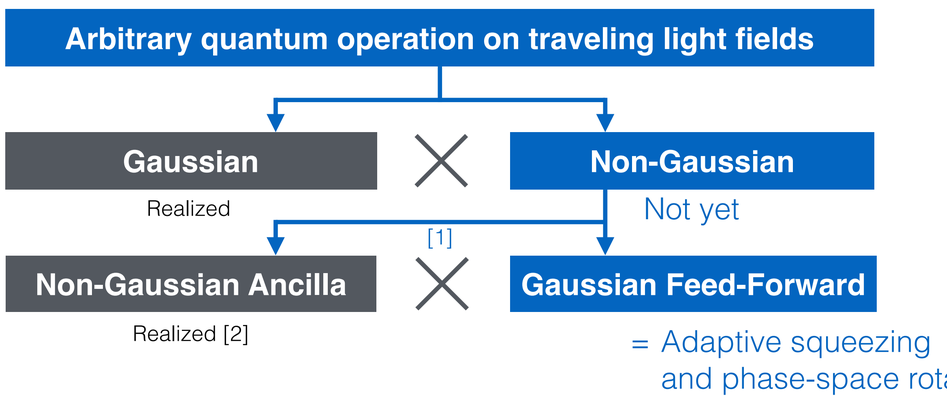
Demonstration of Dynamic Squeezing Gate for Continuous-Variable Quantum Information Processing

K. Miyata[1], H. Ogawa[1], P. Marek[2], R. Filip[2], H. Yonezawa[3], J. Yoshikawa[1] and A. Furusawa[1]

[1]Department of Applied Physics, School of Engineering, The University of Tokyo
[2]Department of Optics, Palacký University
[3]School of Engineering and Information Technology, The University of New South Wales

1. Introduction

Background



Problems

- Previous Gaussian-operation experiments have been performed only with fixed gains
- Gaussian operation which accepts varying input states has not been demonstrated

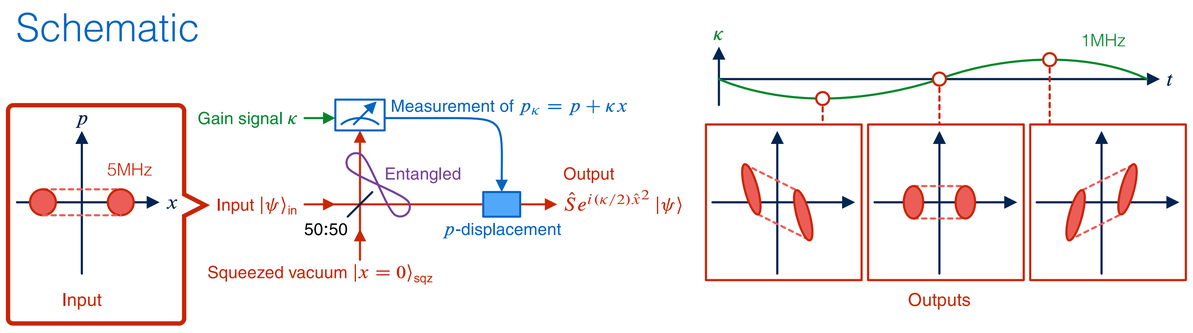
Purpose: implementation of *dynamic* squeezing gate

"Dynamic" implies:

- Squeezing operation according to dynamically-changing gain signals
- Squeezing operation on dynamically-changing input states

2. Method

Schematic

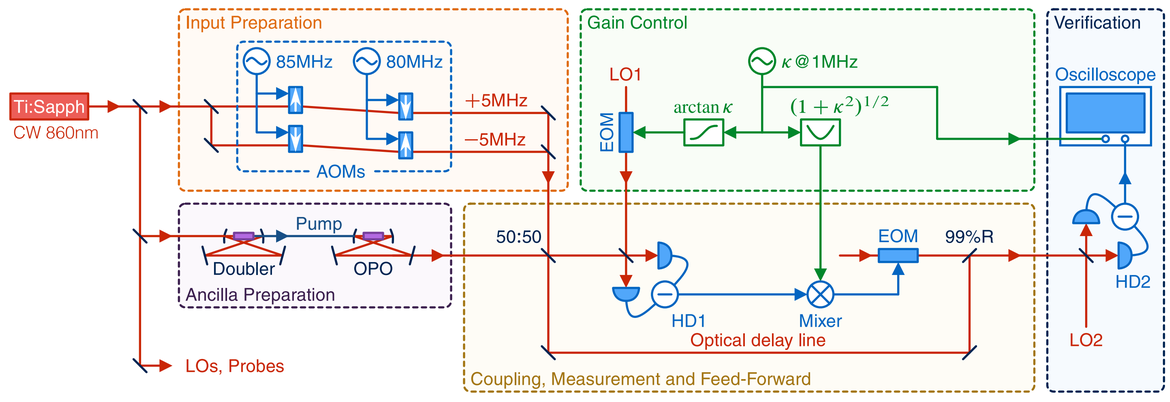


- Input: amplitude-varying coherent state
- Operation:
  1. Prepare an ancillary squeezed vacuum state
  2. Entangle the input and ancilla at a balanced beamsplitter
  3. Measure one of the output modes using a Gaussian basis $p_\kappa = p + \kappa x$
  4. Displace the other output using the measured value
- Output: squeezed and phase-space rotated state

$$\hat{x} = \frac{1}{\sqrt{2}}\hat{x}_{\rm in}, \quad \hat{p} = \sqrt{2}\hat{p}_{\rm in} + \frac{\kappa}{\sqrt{2}}\hat{x}_{\rm in}$$

➡ The operation depends on the measurement basis
(One-way quantum computation scheme)

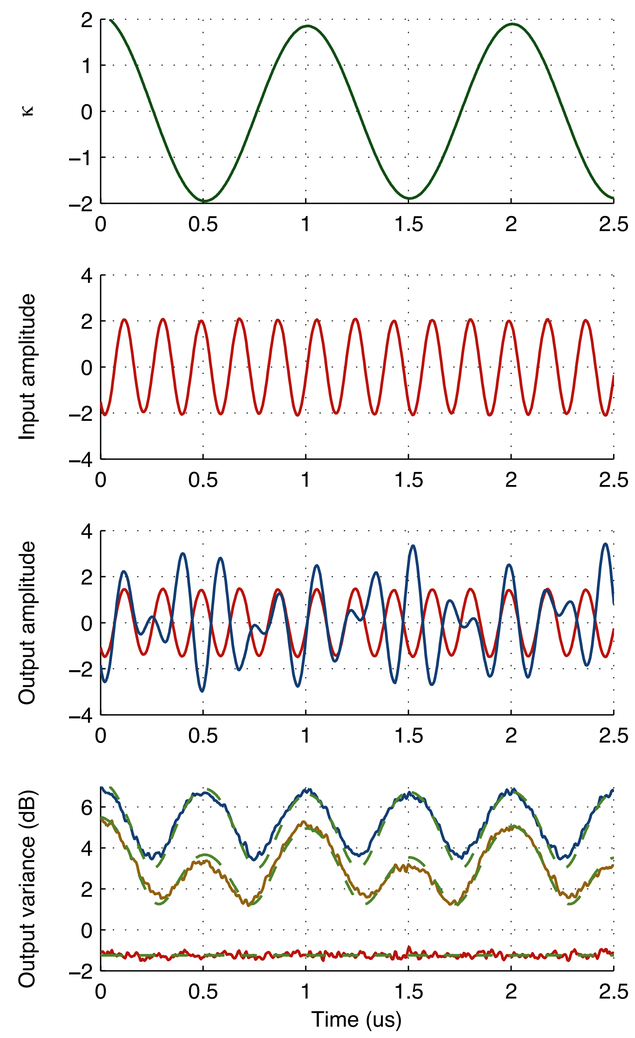
Experimental Setup



- Input preparation
  - Generation of ±5 MHz-sideband modes using acousto-optic modulators (AOMs)
- Ancilla preparation
  - Generation of a squeezed vacuum using optical parametric oscillator (OPO)
  - Over-10 MHz cavity bandwidth sufficiently covers bandwidth of the input state
- Coupling, measurement and feed-forward
  - Measure the quadrature with a homodyne detector (HD1)
  - 13 m optical delay line is used for matching propagation times of the signals
- Gain control
  - Sine wave |κ| ≤ 2 @ 1 MHz is used as the gain signal
  - Measurement basis at HD1 is given by $p_\theta = p\cos\theta + x\sin\theta$ where $\theta = \arctan\kappa$
  - The measured signal is amplified with a factor of $(1+\kappa^2)^{1/2}$
    → The resulting value is $p_\kappa = p + \kappa x$
  - All the functions are implemented by analog circuits with the latency of < 10 nsec
- Verification
  - Quadratures of three different bases are measured by another HD (HD2)

3. Results ($\hbar = 1$)

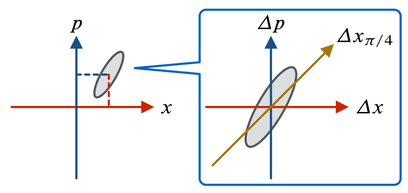
Mean values and variances of the output state



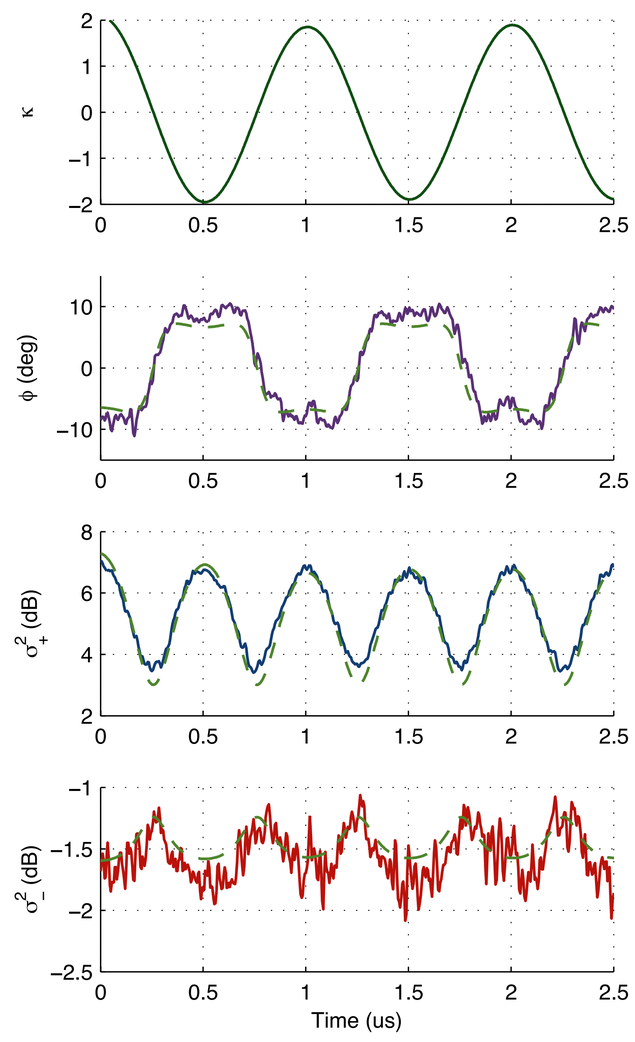
- All the values are calculated from the repeatedly measured data of 10,851 frames
- All the values are plotted in the same time domain

- κ: supplied gain signal @ 1 MHz
- Input state amplitude: ±2.0
- Output state amplitude
  - $\langle x \rangle$: ±1.4, independent with κ
  - $\langle p \rangle$: proportional to $\kappa\langle x \rangle$
- Output variances
  (normalized by shot noise level)
  - σ_x^2: -1.2 dB, constant
  - σ_p^2: starts from 3 dB
    and reaches about 6.6 dB,
    at twice the frequency of κ

- All the variances including $\sigma_{\pi/4}^2$ well agree with theoretical predictions



Analysis in terms of diagonalized covariances and argument



- We can derive the covariance matrix and diagonalize it

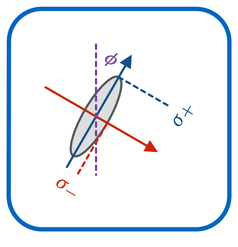
$$\sigma_+^2 = \sigma_x^2\sin^2\phi + \sigma_p^2\cos^2\phi + 2\sigma_{xp}\sin\phi\cos\phi$$

$$\sigma_-^2 = \sigma_x^2\cos^2\phi + \sigma_p^2\sin^2\phi - 2\sigma_{xp}\sin\phi\cos\phi$$

$$\phi = \frac{1}{2}\arctan\left(\frac{-2\sigma_{xp}}{\sigma_x^2 - \sigma_p^2}\right)$$

- ϕ: argument of major axis of the output Gaussian ellipse
  - ±10° rotation
- σ_+^2: maximally-anti-squeezed variance
  - From 3 dB to 6.7 dB
- σ_-^2: maximally-squeezed variance
  - From -1.2 dB to -1.8 dB

- While those values are reduced from that of an ideal case due to the finitely-squeezed ancilla, they still show dependency on the gain signal and well agree with theoretical predictions



4. Summary and Outlook

- We have demonstrated dynamic squeezing operation at 1 MHz, which acts on a coherent state continuously displaced at 5 MHz
- The operation works as an adaptive squeezing and phase-space rotation gate and thus can be applicable to a feed-forward system of non-Gaussian operation

References

[1] P. Marek et al., PRA **84**, 053802 (2011)
[2] M. Yukawa et al., PRA **88**, 053816 (2013)