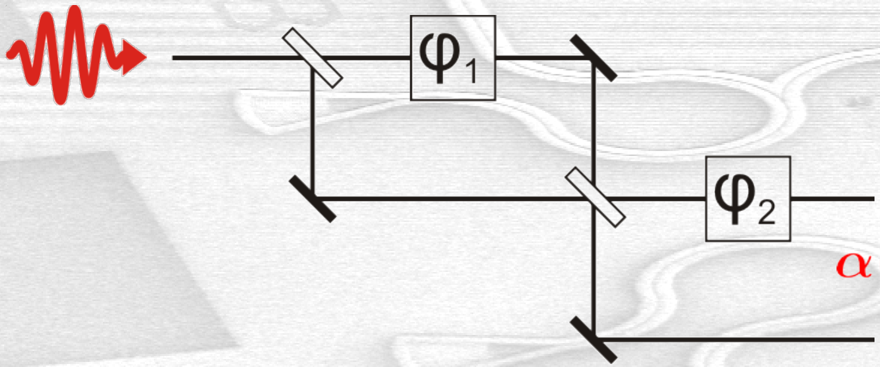




M. Poot *et al.*, Op. Ex. **24** 6843 (2016)

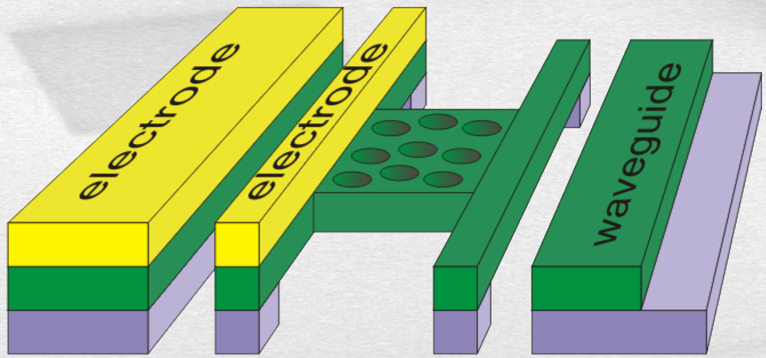
The full circuit – initialization and tomography

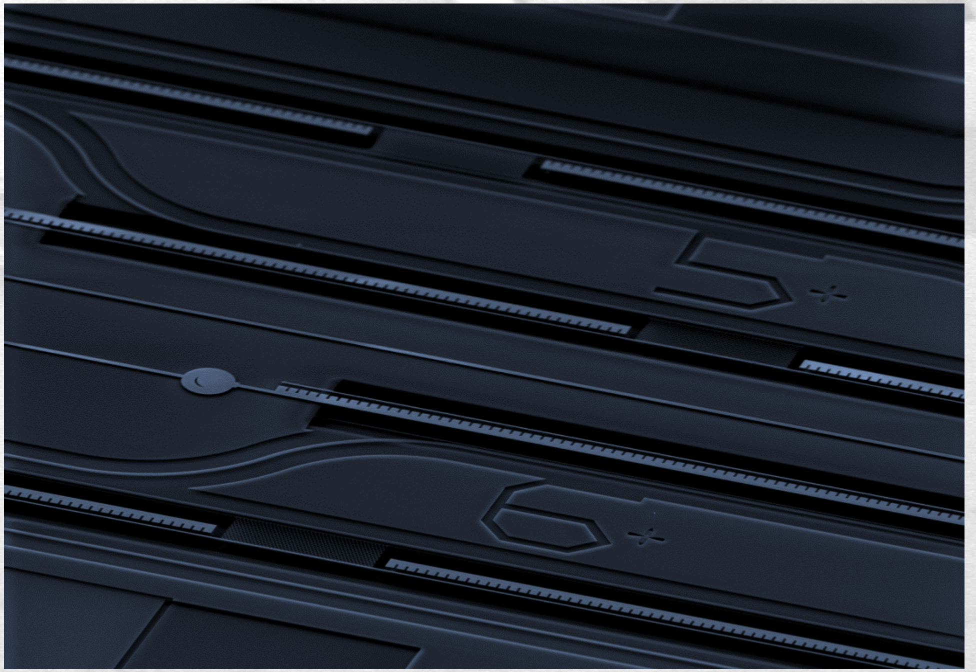
- Need to prepare qubits in arbitrary state



$$\alpha(\varphi_1, \varphi_2)\,|0\rangle + \beta(\varphi_1, \varphi_2)\,|1\rangle$$

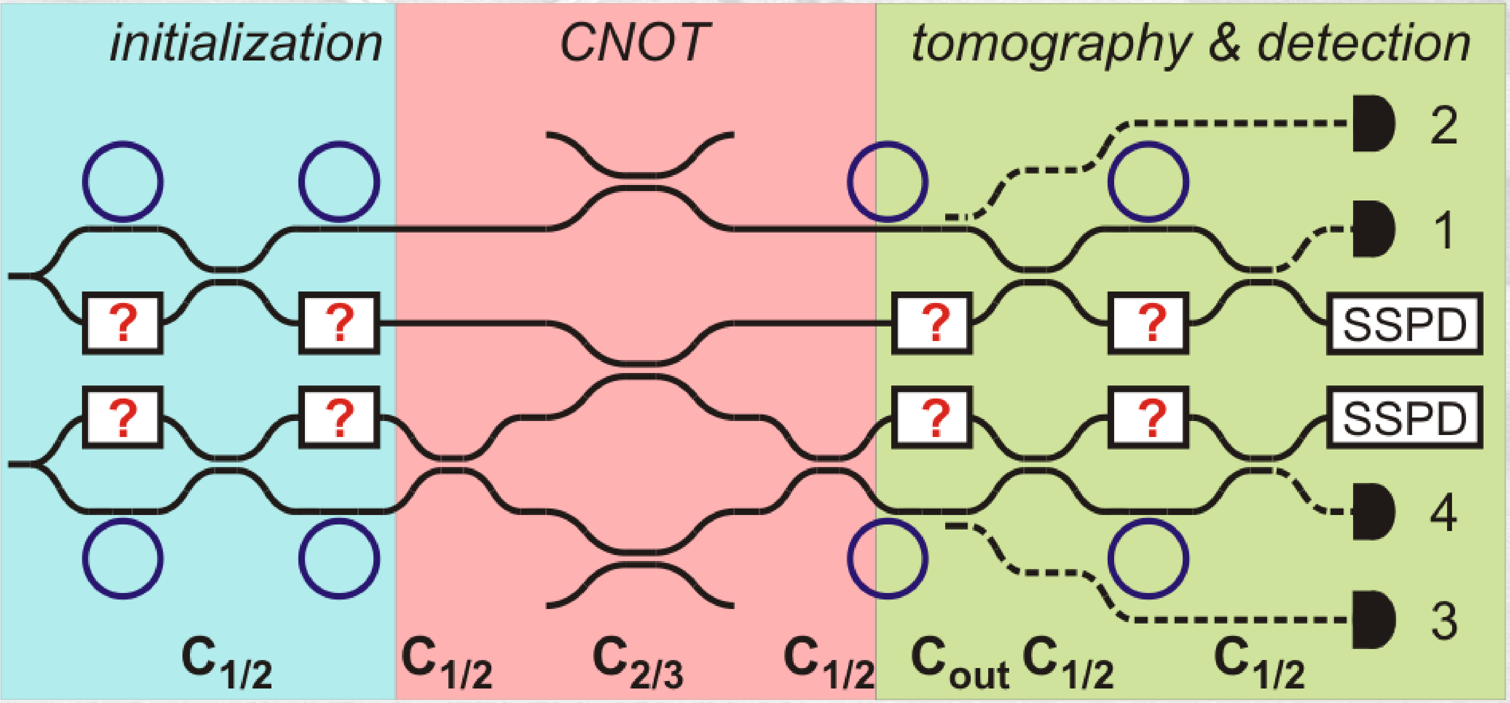
- Use H-resonators as opto-mechanical phase shifters





M. Poot and H. Tang, Appl. Phys. Lett. 104, 061101 (2014)

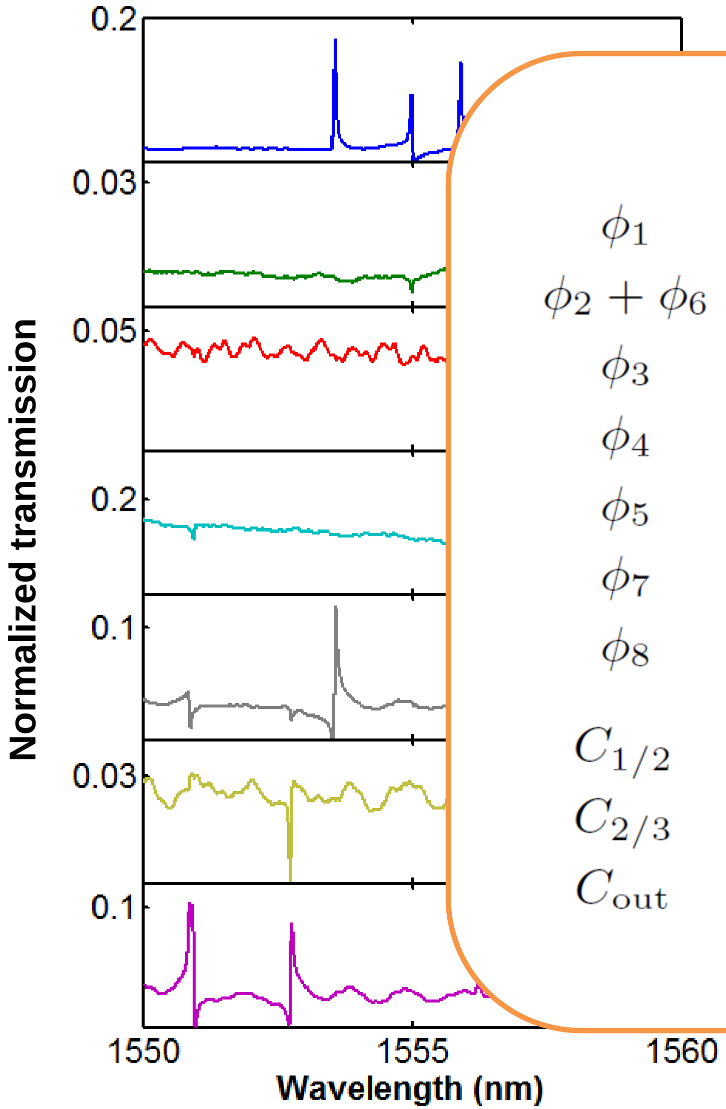
Determining the phases



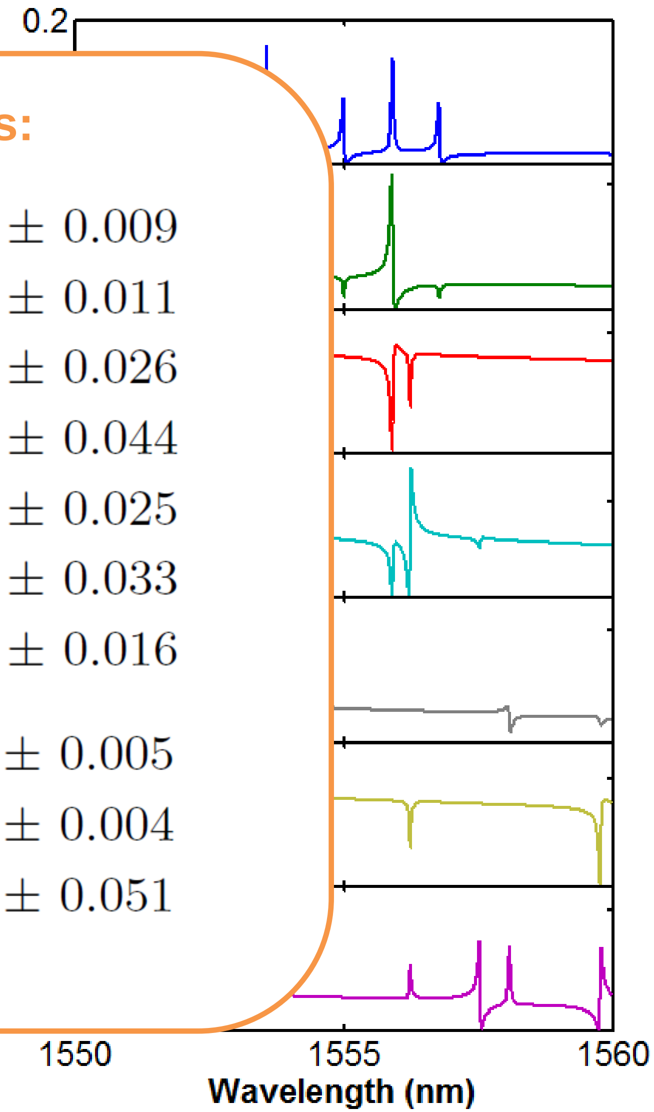
M. Poot et al, Characterization of optical quantum circuits using resonant phase shifts, submitted

Determining the phases

Measurement



Fit

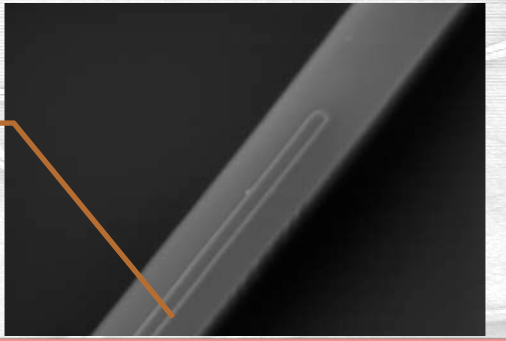


Results:

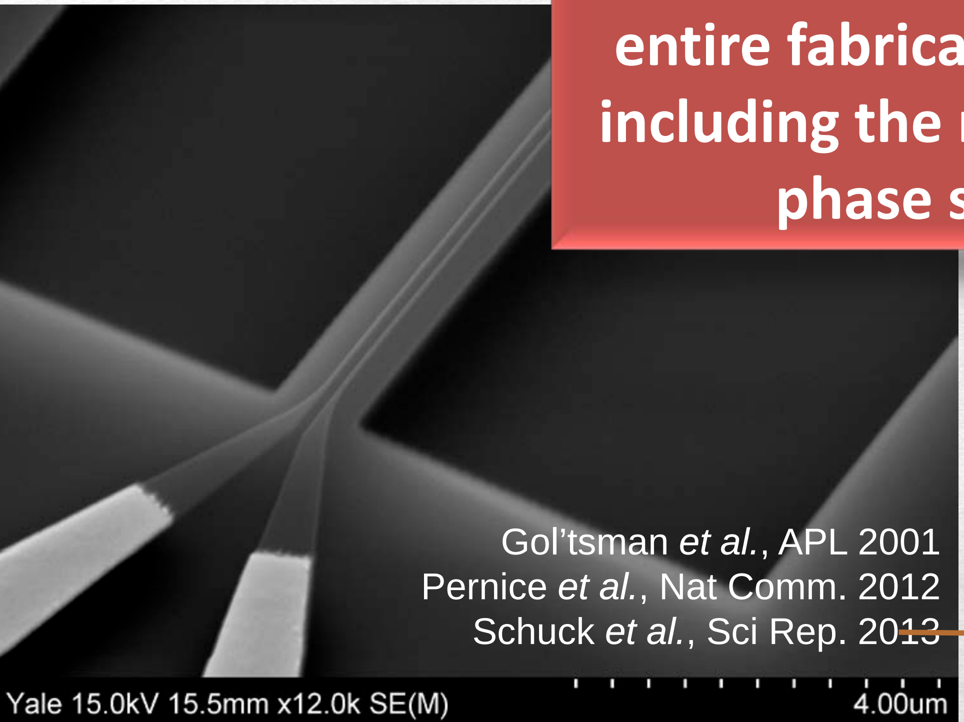
ϕ_1	-2.360 ± 0.009
$\phi_2 + \phi_6$	0.708 ± 0.011
ϕ_3	-2.249 ± 0.026
ϕ_4	0.237 ± 0.044
ϕ_5	2.267 ± 0.025
ϕ_7	1.751 ± 0.033
ϕ_8	0.284 ± 0.016
$C_{1/2}$	0.479 ± 0.005
$C_{2/3}$	0.675 ± 0.004
C_{out}	0.031 ± 0.051

Superconducting single photon detectors

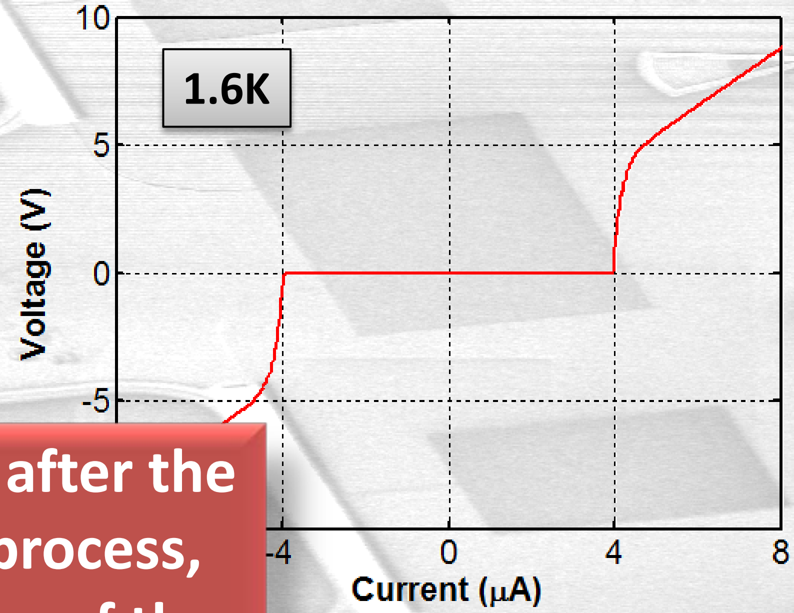
30 .. 70 nm wide
~ 5 nm thick NbTiN
on top of a waveguide

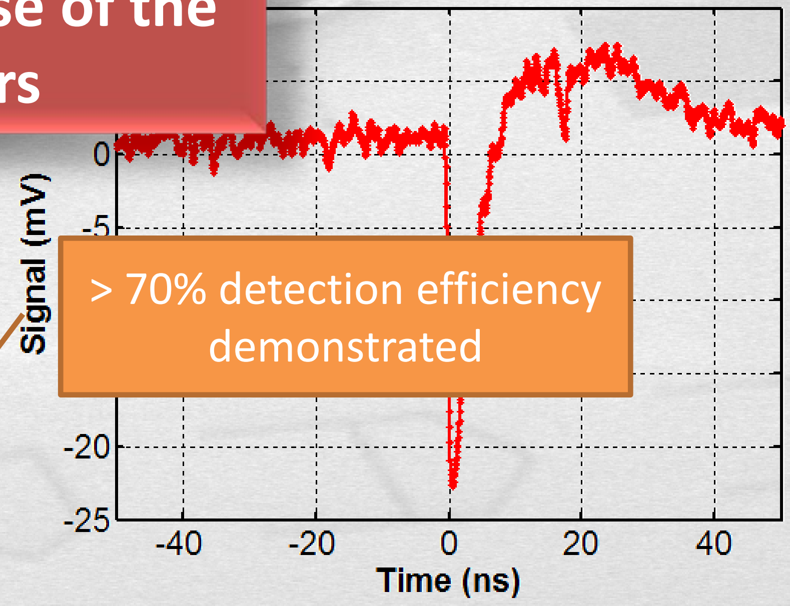


The SSPDs work OK after the entire fabrication process, including the release of the phase shifters



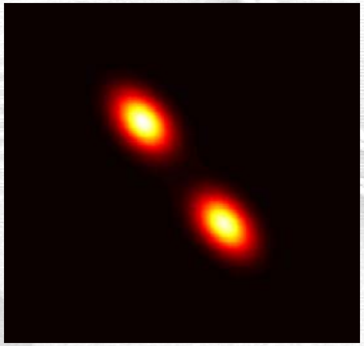
Gol'tsman *et al.*, APL 2001
Pernice *et al.*, Nat Comm. 2012
Schuck *et al.*, Sci Rep. 2013



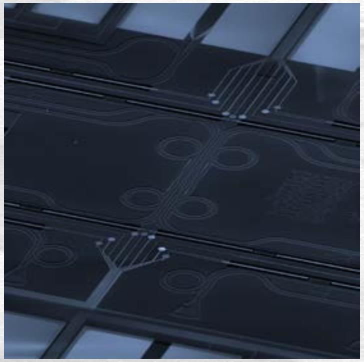


> 70% detection efficiency demonstrated

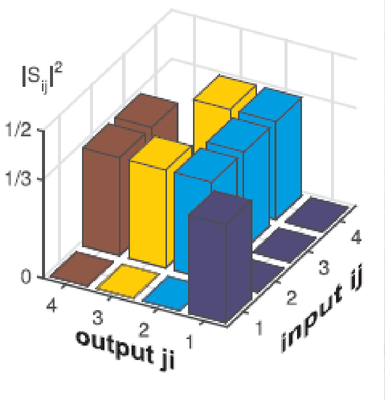
Conclusions and outlook



We demonstrate strong electrostatic interactions, and squeezing with feedback in H-resonators. These experiments can be extended to the quantum regime

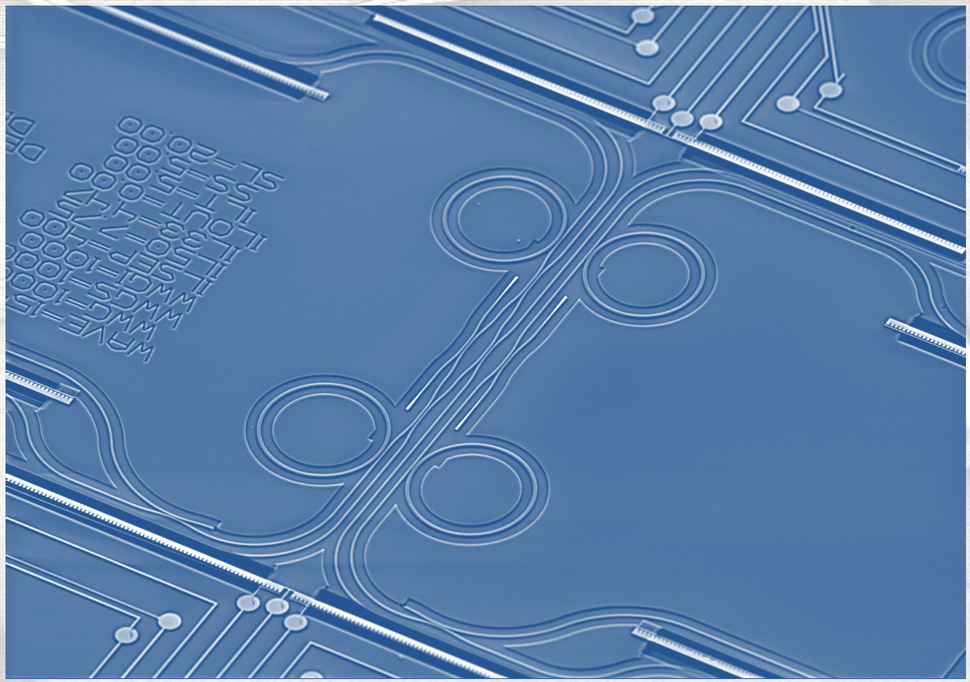


Our “H” phase shifters are not only useful in optomechanics but are essential parts in integrated quantum optics



Integration of all elements - SSPDs, phase shifters and quantum circuitry - is underway and the next step is to send nonclassical light into these exciting devices

Photonic circuits for integrated quantum optics



Yale Institute for Nanoscience and Quantum Engineering

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Netherlands Organisation for Scientific Research

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Currently: TU Delft

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August 4, 2016