Propagation of quantum optical fields under the conditions of multi-photon resonances in a coherent atomic vapor

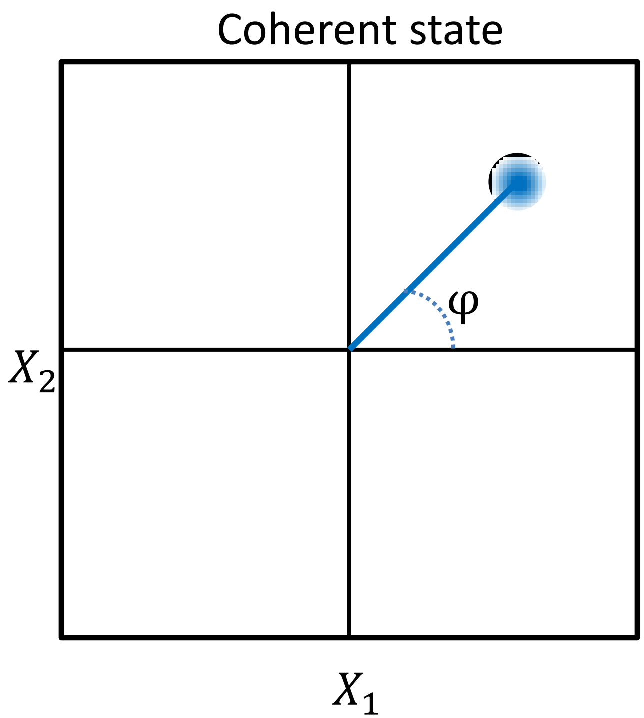
Gleb Romanov

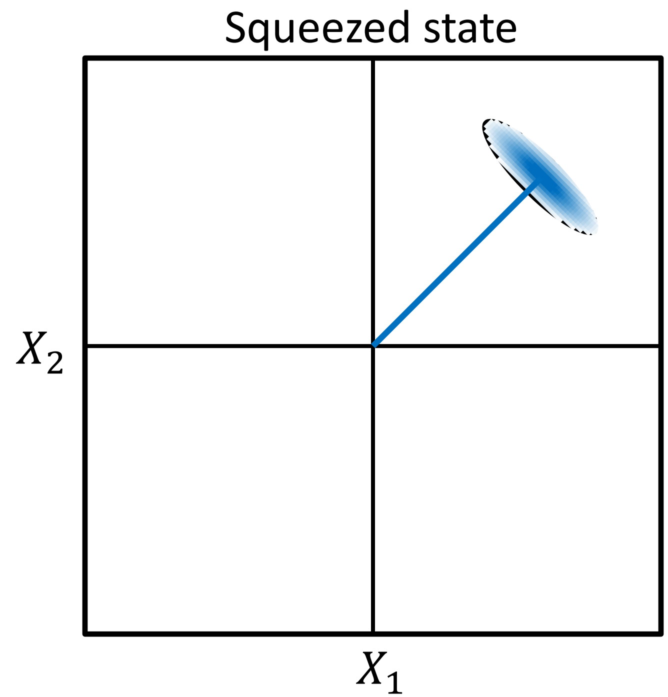
3/12/2013

Outline

- Squeezed states of light
- Previous experiment
- Hyper-fine EIT filtering experiment
- “Fast” squeezing experiment
- Future plans

Squeezed states of light





$E(t) = \varepsilon(ae^{-i\omega t} + a^\dagger e^{i\omega t})$ -> $E(t) = 2\varepsilon(X_1 \cos\omega t + X_2 \sin\omega t)$

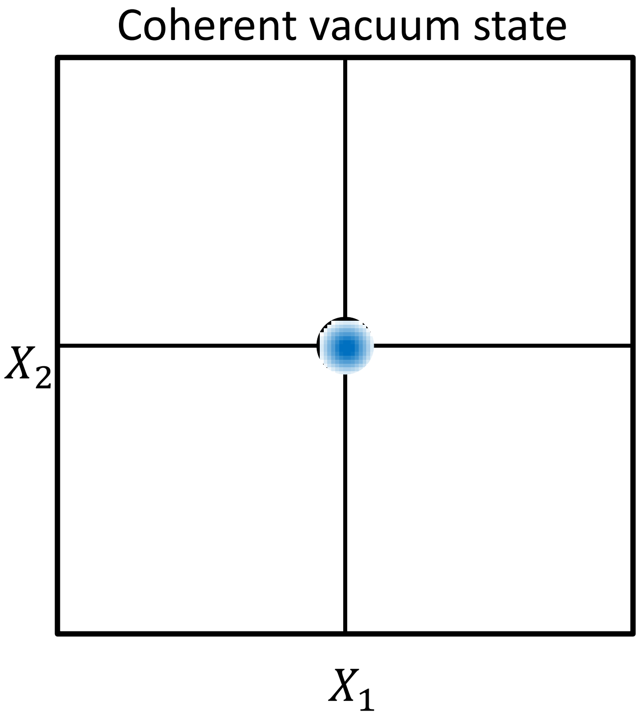
$[a, a^\dagger] = 1$ $[X_1, X_2] = \frac{i}{2}$

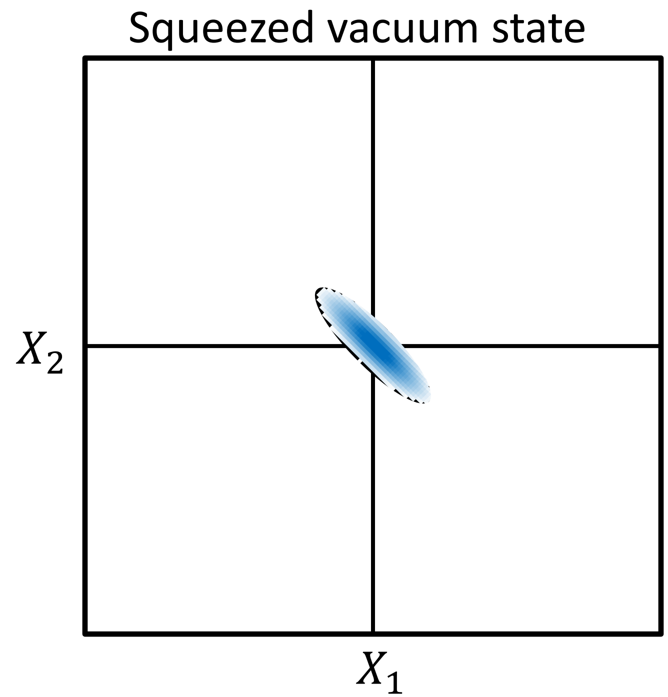
Coherent state:

$\Delta X_1 \Delta X_2 = \frac{1}{4}$

Squeezed state:

$\Delta X_1 \Delta X_2 \geq \frac{1}{4}$





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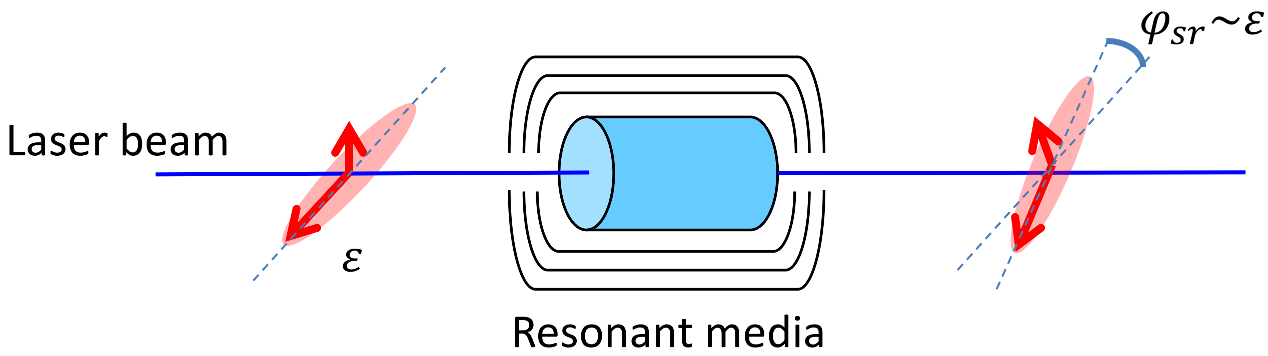
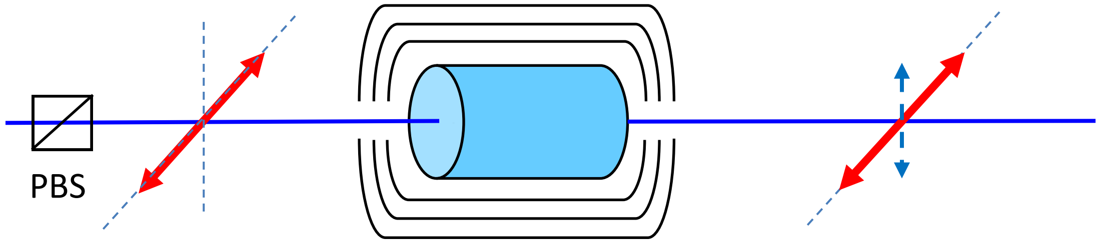
Polarization self-rotation



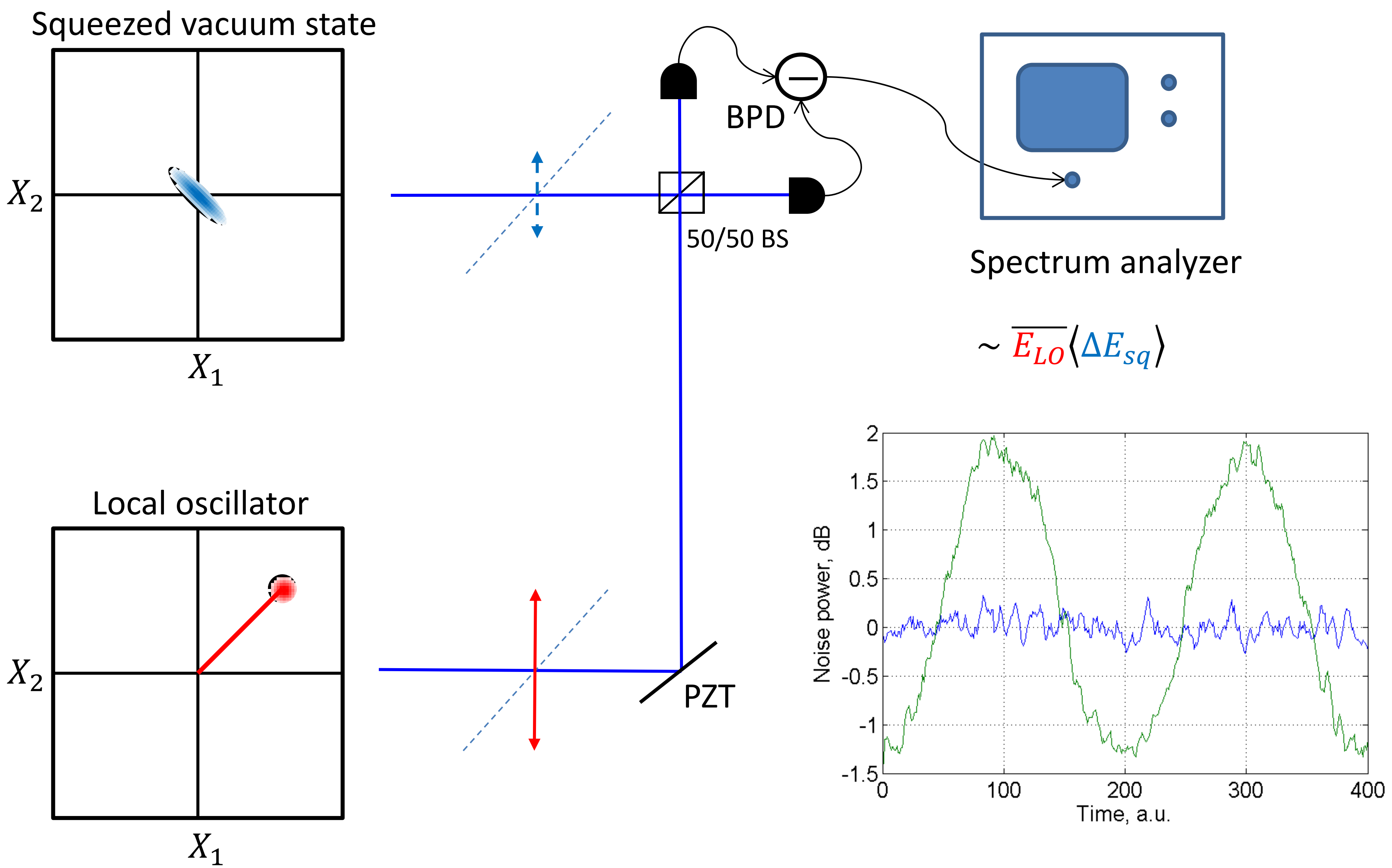
$$\varphi_{sr} \simeq \frac{3}{4\,\pi} N\,\lambda^2 \frac{\gamma}{\Delta} L\,\varepsilon$$

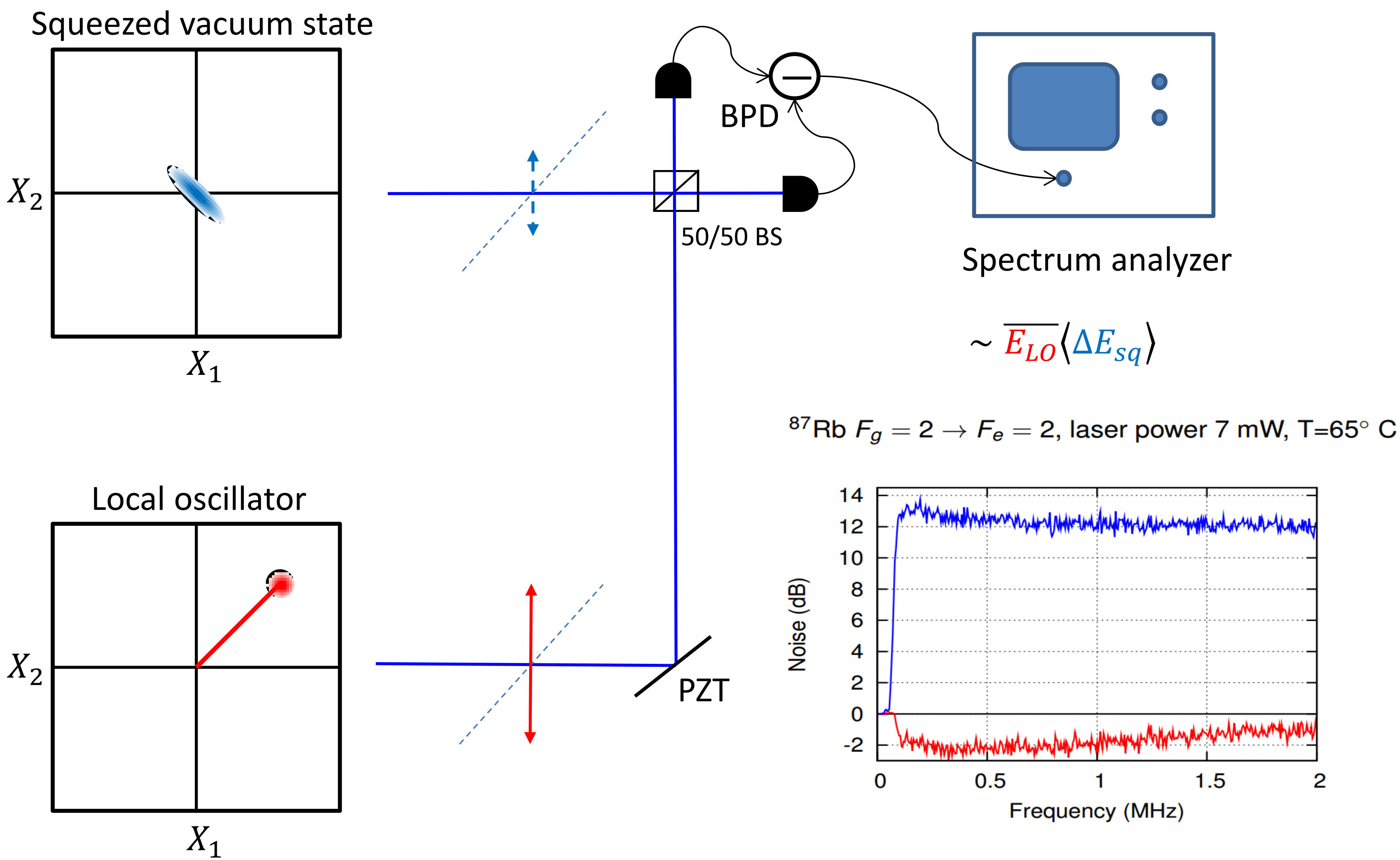
Polarization self-rotation



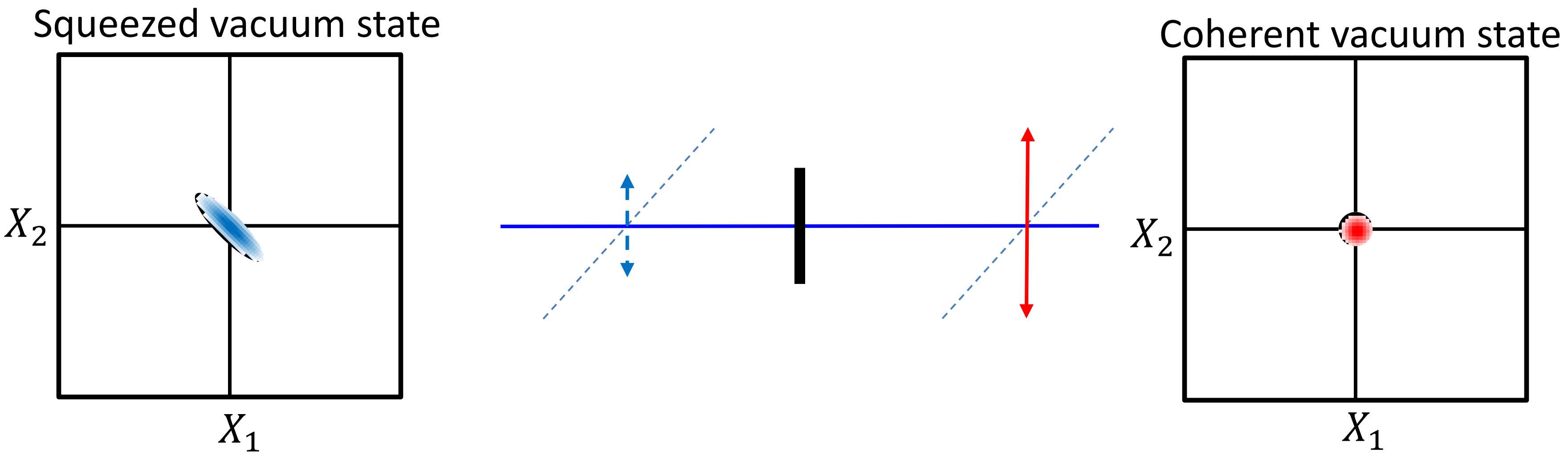
Horizontally polarized
pump field

Vertically polarized
squeezed vacuum field

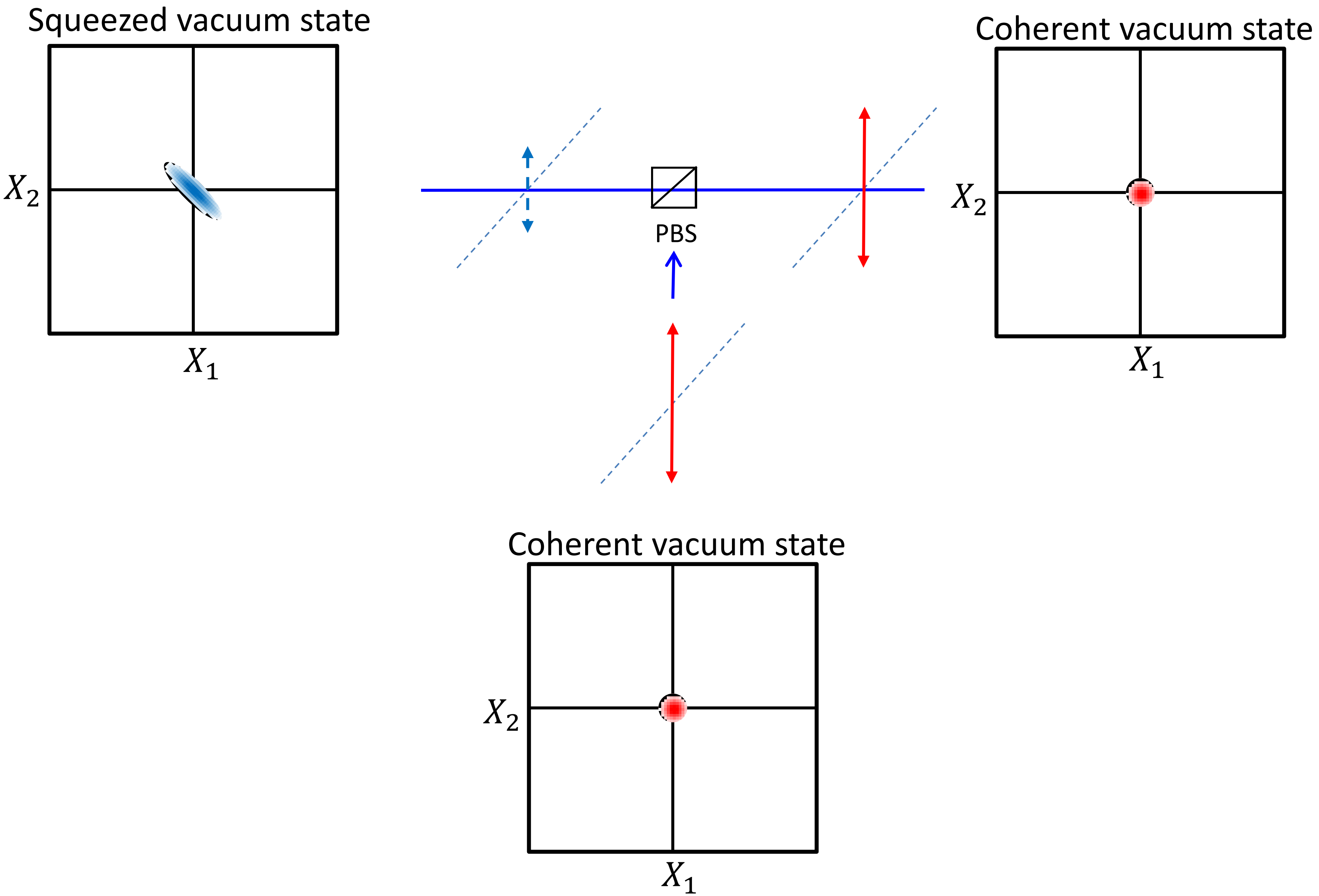

Squeezed vacuum state
X_2
X_1
Local oscillator
X_2
X_1
BPD
50/50 BS
PZT
Spectrum analyzer
$\sim \overline{E_{LO}}\langle \Delta E_{sq} \rangle$
Noise power, dB
Time, a.u.
2
1.5
1
0.5
0
-0.5
-1
-1.5
0
100
200
300
400


Squeezed vacuum state
X_2
X_1
Local oscillator
X_2
X_1
BPD
50/50 BS
PZT
Spectrum analyzer
$\sim \overline{E_{LO}}\langle \Delta E_{sq} \rangle$
^{87}Rb $F_g = 2 \rightarrow F_e = 2$, laser power 7 mW, T=65° C
Noise (dB)
Frequency (MHz)
14
12
10
8
6
4
2
0
-2
0
0.5
1
1.5
2

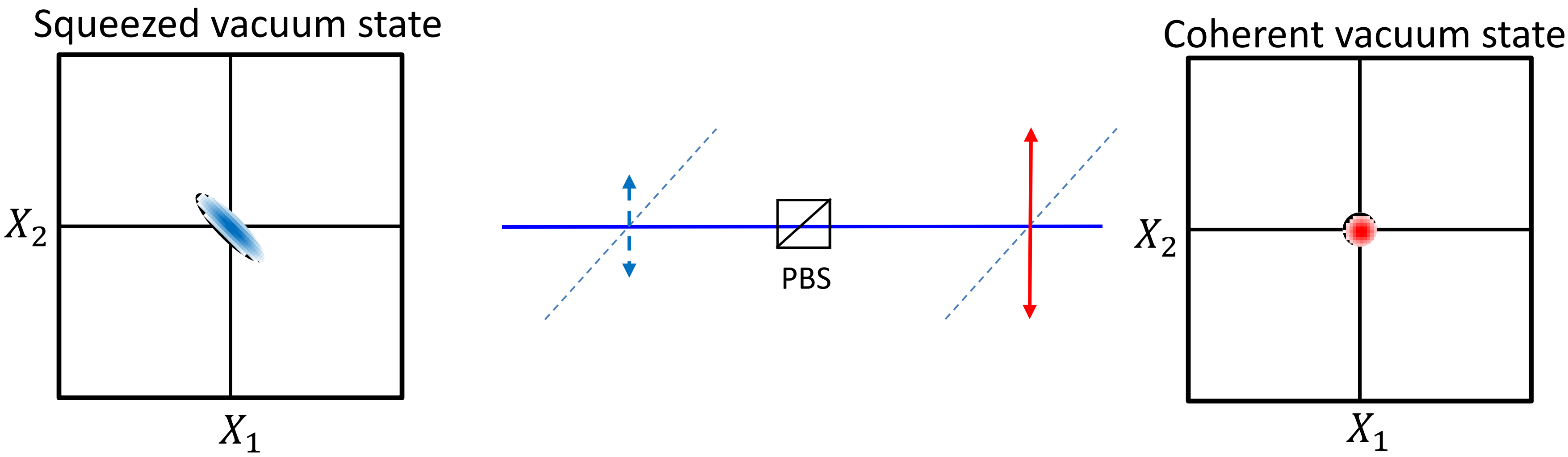
Detection of squeezed vacuum

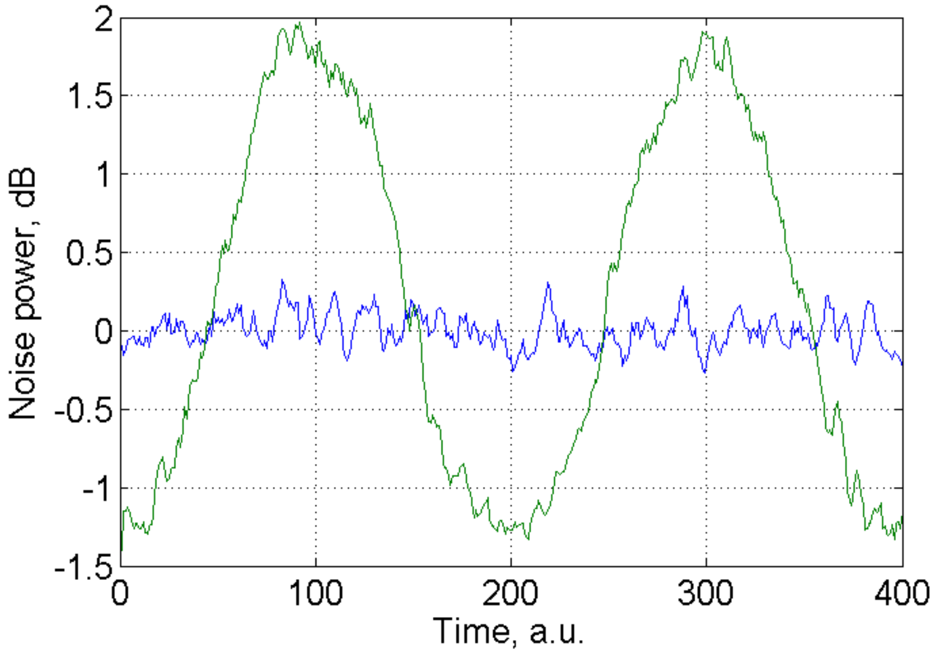


Detection of squeezed vacuum



Detection of squeezed vacuum





Beam splitter model

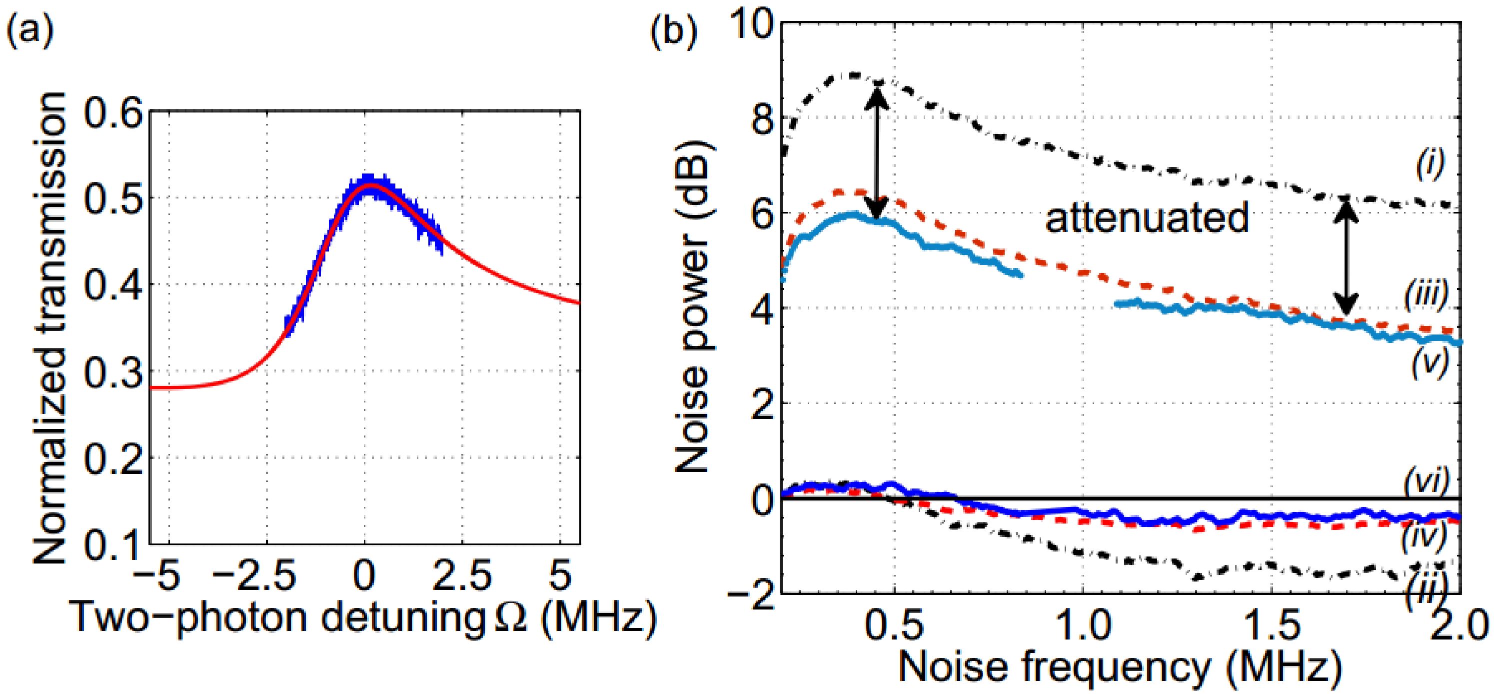
$$\begin{pmatrix} V_{+,out} \\ V_{-,out} \end{pmatrix} = \begin{pmatrix} {A_+}^2 & {A_-}^2 \\ {A_-}^2 & {A_+}^2 \end{pmatrix} \begin{pmatrix} V_{+,in} \\ V_{-,in} \end{pmatrix} + \begin{pmatrix} 1-({A_+}^2+{A_-}^2) \\ 1-({A_+}^2+{A_-}^2) \end{pmatrix}$$

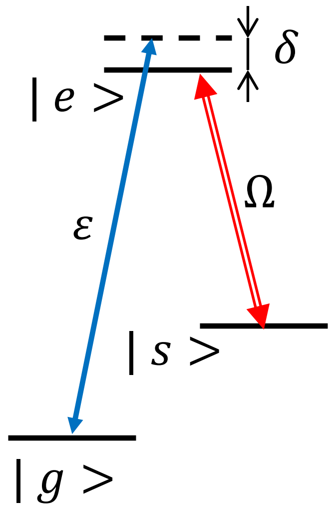
Where $A_\pm = \frac{1}{2}(T(\omega) \pm T(-\omega))$

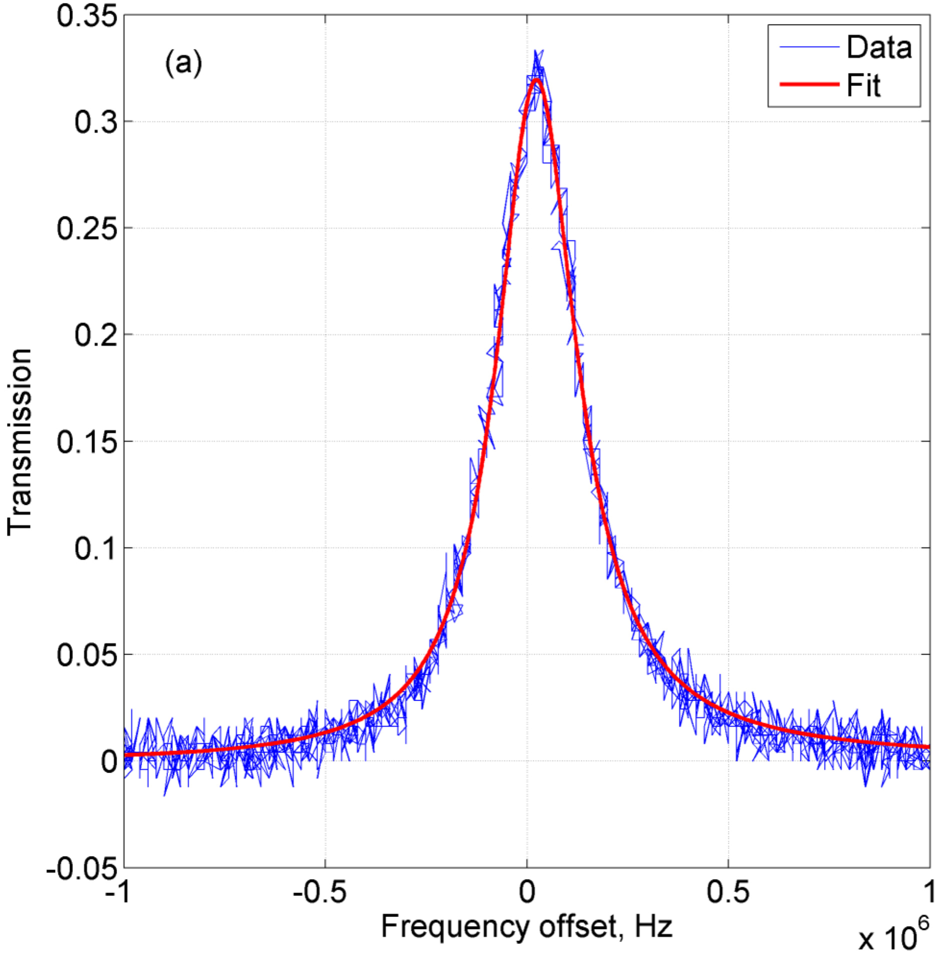
$T(\omega)$ – normalized transmission at the frequency ω

$V_{\pm,in}$ - input noise variance

$V_{\pm,out}$ - output noise variance




δ
$|e>$
Ω
ε
$|s>$
$|g>$


(a)
Data
Fit
Transmission
Frequency offset, Hz
x 10^6
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-1
-0.5
0
0.5
1

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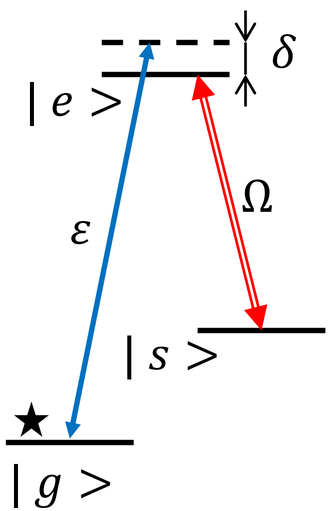
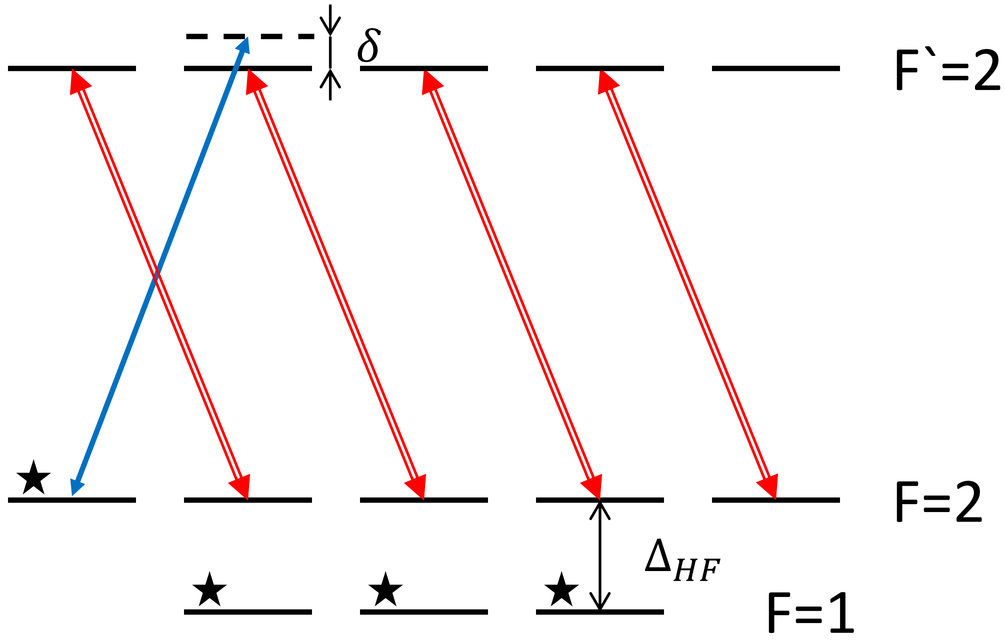
The atoms: ^{87}Rb

Simple model



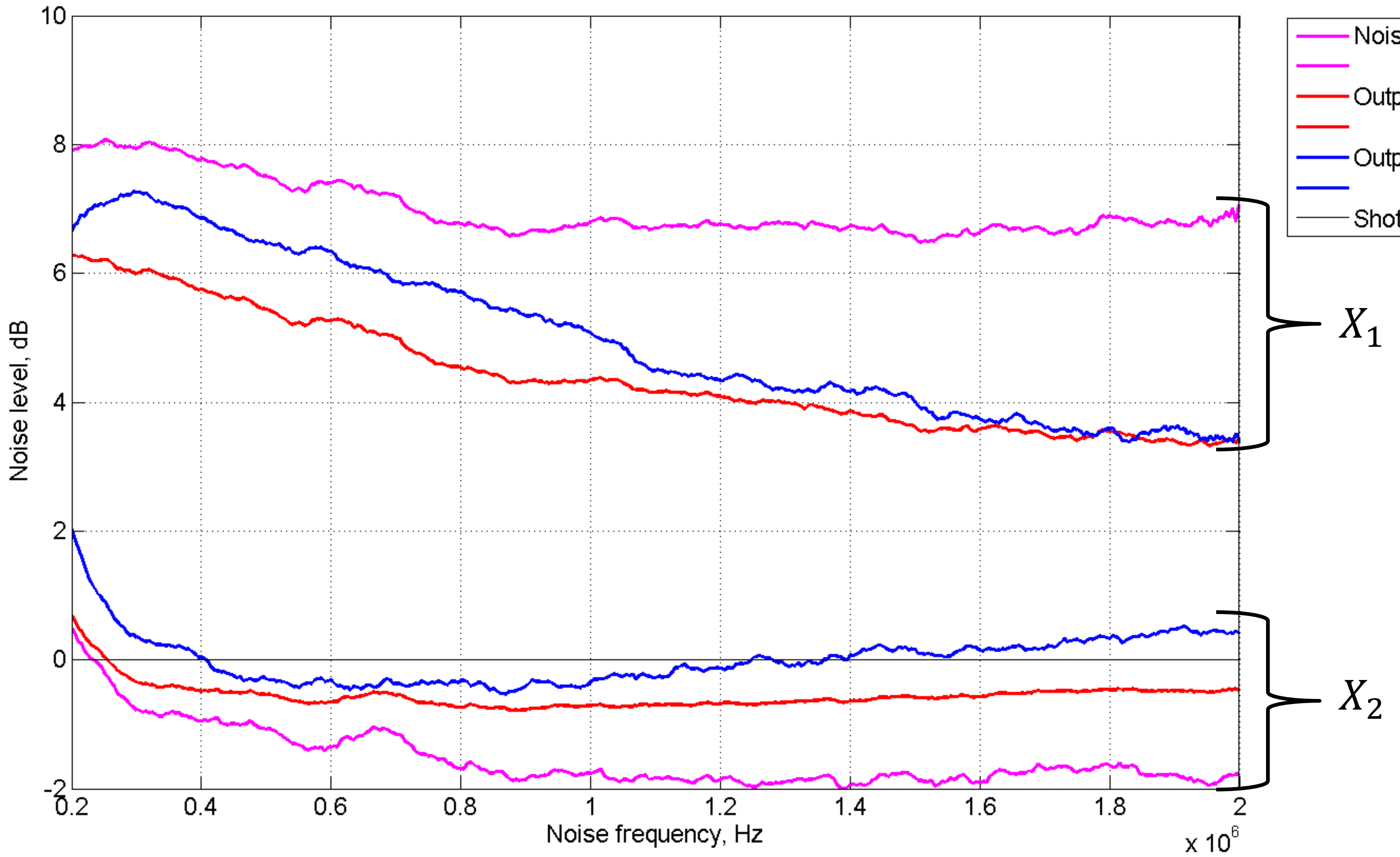
★ = populated

Real atoms



(Zeeman structure shown)

Sample data



10
8
6
4
2
0
-2
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Noise level, dB
Noise frequency, Hz
x 10^6
Noise input
Output expected
Output measured
Shot noise level
X_1
X_2

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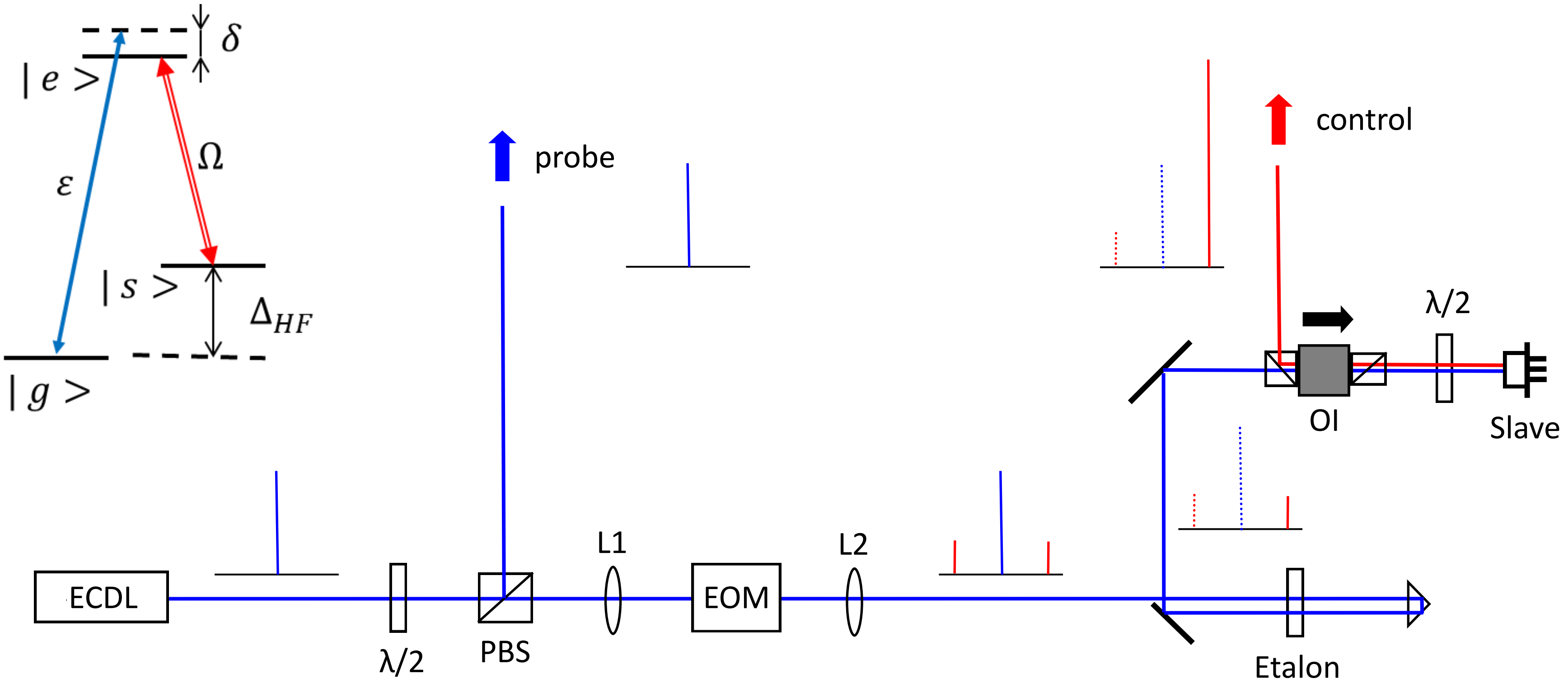
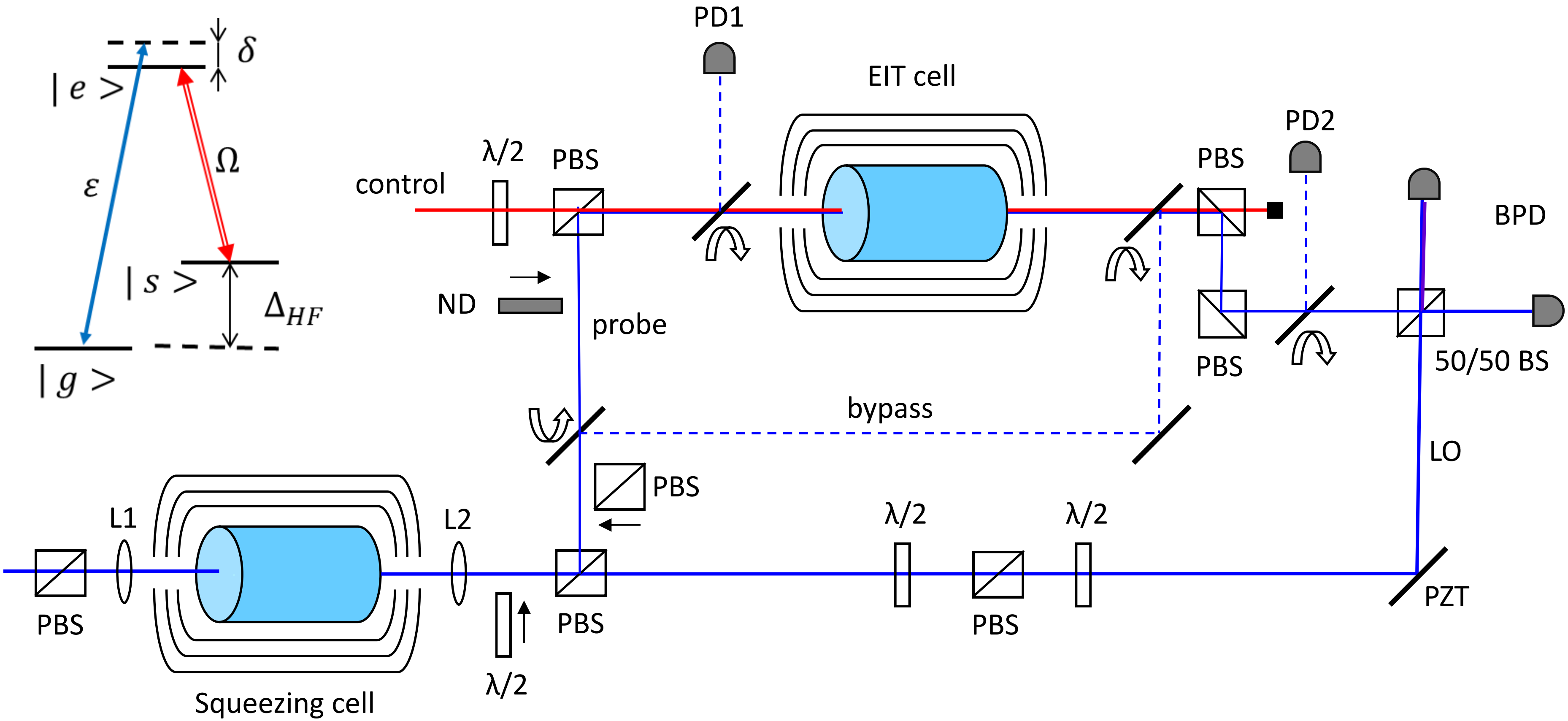
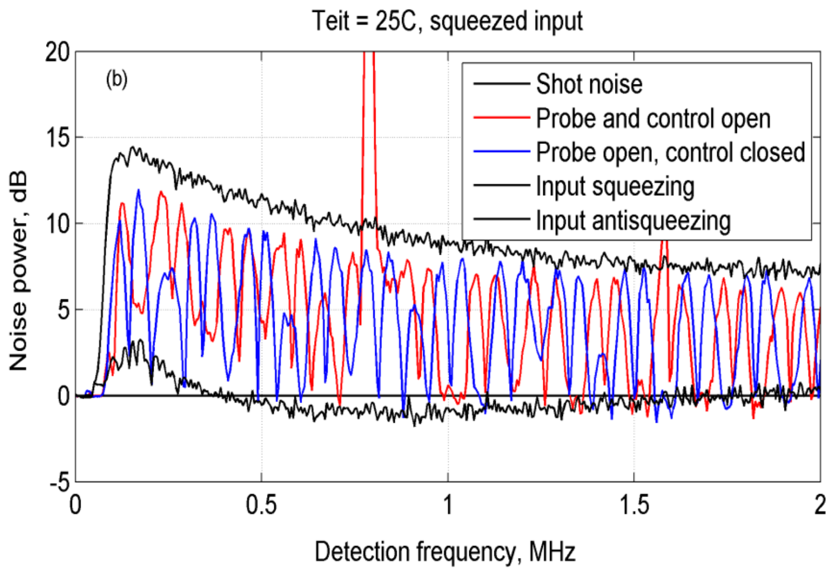


$\Delta_{HF} = 6.835\ GHz\ for\ ^{87}Rb$

Experimental setup

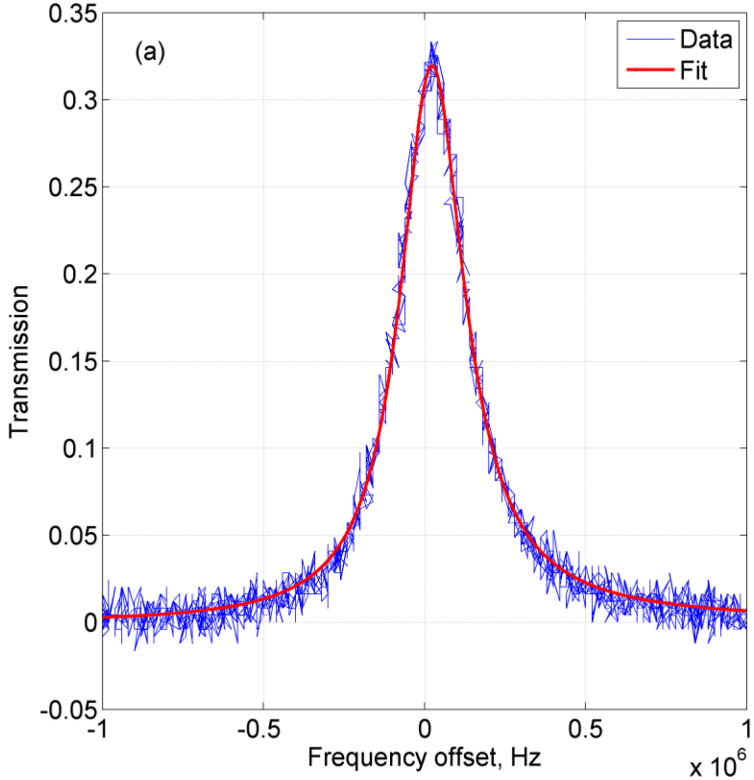


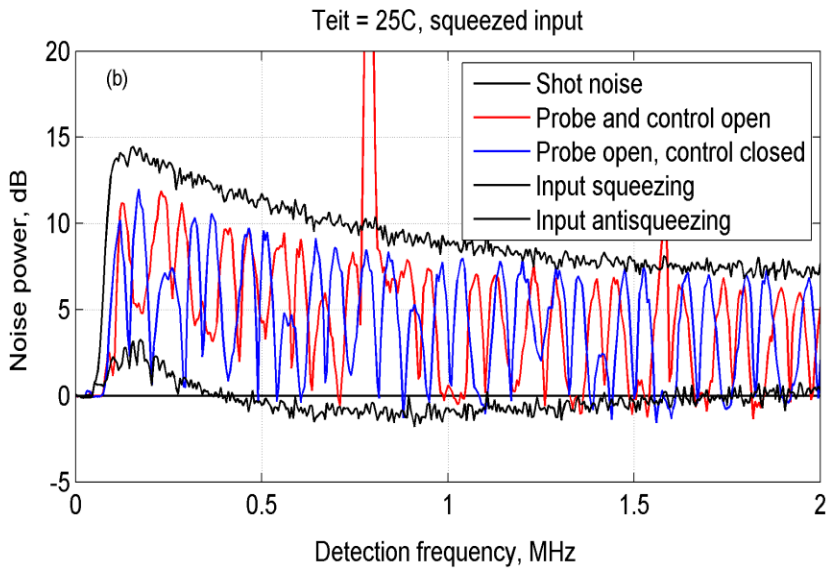
Experimental results

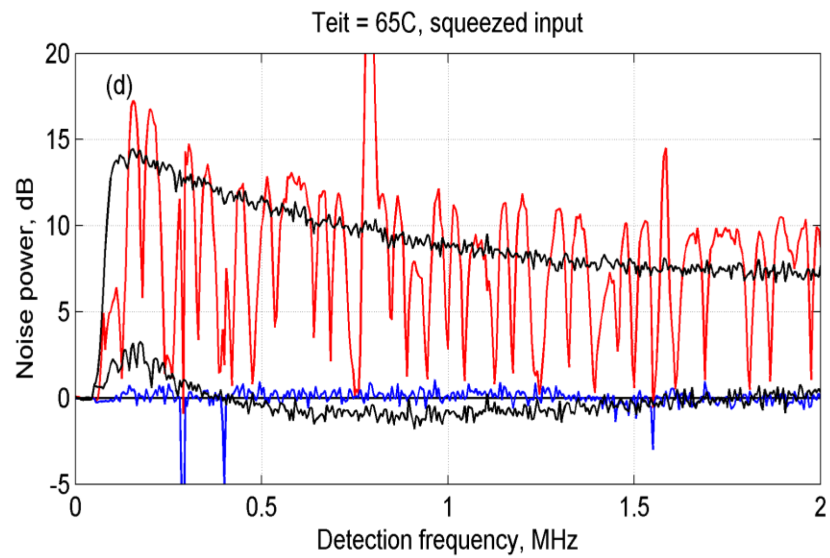


+ Squeeze angle scan

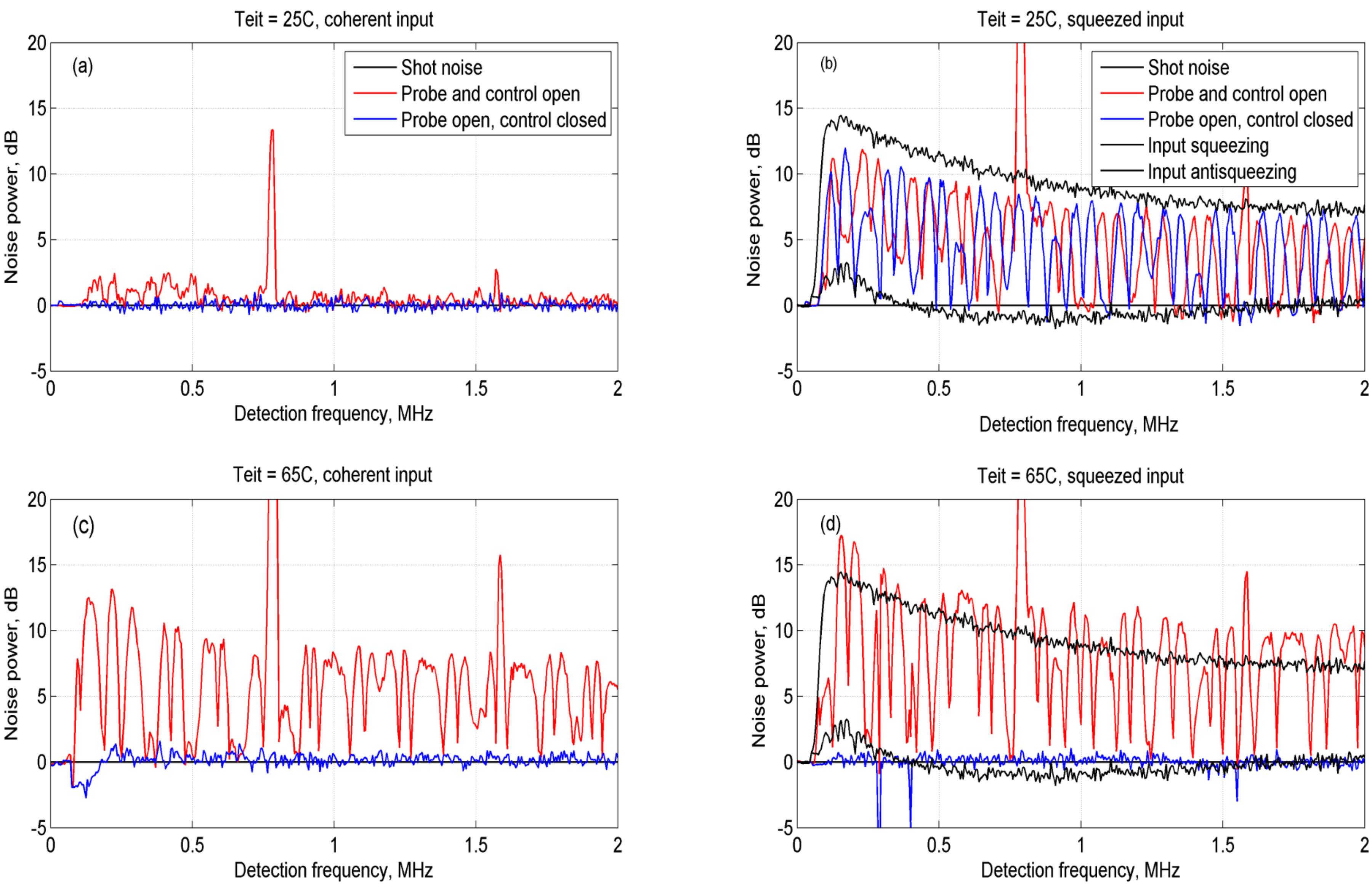
Experimental results

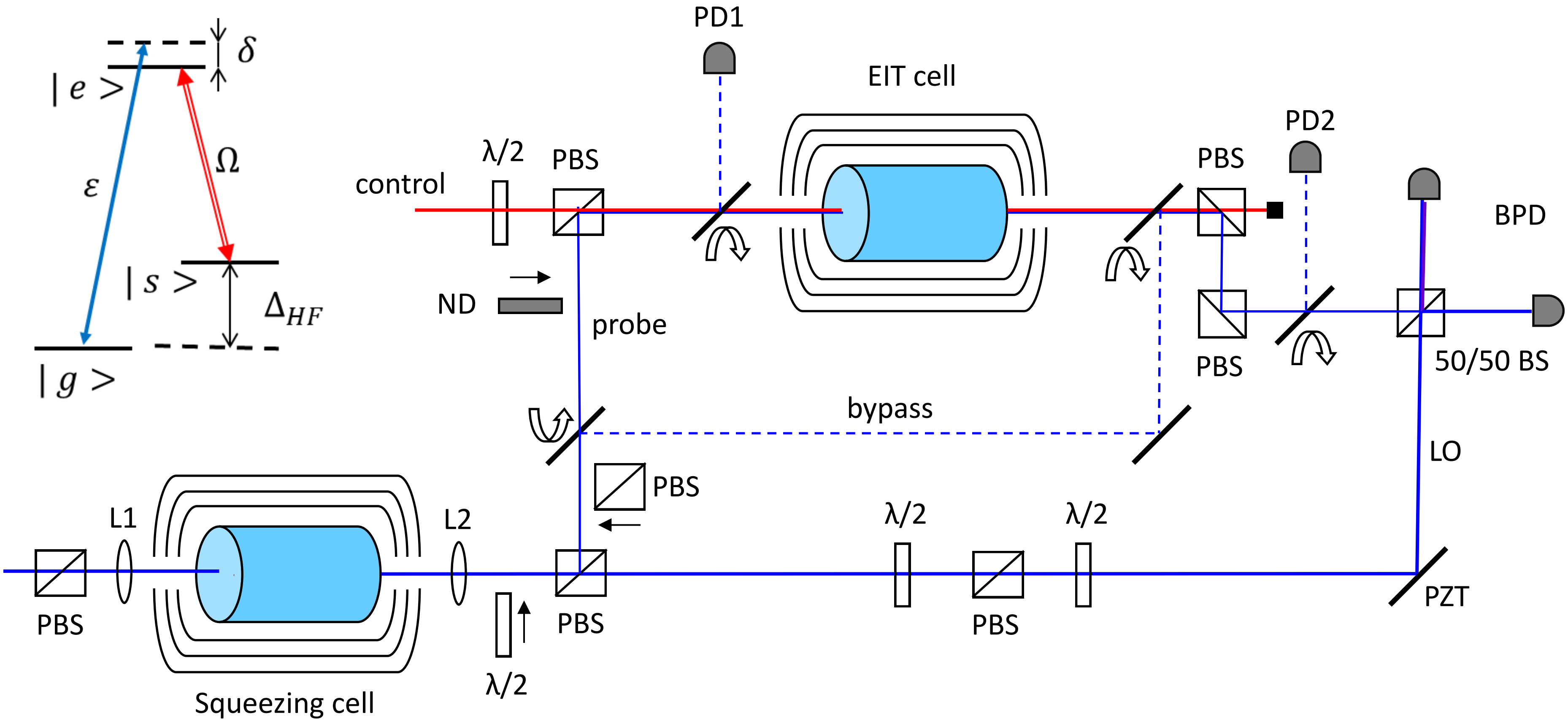






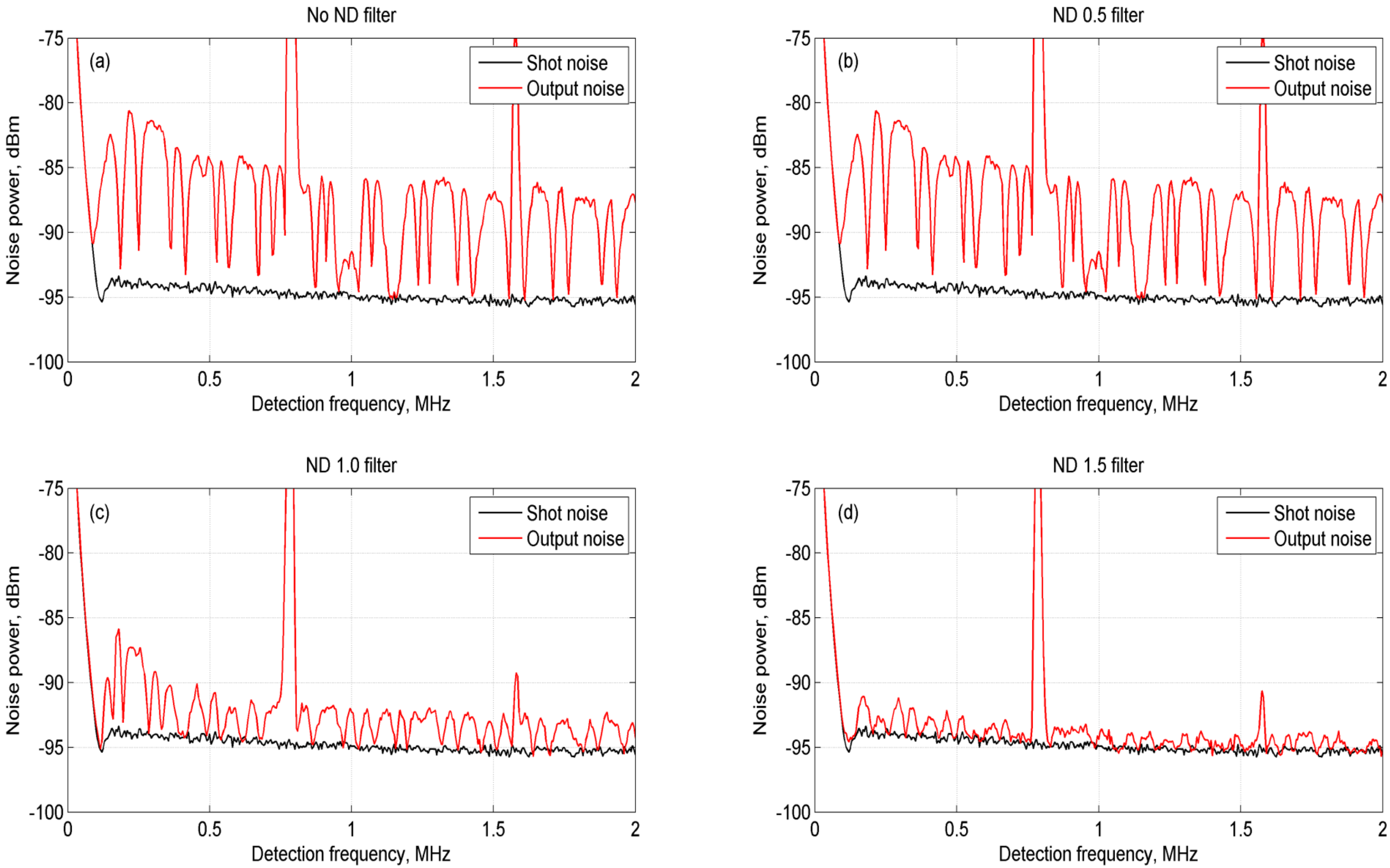
Experimental results



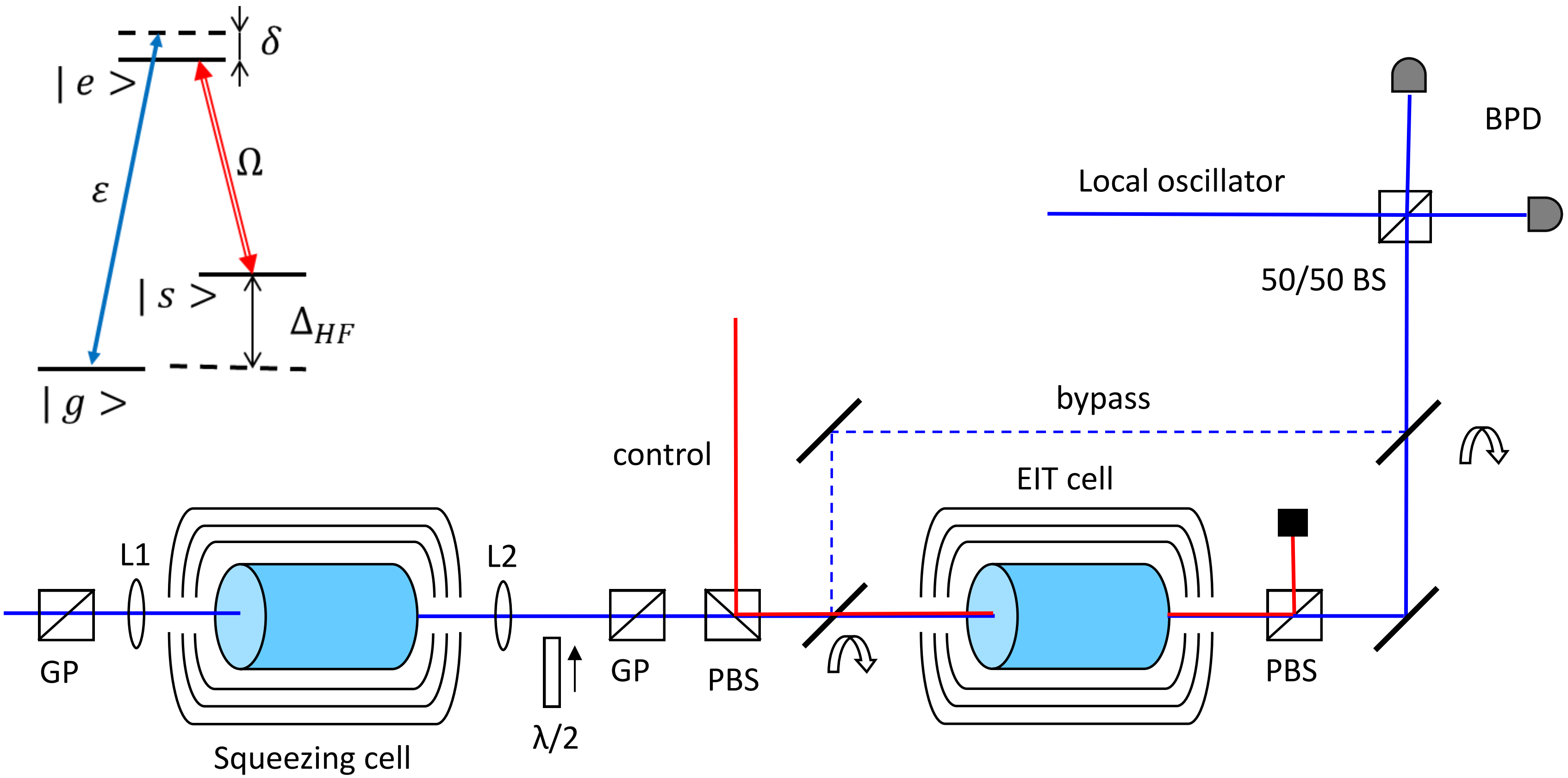


δ
| e >
ε
Ω
| s >
Δ_{HF}
| g >
PD1
EIT cell
PD2
control
λ/2
PBS
PBS
BPD
ND
probe
PBS
50/50 BS
bypass
LO
PBS
L1
L2
λ/2
λ/2
PBS
PBS
PBS
PZT
λ/2
Squeezing cell

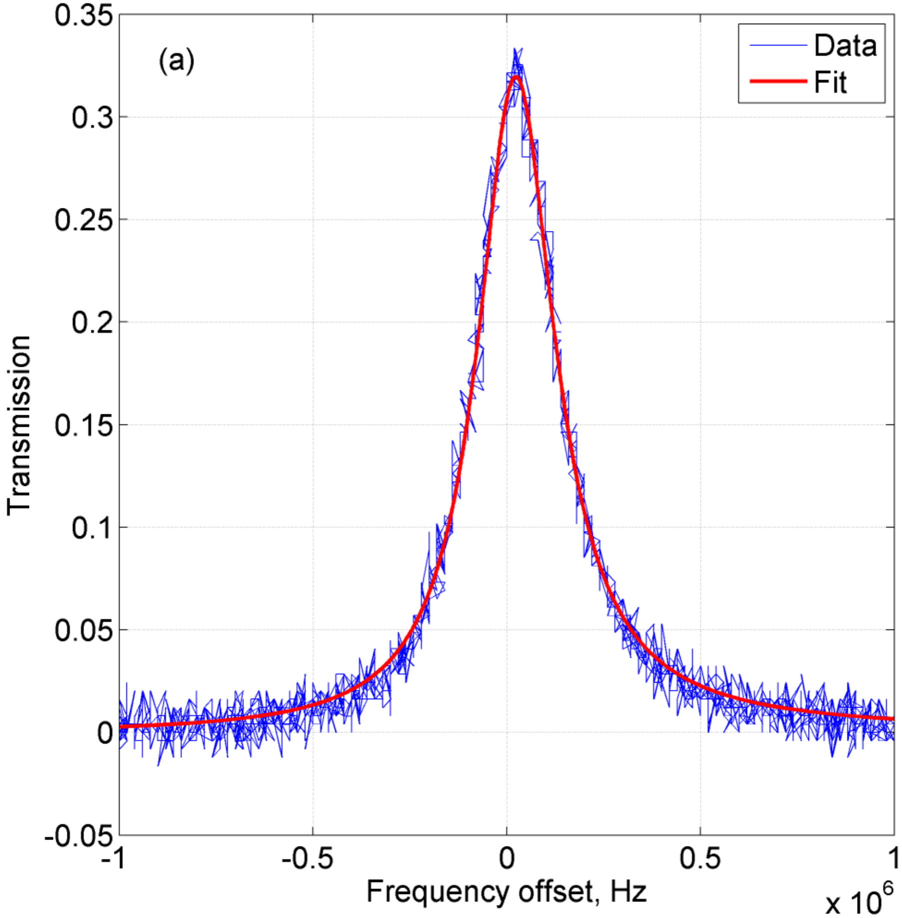
Excess noise power for different coherent probe input powers.

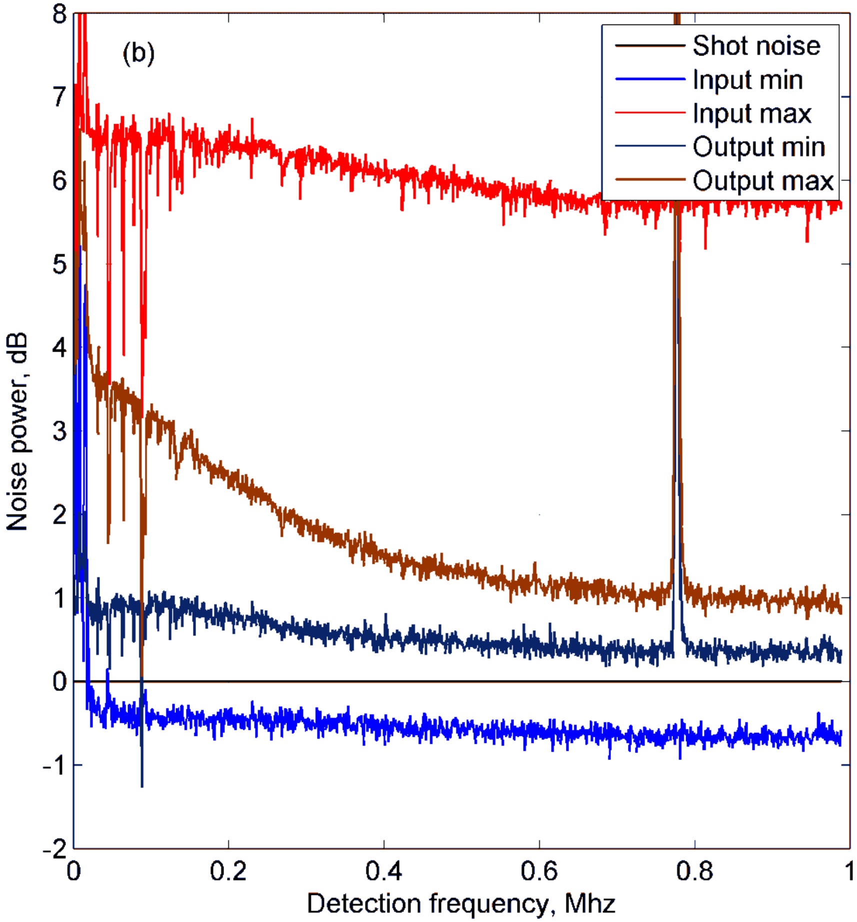


Improved setup

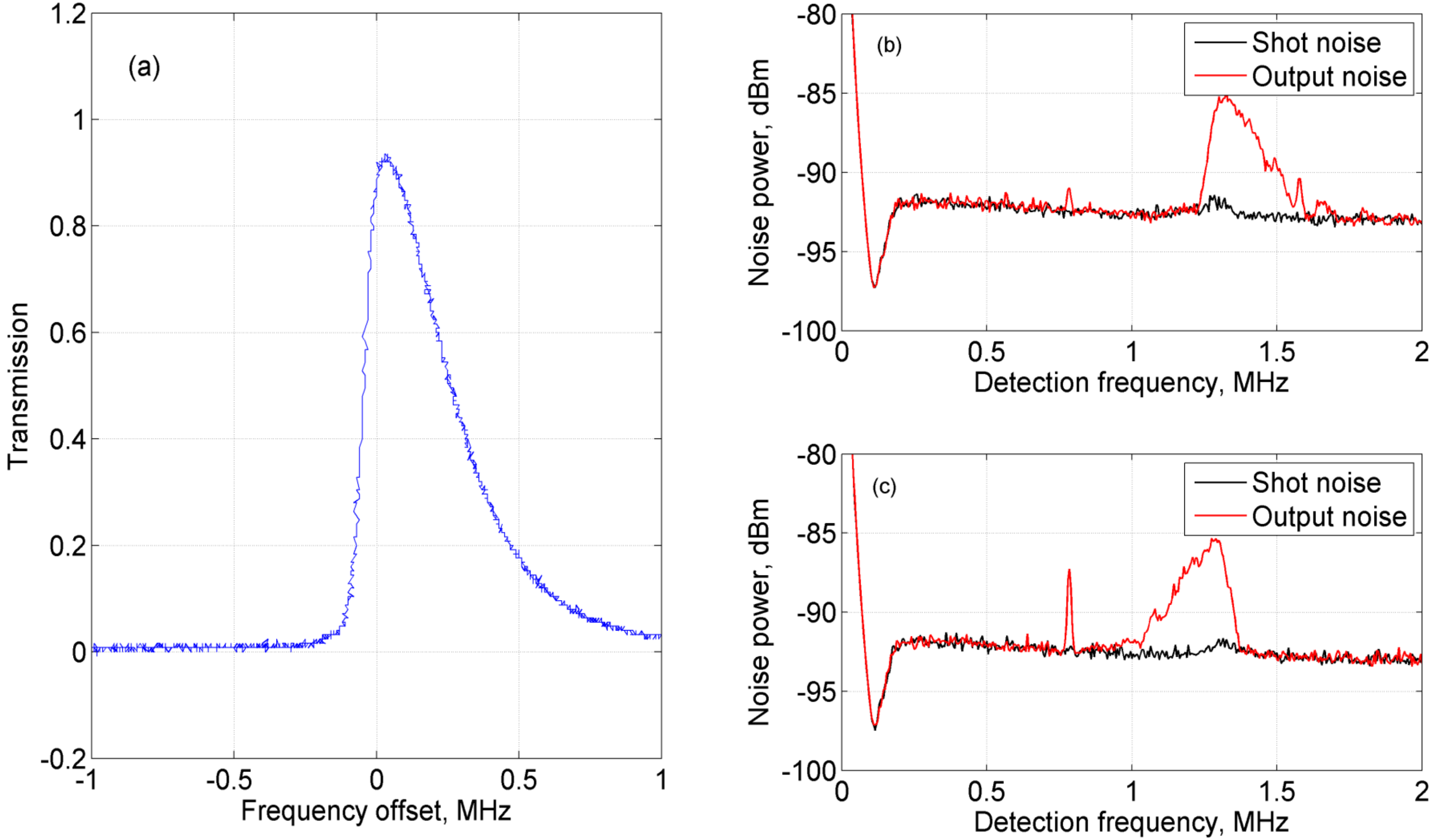


Pump leakage reduced from 0.5 uW to 20 nW


(a)
Data
Fit
Transmission
Frequency offset, Hz
x 10^6
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-1
-0.5
0
0.5
1


(b)
Shot noise
Input min
Input max
Output min
Output max
Noise power, dB
Detection frequency, Mhz
8
7
6
5
4
3
2
1
0
-1
-2
0
0.2
0.4
0.6
0.8
1

Probing dense atomic media with noise



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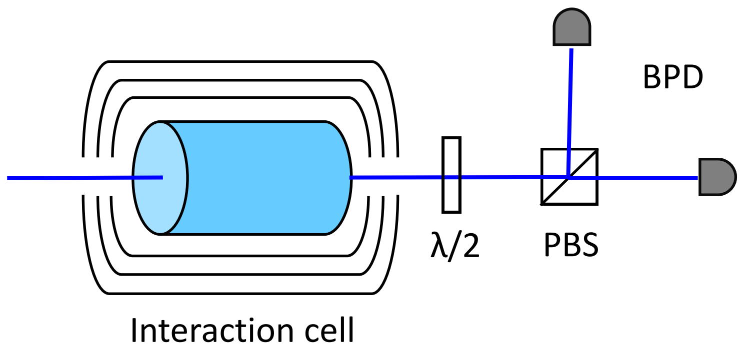
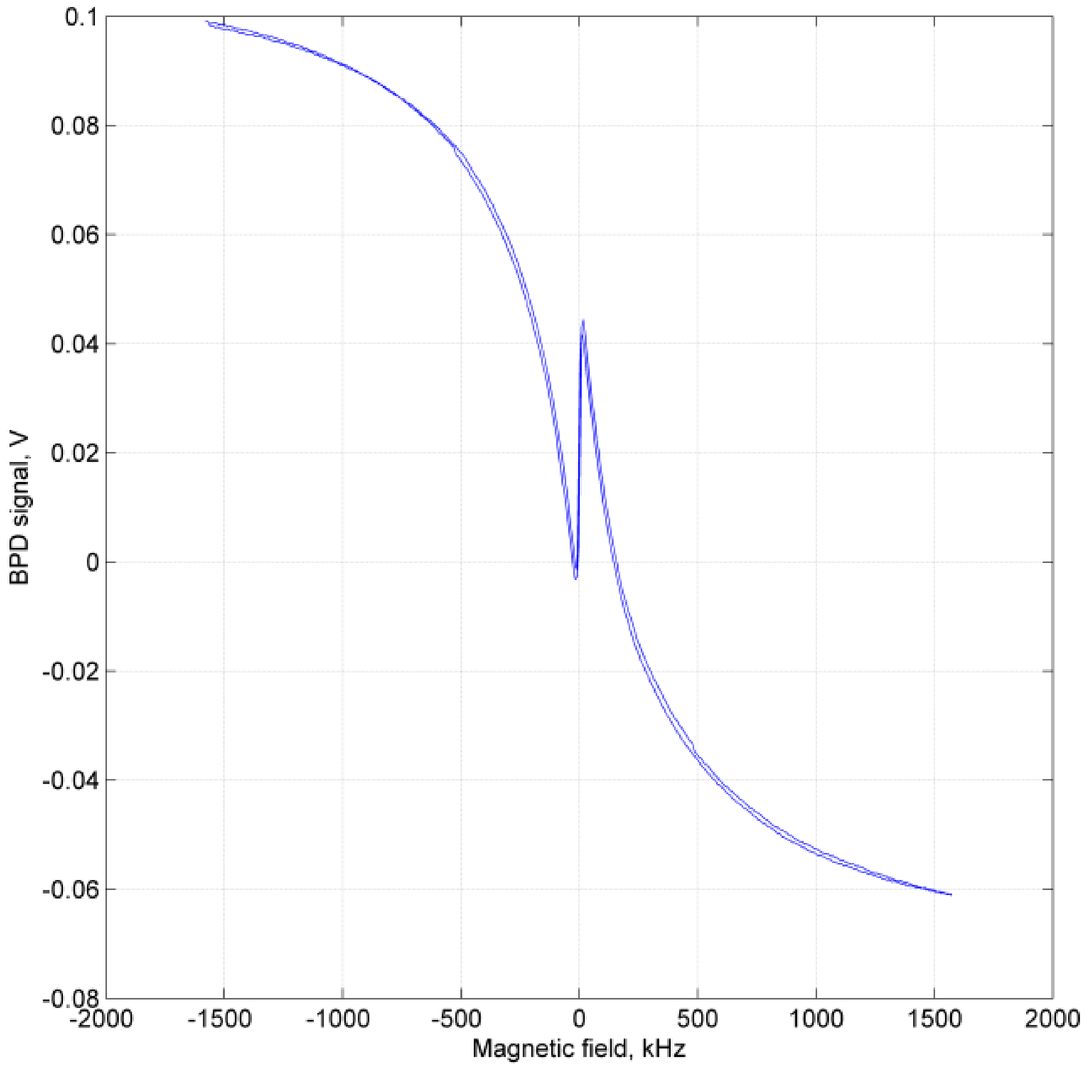
"Fast" squeezing experiment motivation

- Phys. Rev. Letters **86** (2001) 3925
  A. Kuzmich et al., "Signal Velocity, Causality, and Quantum Noise in Superluminal Light Pulse Propagation"

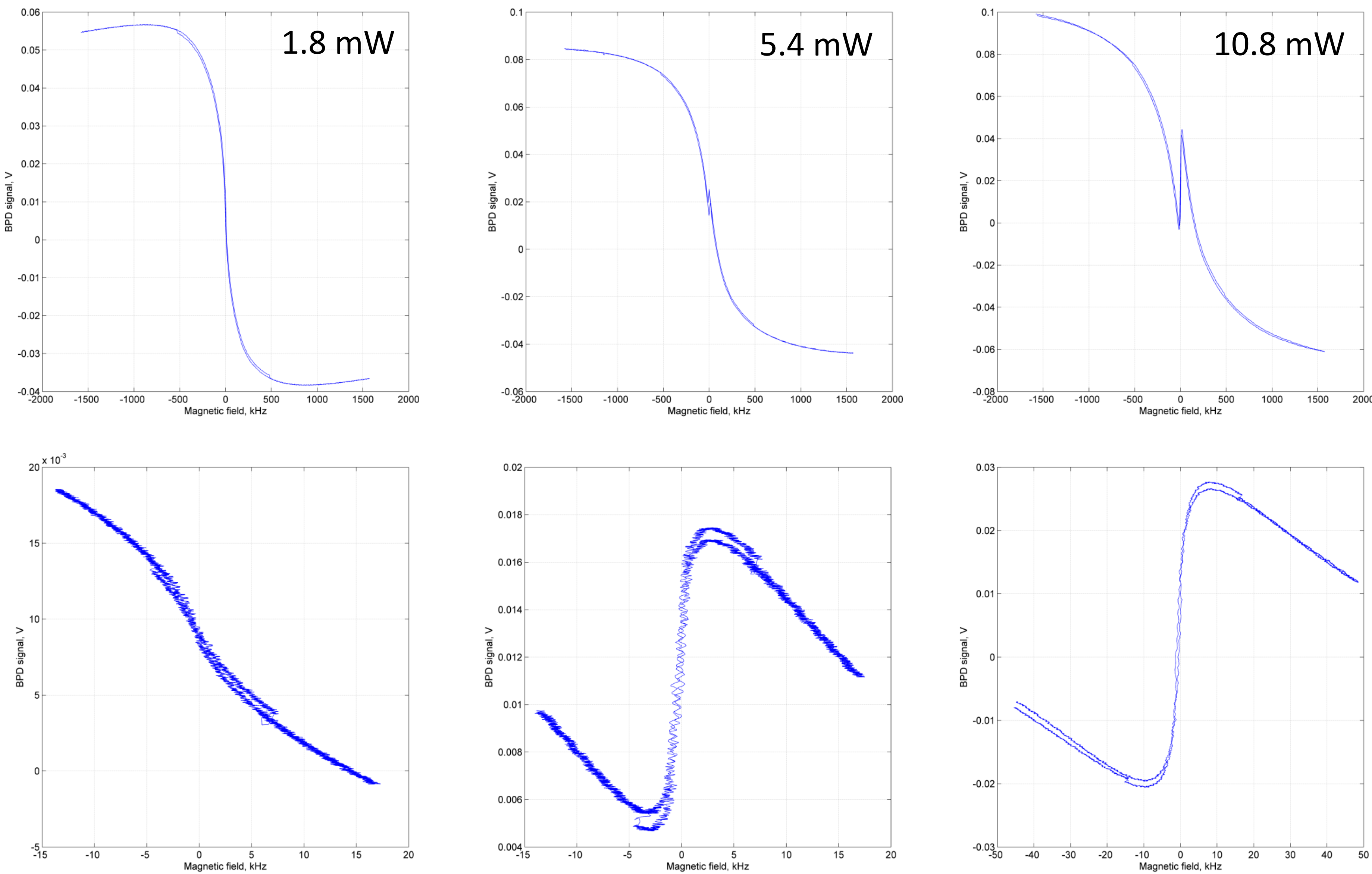
- Journal of Optics **12** (2010) 104007
  R. W. Boyd et al., "Noise properties of propagation through slow- and fast-light media"

Faraday rotation



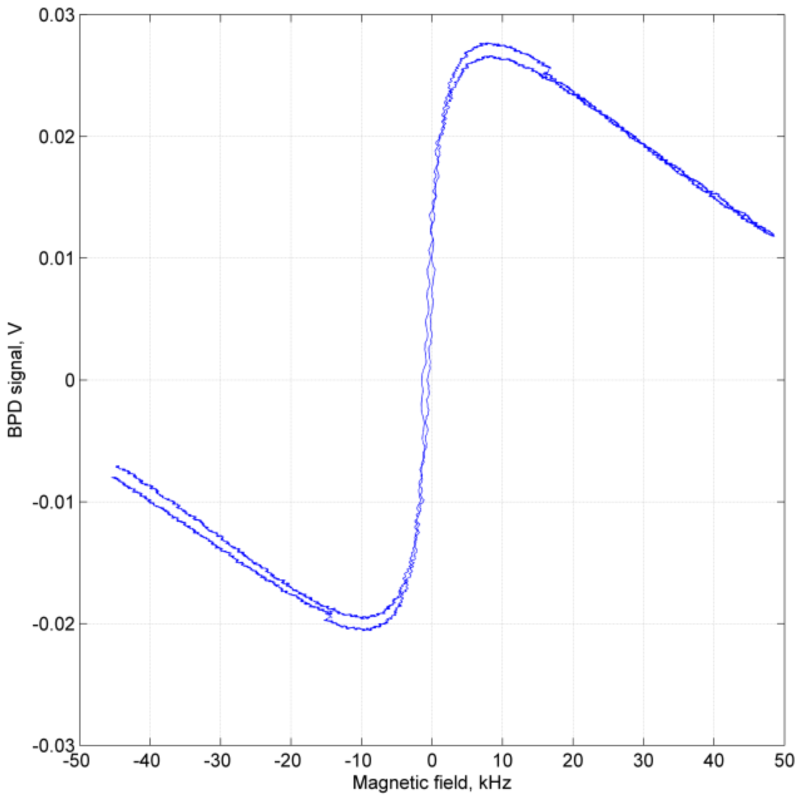


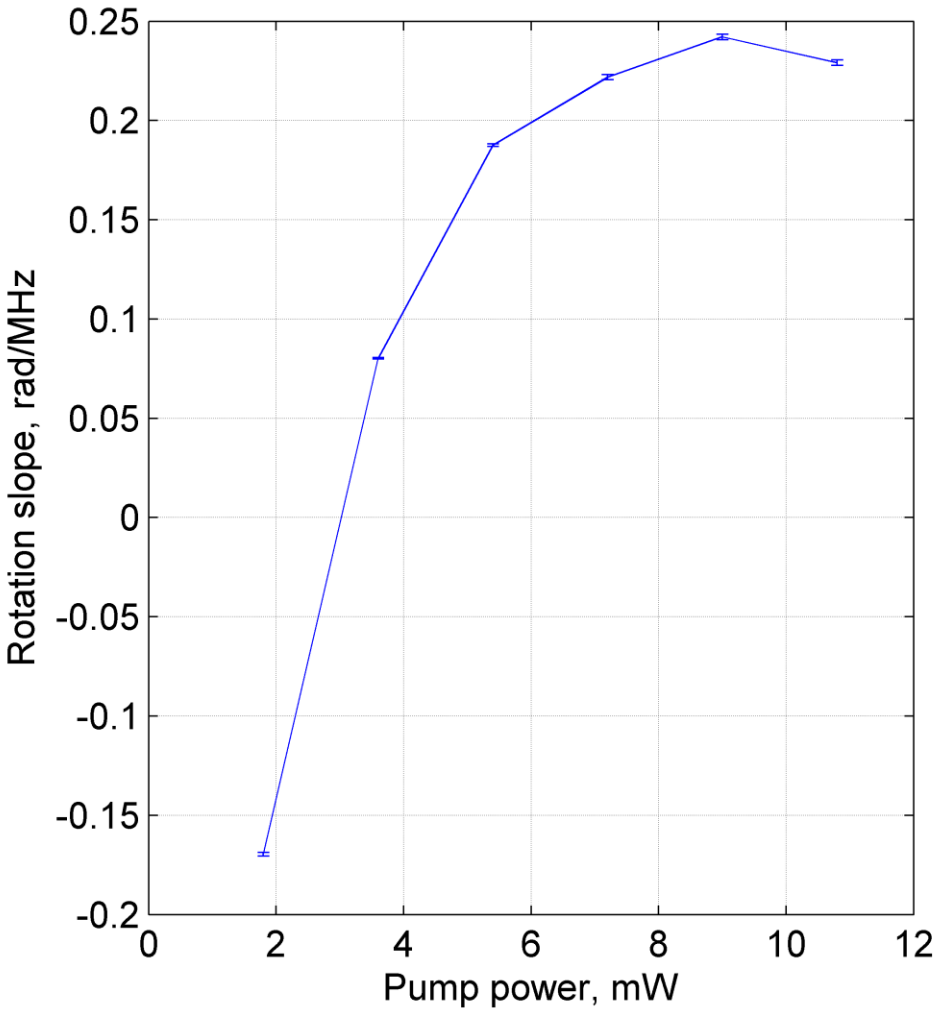
Faraday rotation



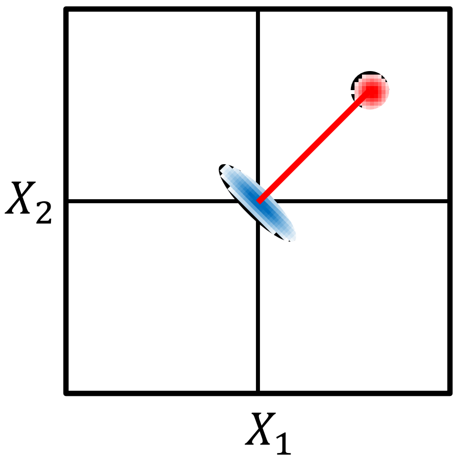
BPD signal vs magnetic field in the interaction cell $^{87}Rb, \mathrm{F} = 2 \rightarrow \mathrm{F}' = 1, T = 50\ ^{o}C$

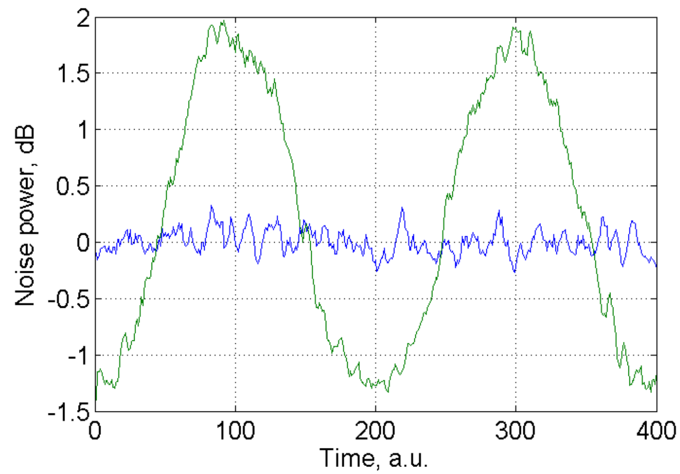
$$v_g = \frac{c}{n + \omega \frac{\partial n}{\partial \omega}}$$

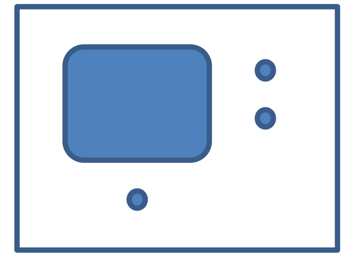




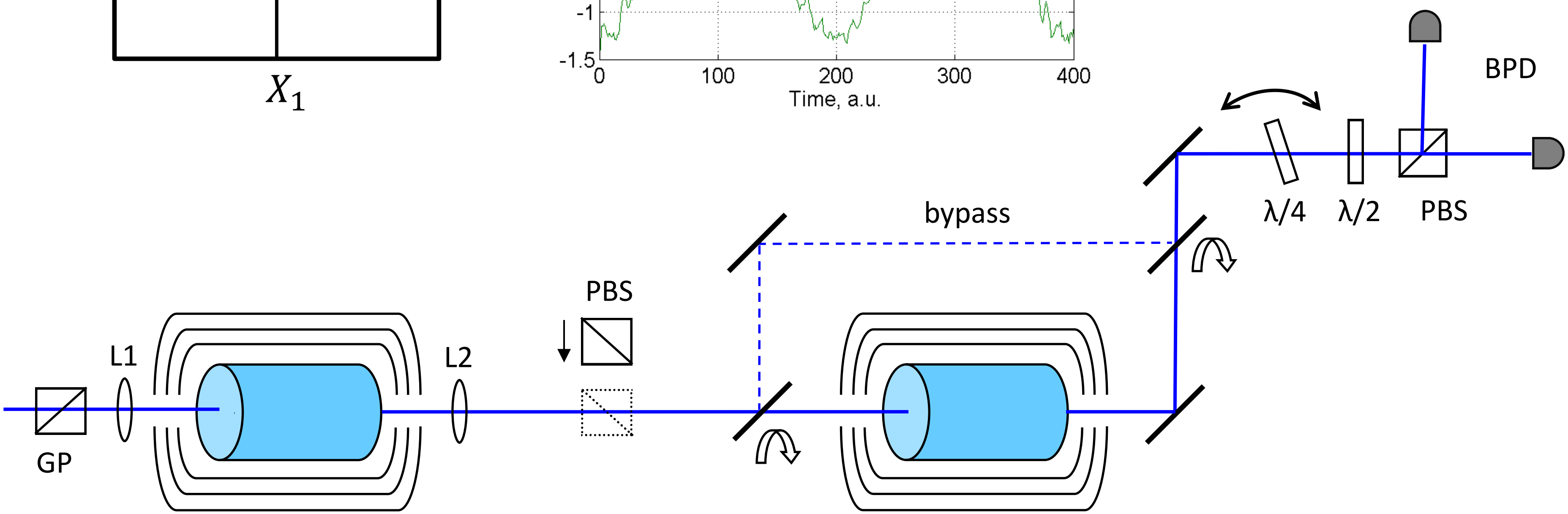
Squeezed vacuum state
+ Local oscillator







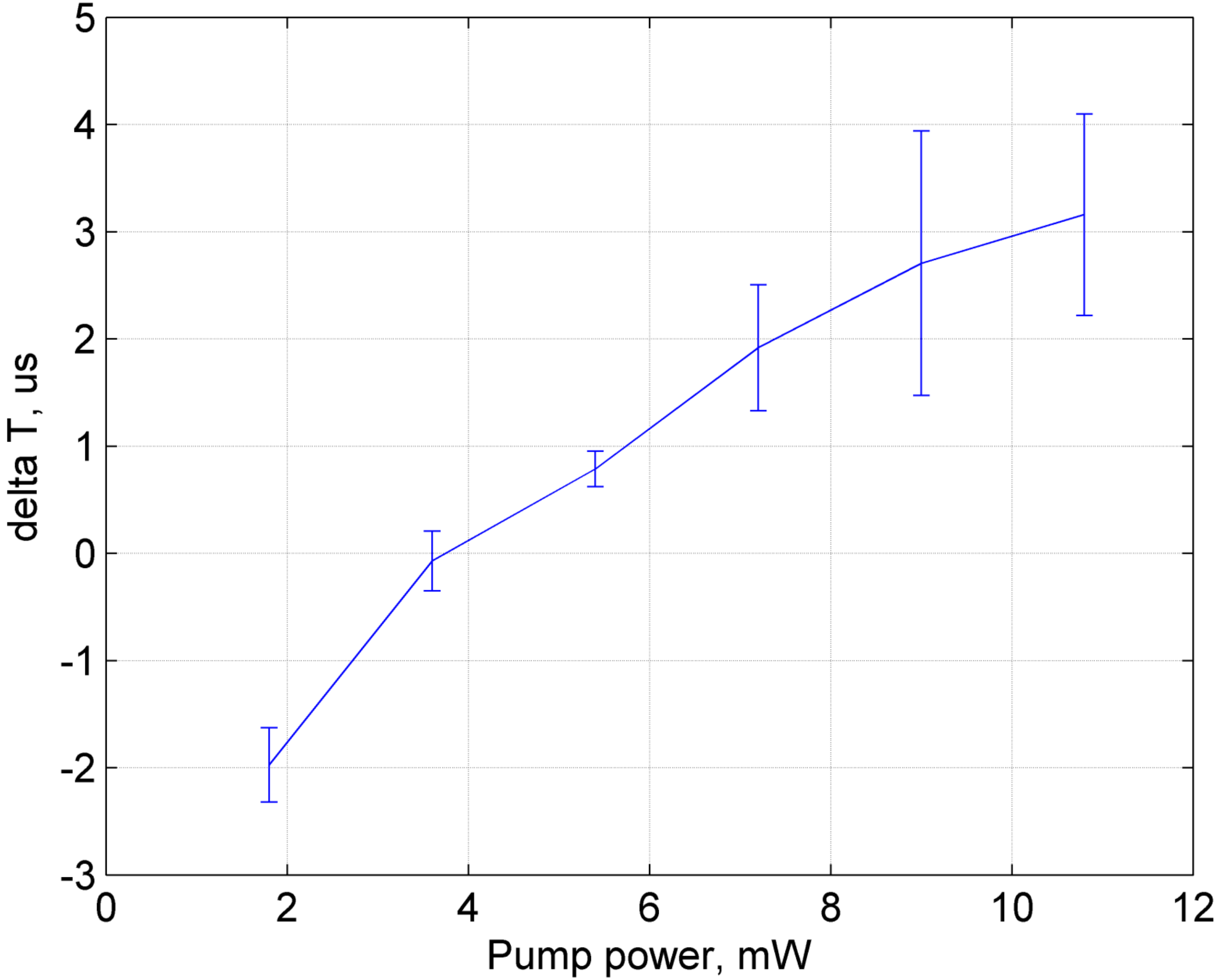
Spectrum analyzer



Squeezing cell

Interaction cell

Results



Error bars are $\pm 2\sigma$ *from statistics*

Future plans

- Finish “fast” squeezing experiment
- Optical gyroscopes based on slow/fast light

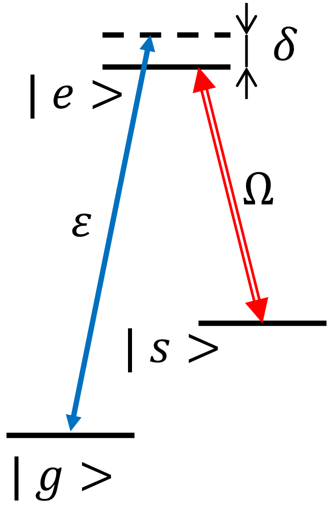
Summary

- Fully atomic generation and manipulation of squeezing
- $\sim$2 dB of noise suppression
- It is important to keep the pump leakage as small as possible
- Can probe dense atomic media with noise
- Demonstration of superluminal squeezing propagation

EIT effect

Consider a 3 level system with two optical fields:

- Weak probe field ε
- Strong control field with the Rabi frequency Ω



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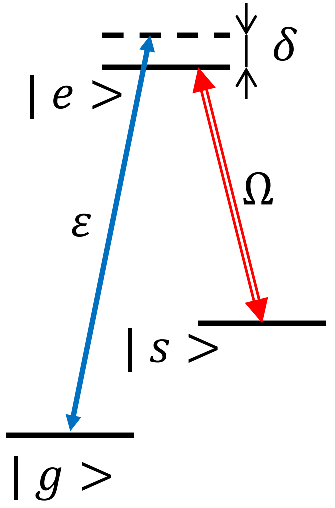


Electric susceptibility:

$$\chi(\delta) = \frac{N}{V}\frac{{D_{eg}}^2}{\epsilon_0 \hbar}\frac{\delta + i\gamma_0}{|\Omega|^2 + \Gamma_0 \Gamma}$$

Where D_{eg} - electric dipole moment

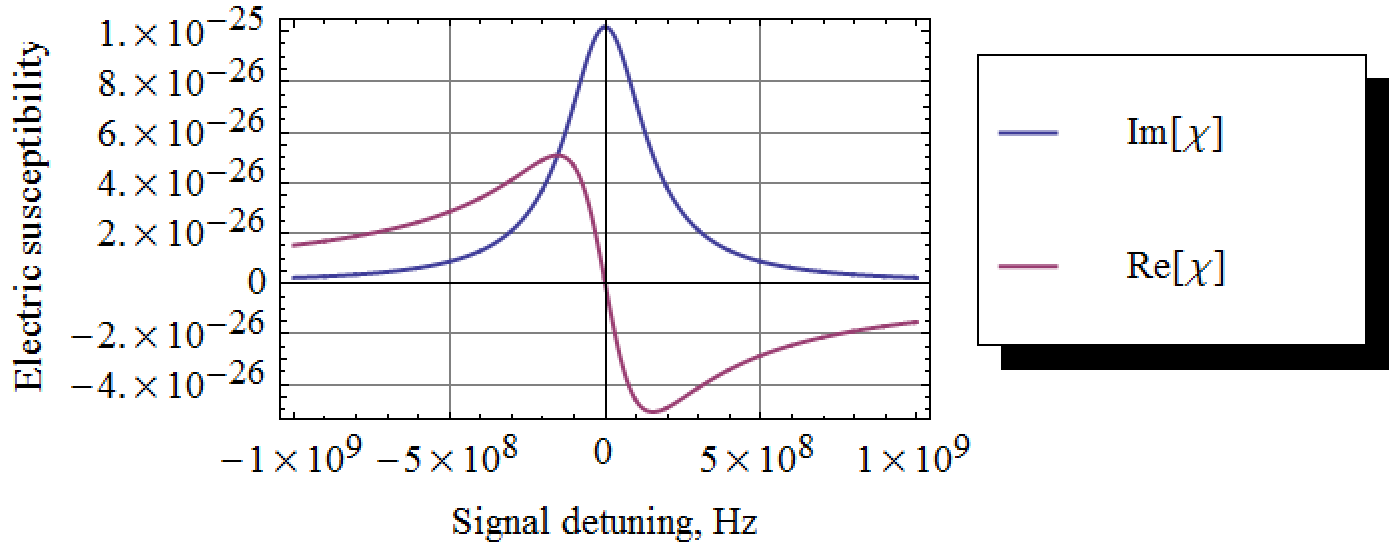
$$\Gamma_0 = \gamma_0 - i\delta$$

$$\Gamma = \gamma - i\delta$$

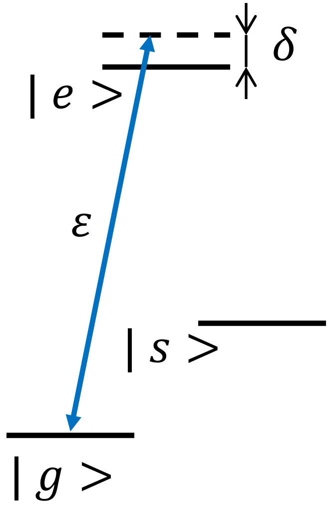
γ – atomic polarization decay rate

γ_0 - coherence decay rate

EIT effect

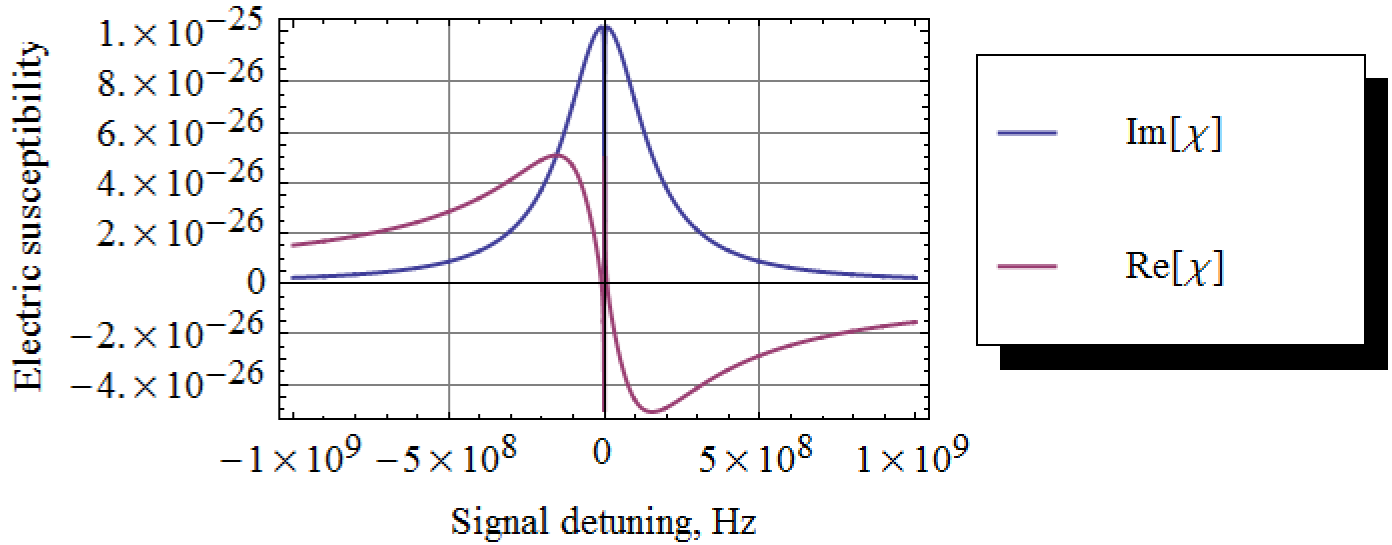


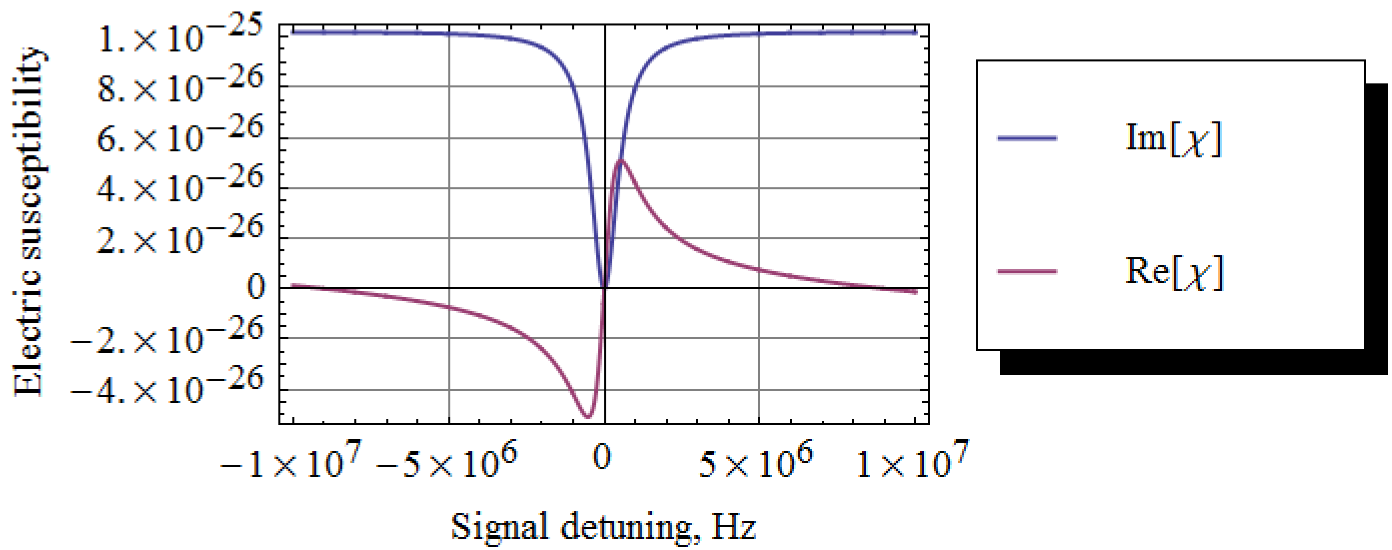
Electric susceptibility
1. × 10−25
8. × 10−26
6. × 10−26
4. × 10−26
2. × 10−26
0
−2. × 10−26
−4. × 10−26
−1 × 10^9
−5 × 10^8
0
5 × 10^8
1 × 10^9
Signal detuning, Hz
Im[χ]
Re[χ]

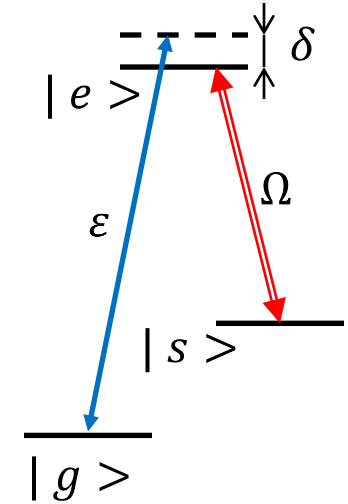


δ
| e >
ε
| s >
| g >

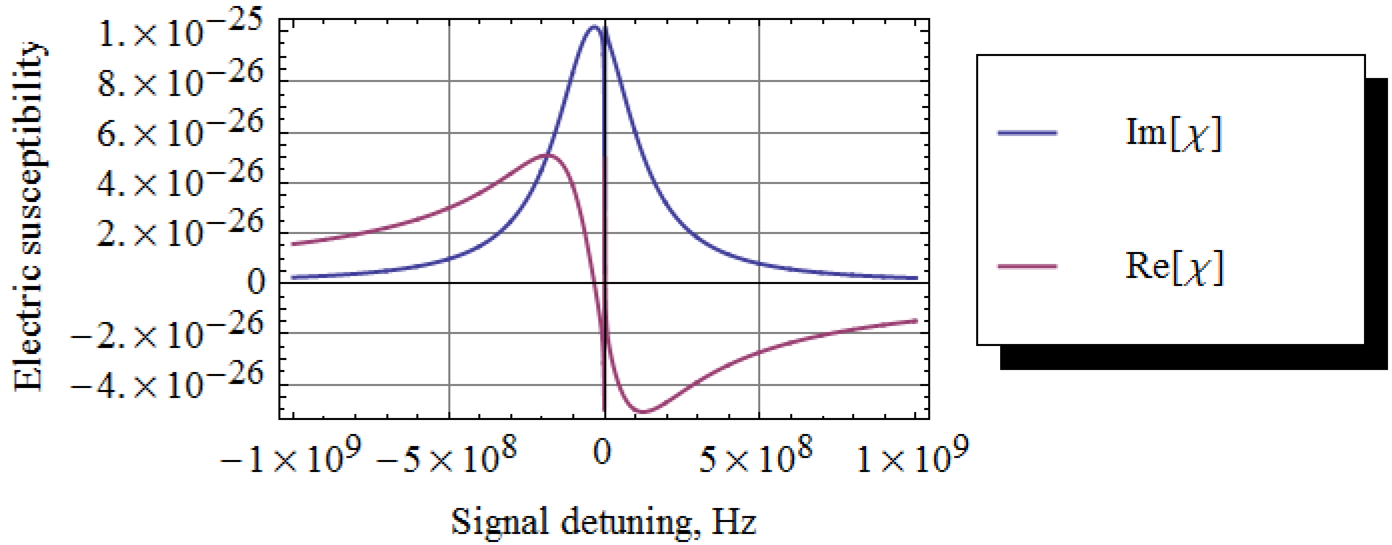
EIT effect

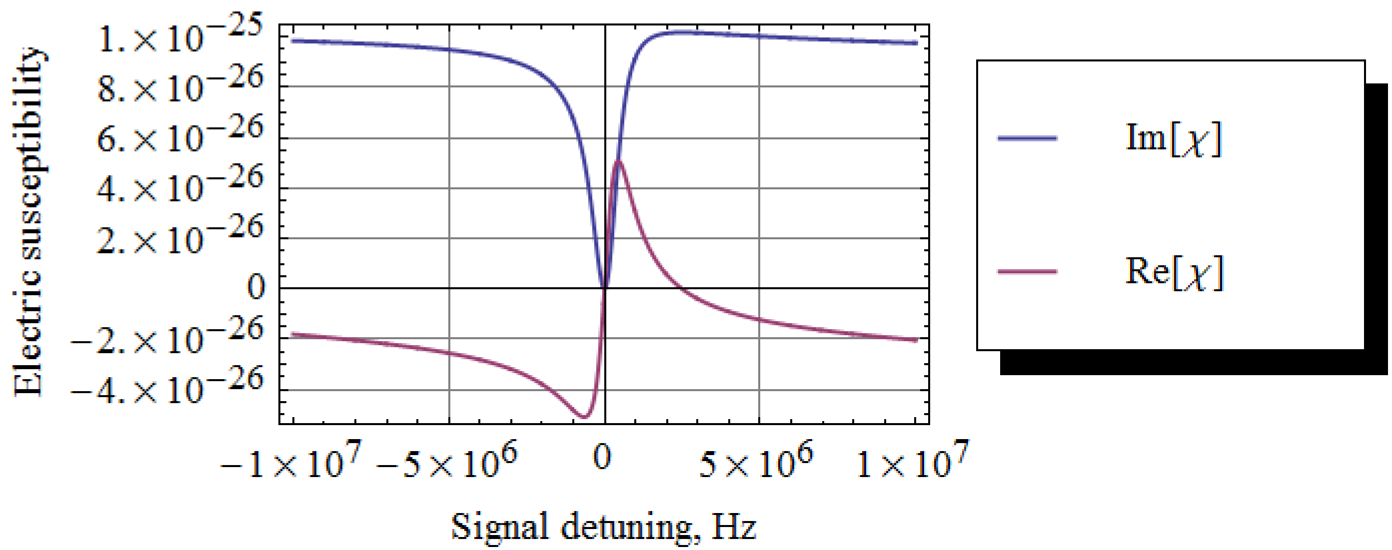

Electric susceptibility
1.×10^-25
8.×10^-26
6.×10^-26
4.×10^-26
2.×10^-26
0
-2.×10^-26
-4.×10^-26
-1×10^9
-5×10^8
0
5×10^8
1×10^9
Signal detuning, Hz
Im[χ]
Re[χ]

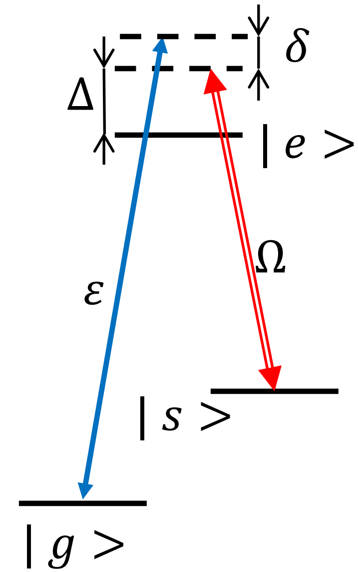

Electric susceptibility
1.×10^-25
8.×10^-26
6.×10^-26
4.×10^-26
2.×10^-26
0
-2.×10^-26
-4.×10^-26
-1×10^7
-5×10^6
0
5×10^6
1×10^7
Signal detuning, Hz
Im[χ]
Re[χ]


δ
| e >
Ω
ε
| s >
| g >

EIT effect







$\Delta = 30\ MHz$

$\gamma = 150$ MHz