Toward Quantum Enhanced Plasmonic Sensors

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1890

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Motivation

- Use reduced noise properties of quantum states of light to enhance sensitivity of sensors.

- Is possible to do so for a practical application?

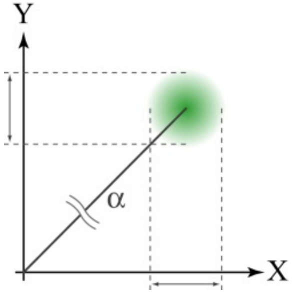
➡ Plasmonic sensors

- Plasmonic sensors have found applications in areas such as:
  - Biological marker detection
  - DNA molecule trapping and detection
  - Pathogen trapping and detection
  - Chemical sensing

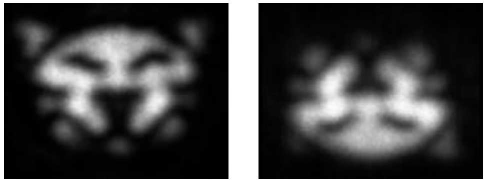
- Plasmonic sensors have reached their ultimate sensitivity given by the shot noise limit (fundamental limit).

Outline

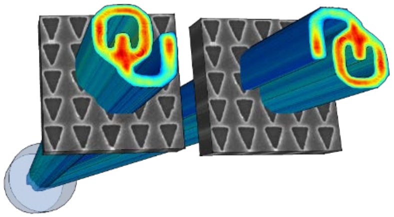
- Background
  - Continuous variable (CV)
  - Characterization of CV entanglement



- Generation of quantum states of light
  - Four-wave mixing
  - Squeezed states of light
  - Entangled twin beams and entangled images



- Interface with plasmonic structures
  - Transduction of entangled images
  - Quantum enhanced plasmonic sensors



- Conclusion

BACKGROUND

Characterization of Continuous Variables

- For the case of the electromagnetic field the continuous variables that are typically measured are the quadratures:

$$\hat{E}(t) = E_0(\hat{a}e^{-i\omega t} + \hat{a}^\dagger e^{i\omega t}) = E_0[\underset{\substack{\nearrow \\ \textit{Amplitude}}}{\hat{X}}\cos(\omega t) + \underset{\substack{\nwarrow \\ \textit{Phase}}}{\hat{Y}}\sin(\omega t)]$$

- Quantum properties directly related to their noise properties.

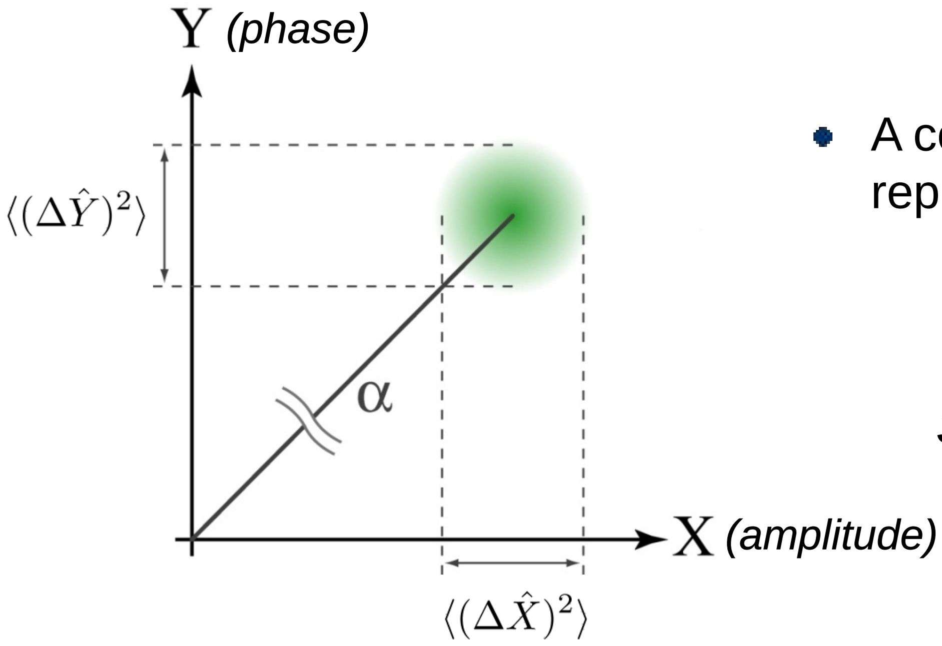
- Quantum mechanics imposes a minimum noise level on the field:

$$\langle(\Delta\hat{X})^2\rangle\langle(\Delta\hat{Y})^2\rangle \geq 1 \;\longleftarrow\; \textit{Heisenberg Uncertainty Principle}$$

- Experimental characterization of quantum properties through noise measurements.

Phase Space Diagram

- A useful way of visualizing the noise is in terms of its distribution along the quadratures (phase space).



- A coherent state is the quantum representation of a classical state.

$$\langle(\Delta\hat{X})^2\rangle = \langle(\Delta\hat{Y})^2\rangle = 1$$

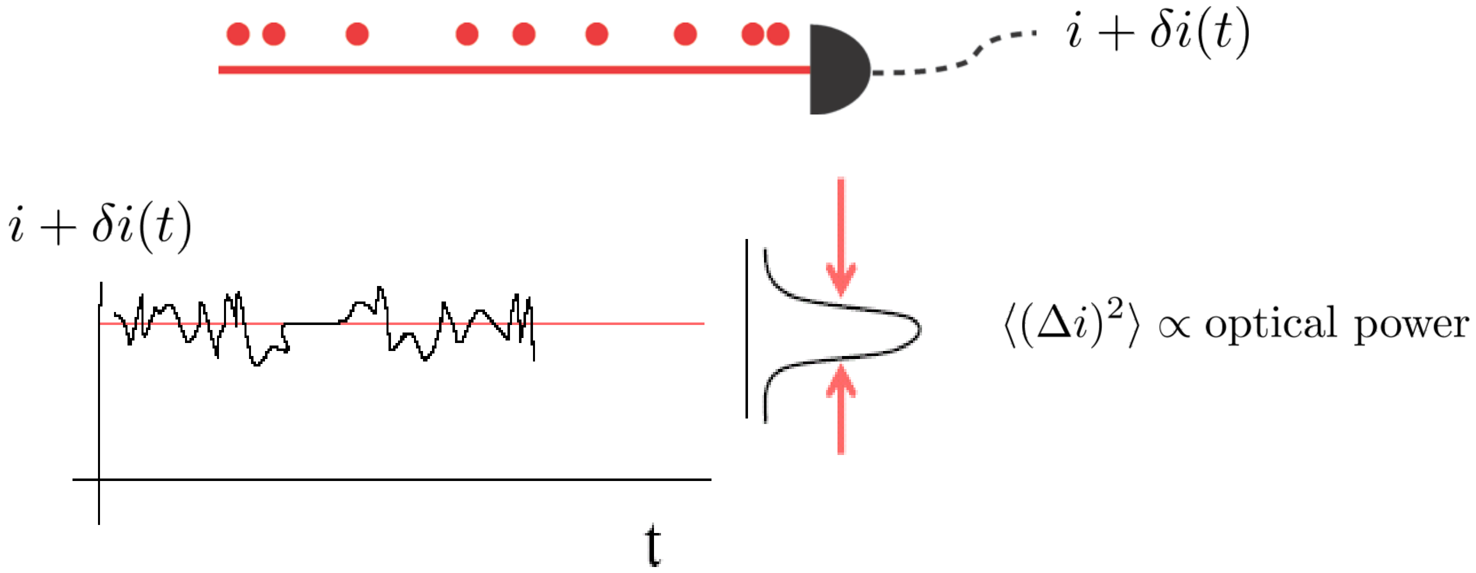
↑

Standard Quantum Limit (SQL)

- Fundamental limit in sensitivity of sensor using classical states of light.

Origin of Quantum Noise

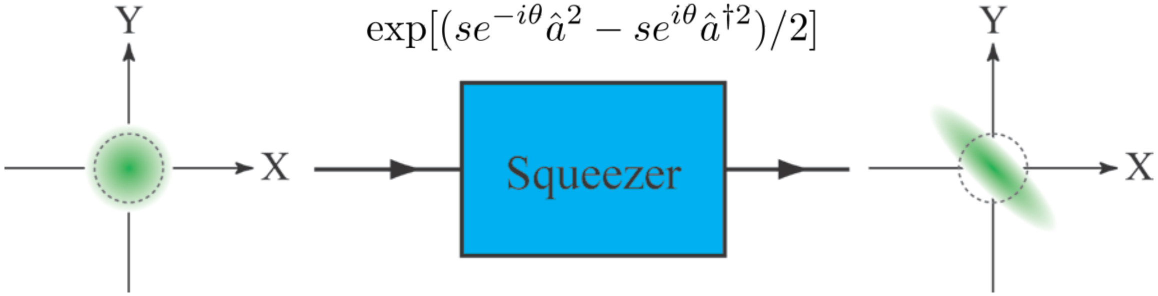
- Quantum noise can be viewed as a result of the quantization of the field (photons) and the random distribution of the photons.



- This noise represents the SQL, or shot noise.
- Quantum mechanics allows to redistribute the noise: $\langle (\Delta \hat{X})^2 \rangle \langle (\Delta \hat{Y})^2 \rangle \geq 1$
- Possible to have $\langle (\Delta \hat{X})^2 \rangle < 1$ or $\langle (\Delta \hat{Y})^2 \rangle < 1$ (squeezed state).

Squeezed States

- Generation of squeezed states requires a nonlinear process that can emit pairs of photons into the field.



$$\exp[(se^{-i\theta}\hat{a}^2 - se^{i\theta}\hat{a}^{\dagger 2})/2]$$

$$\langle(\Delta\hat{X}')^2\rangle = e^{-2s}$$

$$\langle(\Delta\hat{Y}')^2\rangle = e^{2s}$$

Coherent state

Squeezed state

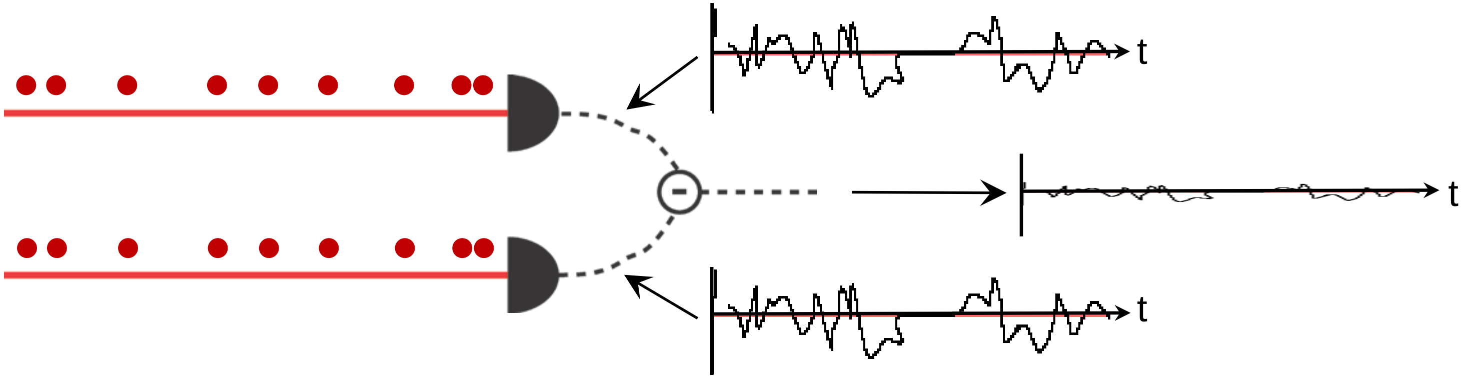
- Amount of squeezing grows with the strength of the nonlinearity.
- An amplitude squeezed states implies ordering in the temporal distribution of photons.

Coherent state

Amplitude squeezed state

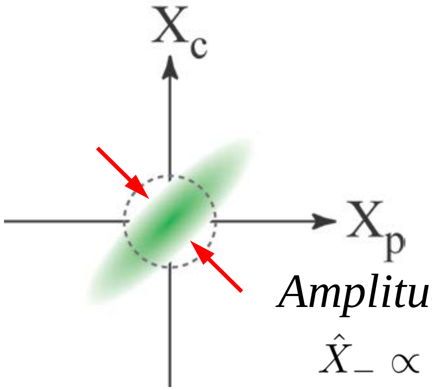
Twin Beams (two-mode squeezed states)

- Pair of photons can also be emitted into separate beams of light.



- Twin beams have a relative ordering of the temporal distribution of photons between the two beams.

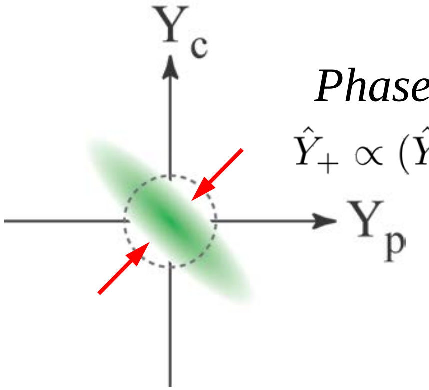
Emission of photons in pairs:



Amplitude difference

$\hat{X}_- \propto (\hat{X}_p - \hat{X}_c)$

Conservation of energy:

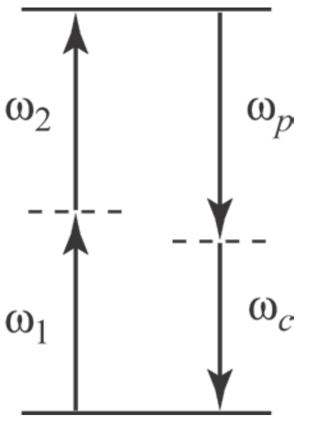


Phase sum

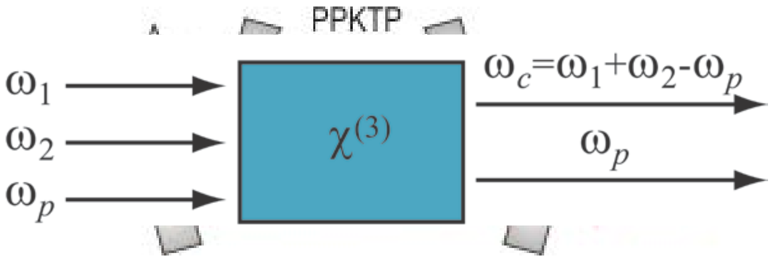
$\hat{Y}_+ \propto (\hat{Y}_p + \hat{Y}_c)$

Generation of Twin Beams

- Nonlinear process that can emit pair of photons needed to generate two-mode squeezed states or twin beams.
  - Four-wave mixing (FWM)
  - Optical parametric oscillator (OPO)



Parametric down conversion

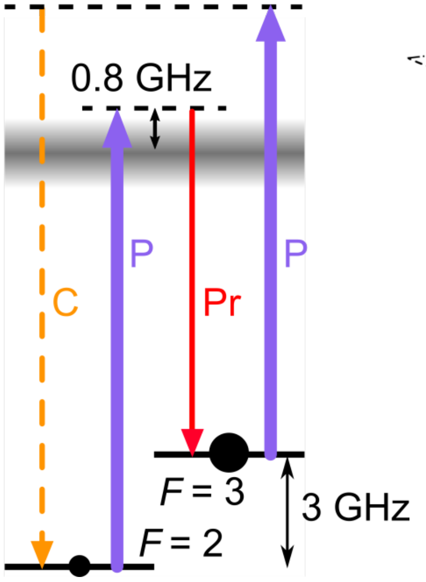


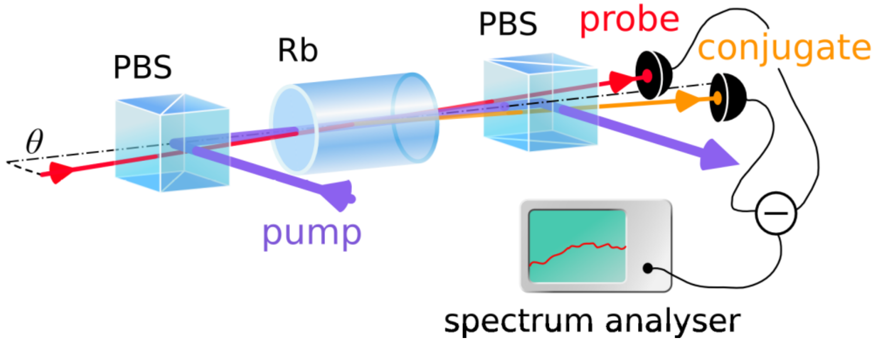
- Probe and conjugate photons are always generated in pairs. ➡ Quantum correlations

GENERATION OF QUANTUM STATES

Four-Wave Mixing

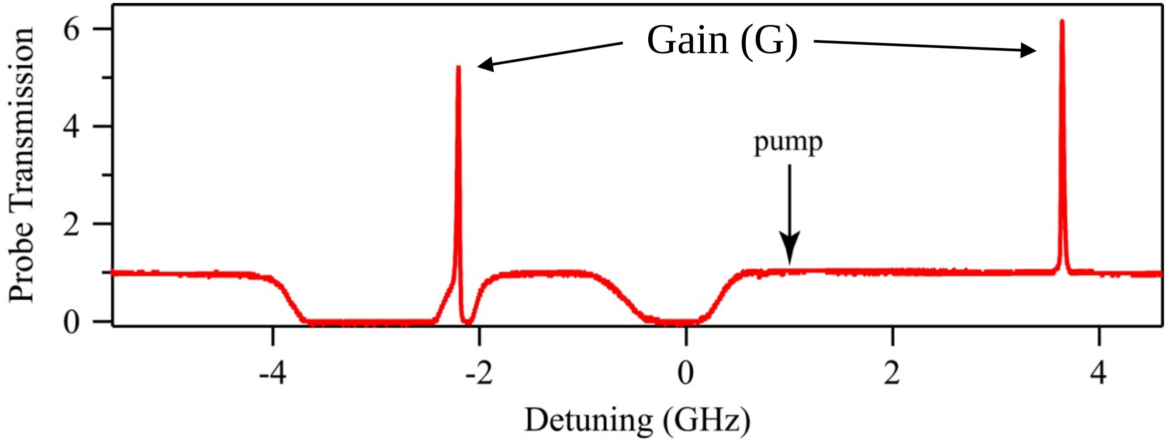
- Non-degenerate four-wave mixing in a double-Λ system in D1 line of ^{85}Rb.





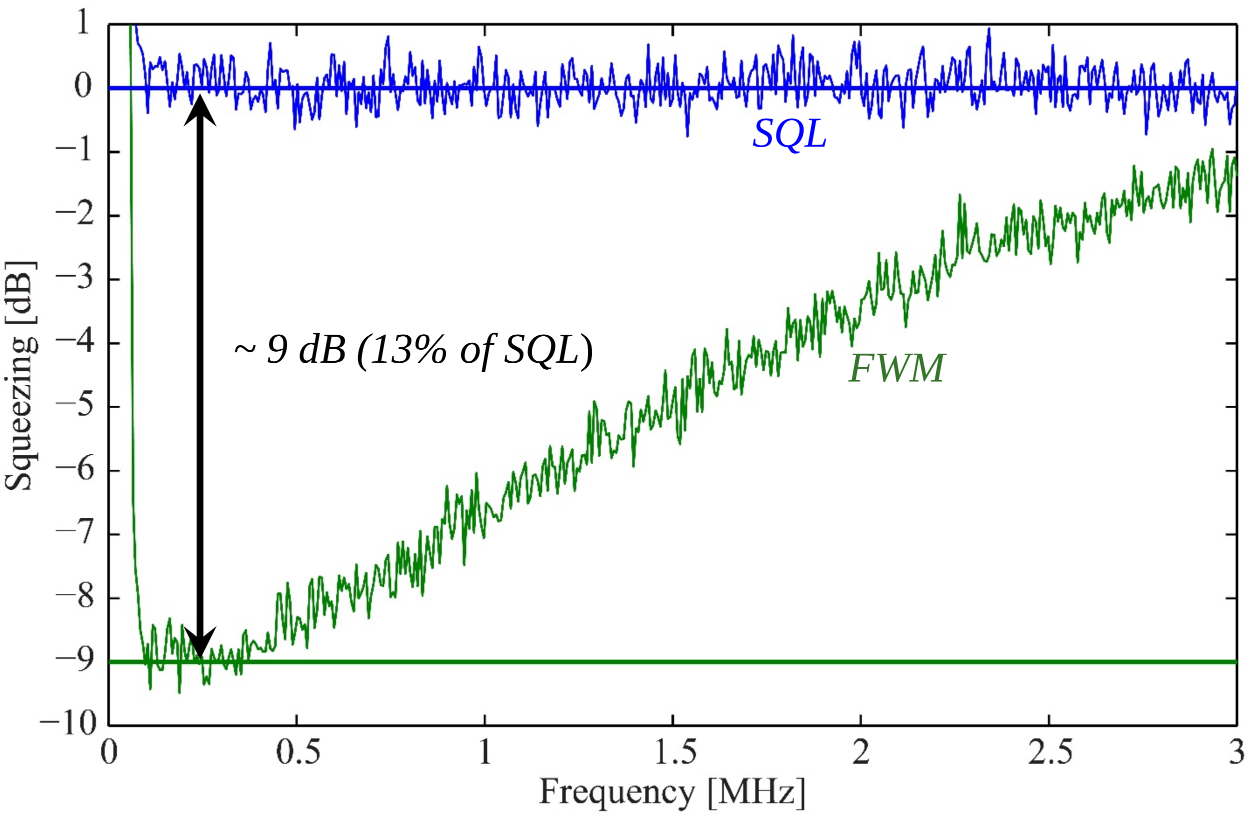
Experimental parameters:

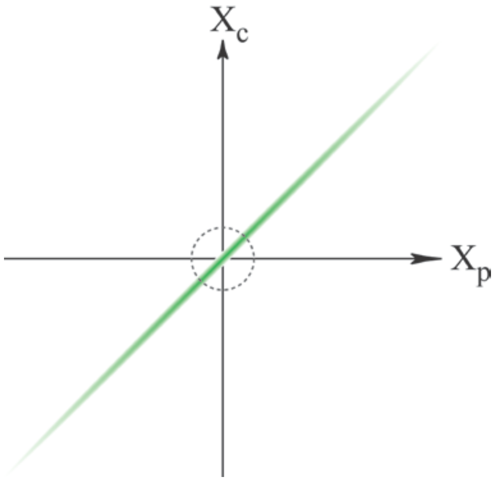
Pump ~ 400 mW
Probe ~ 10 – 100 μW
Cell ~ 12 mm
Gain ~ 6
θ ~ 0.3 degrees



- C.F. McCormick, V. Boyer, E. Arimondo, and P.D. Lett, *Opt. Lett.* **32**, 178 (2007).
- C.F. McCormick, A.M. Marino, V. Boyer, and P. D. Lett, *PRA* **78**, 043816 (2008).

Intensity-Difference Squeezing



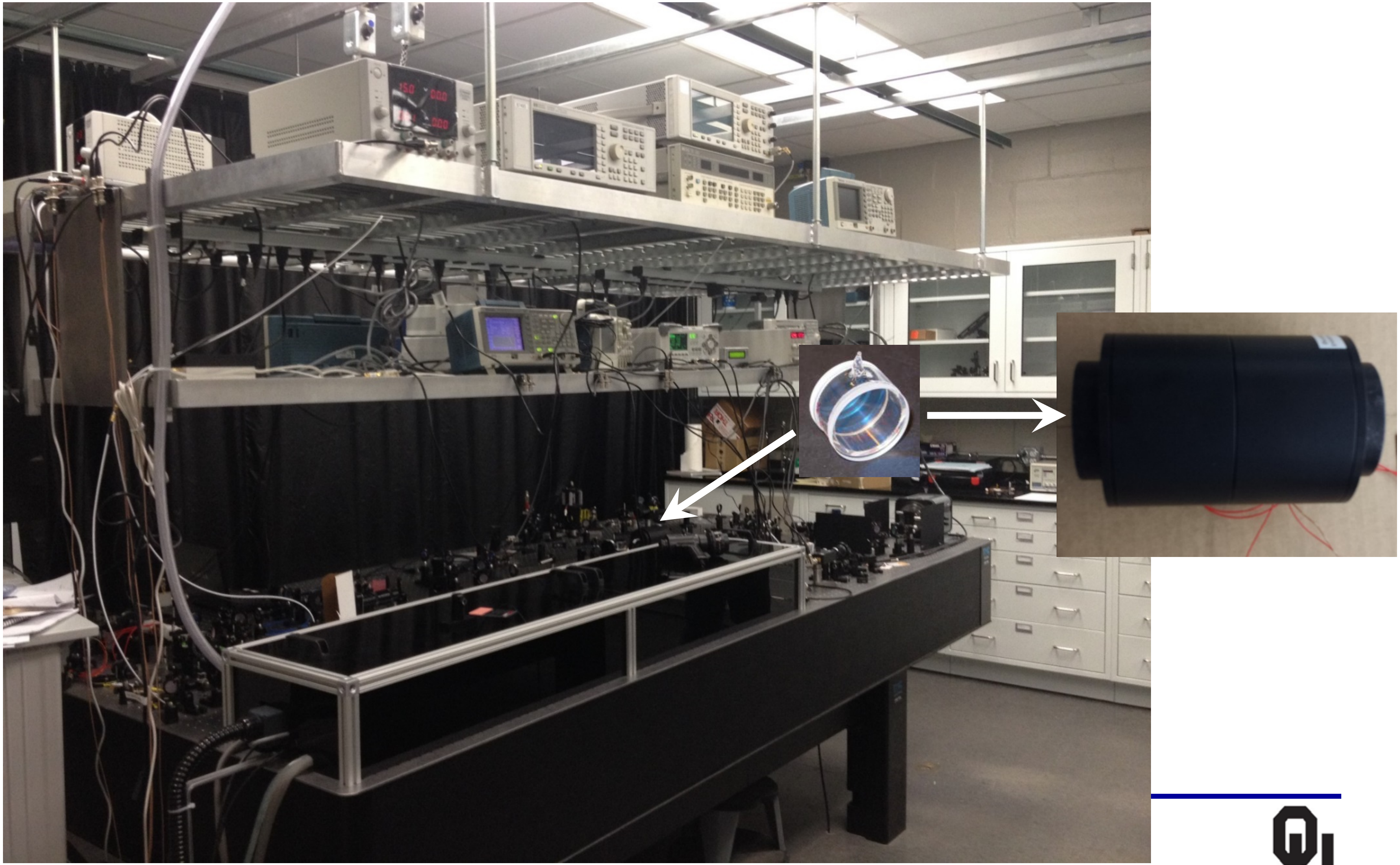


Experimental parameters:

Pump ~ 500 mW
Probe ~ 100 µW
Cell ~ 12 mm

- Squeezing bandwidth ~ 15 to 20 MHz

Experimental Setup



Entanglement Criteria

- Two systems, a and b, are entangled or inseparable if it is not possible to describe them independently.

$$|\psi\rangle_{ab} = \frac{1}{\sqrt{2}}(|\uparrow\rangle_a|\downarrow\rangle_b - |\downarrow\rangle_a|\uparrow\rangle_b) \neq |\psi\rangle_a|\psi\rangle_b$$

- For variables that have a continuous range of possible values (e.g. amplitude and phase):

$$|\psi\rangle_{ab} = \int f(X_a, X_b)|X_a\rangle_a|X_b\rangle_b \mathrm{d}X_a \mathrm{d}X_b \quad \text{with} \quad f(X_a, X_b) \neq f(X_a)f(X_b)$$

- Need to look at collective variables:

Joint quadratures

$$\begin{cases} \hat{X}_- = \frac{1}{\sqrt{2}}(\hat{X}_p - \hat{X}_c) & \textit{Amplitude difference} \\ \hat{Y}_+ = \frac{1}{\sqrt{2}}(\hat{Y}_p + \hat{Y}_c) & \textit{Phase sum} \end{cases}$$

➡ SQL:

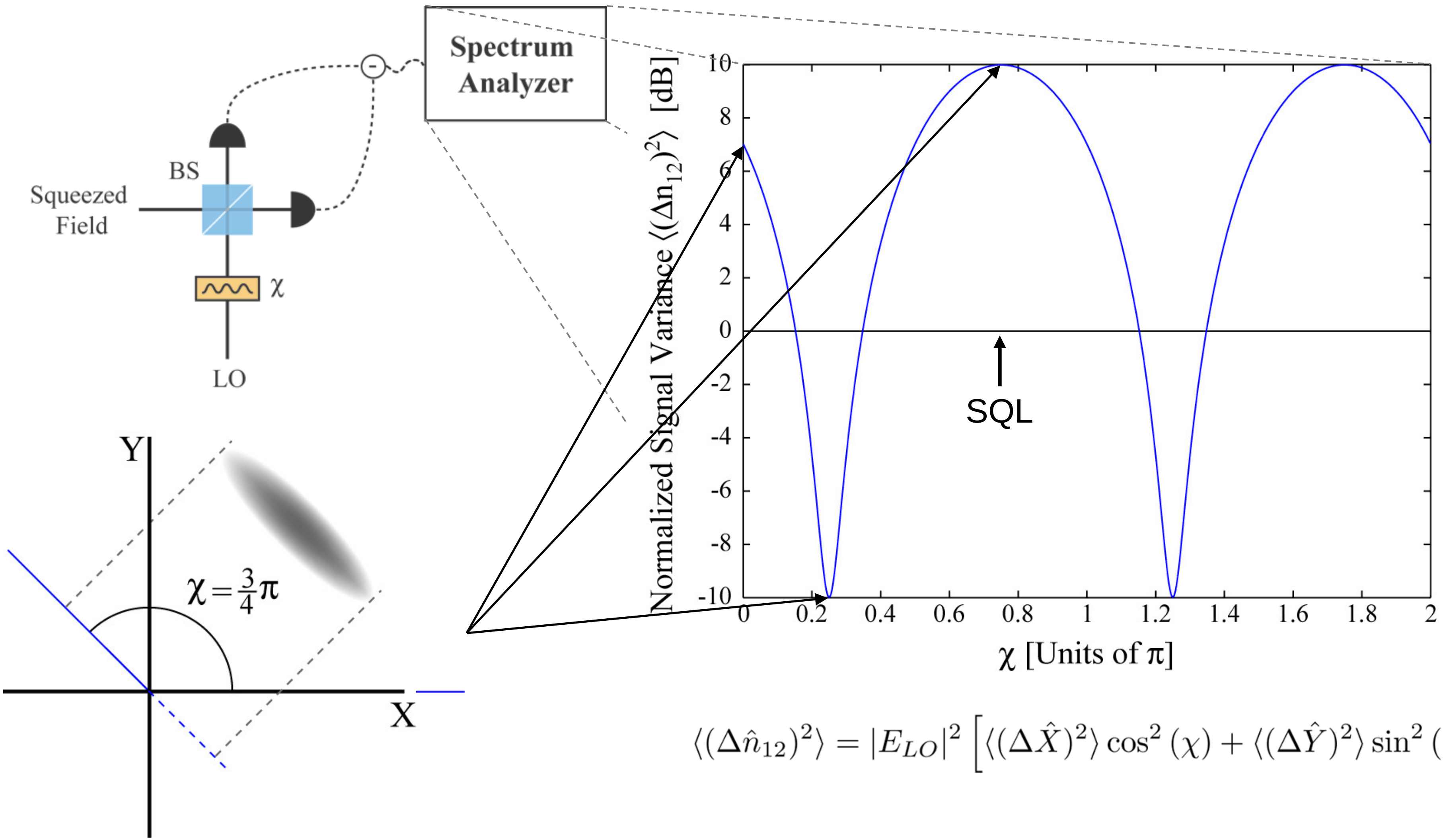
$$\langle(\Delta\hat{X}_-)^2\rangle = \langle(\Delta\hat{Y}_+)^2\rangle = 1$$

- Inseparability criterion:

$$\mathcal{I} \equiv \langle(\Delta\hat{X}_-)^2\rangle + \langle(\Delta\hat{Y}_+)^2\rangle < 2$$

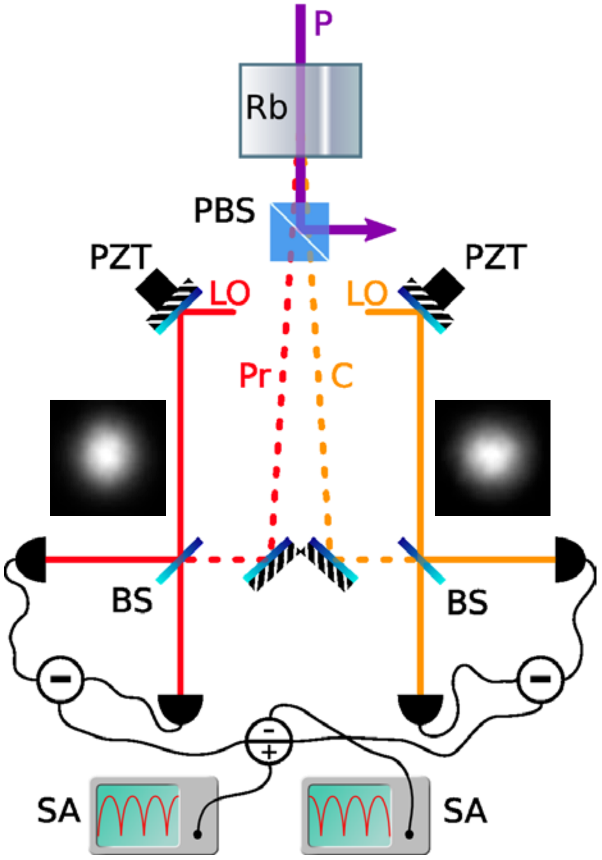
- L.M. Duan, G. Giedke, J. I. Cirac, and P. Zoller, *PRL* **84**, 2722 (2000).
- R. Simon, *PRL* **84**, 2726 (2000).

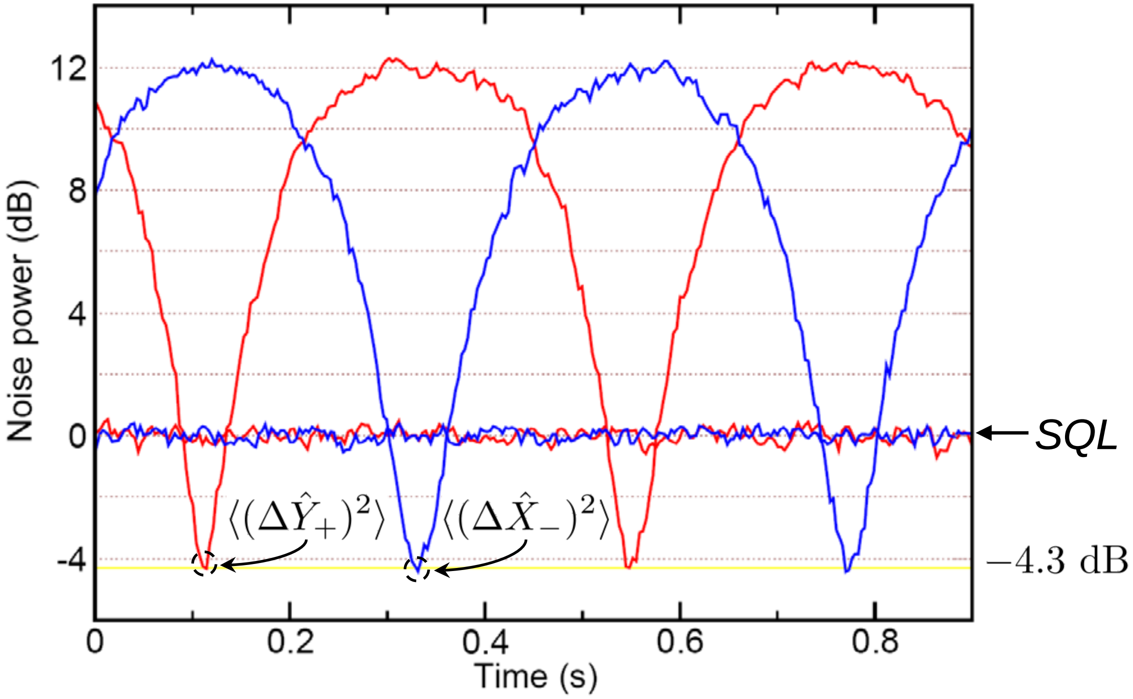
Homodyne Detection



$$\langle(\Delta\hat{n}_{12})^2\rangle = |E_{LO}|^2\left[\langle(\Delta\hat{X})^2\rangle\cos^2(\chi) + \langle(\Delta\hat{Y})^2\rangle\sin^2(\chi)\right]$$

Entanglement Measurements





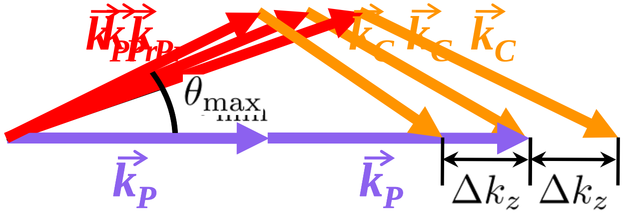
$$\mathcal{I} = 0.74 < 2$$

- Phases of local oscillators scanned synchronously.

SPATIAL PROPERTIES

Phase-Matching Condition

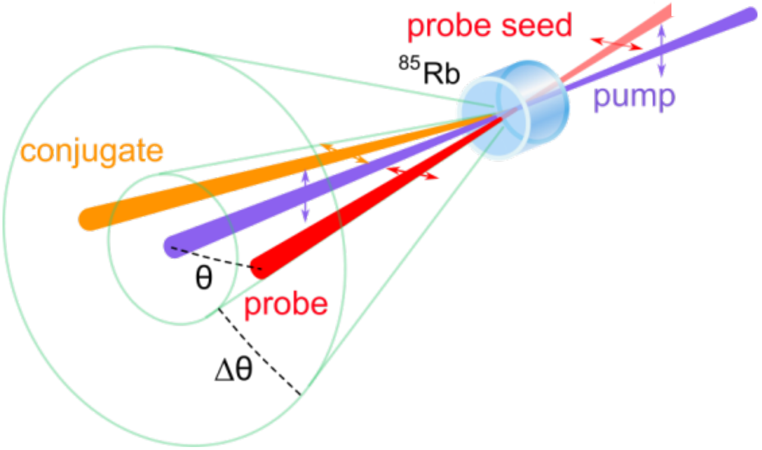
- In FWM fields need to conserve momentum

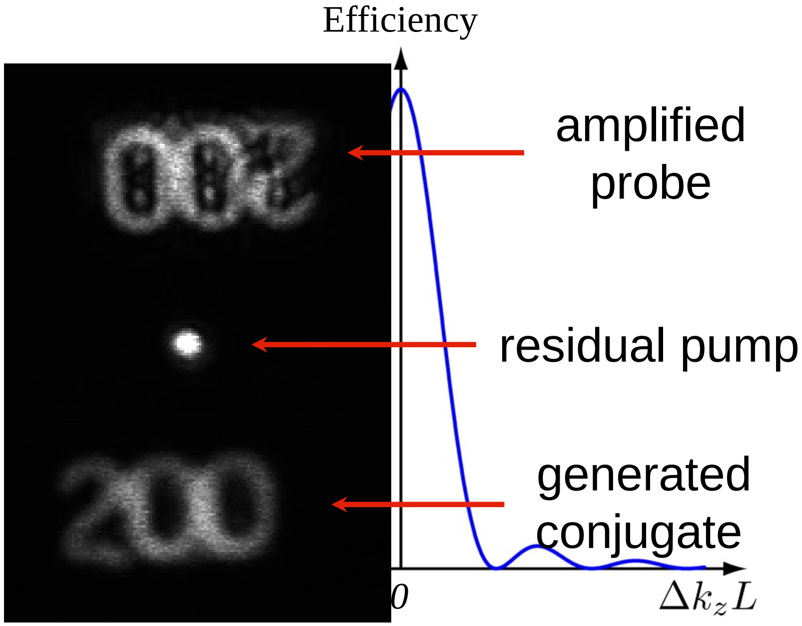


Phase-matching condition:

$$k^x_{Pr} = -k^x_C$$
$$\Delta k_z = 2k^z_P - k^z_{Pr} - k^z_C \approx 0$$

- Phase-matching is needed for efficient FWM.
- Lack of cavity make system multi-spatial-mode.

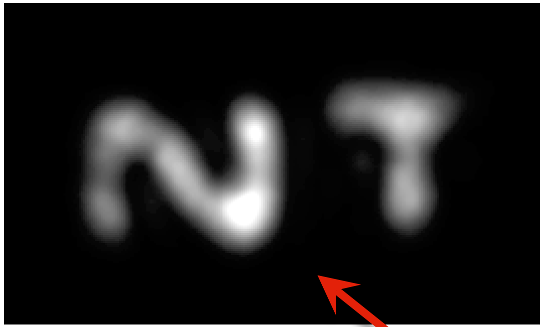




Spatial Quantum Correlations

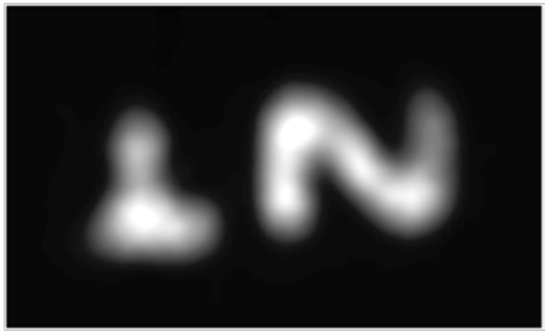
- Verify independence of spatial regions through noise analysis
  [M. Martinelli *et al.*, *PRA* **67**, 023808 (2003)].

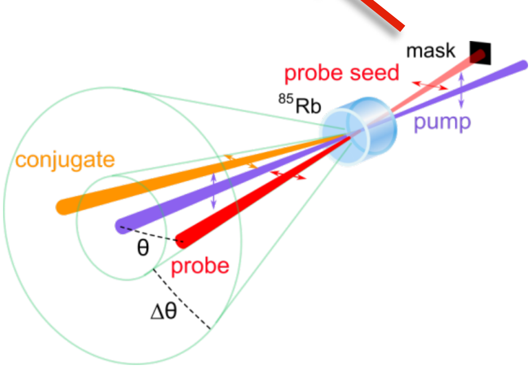
Probe seed



Probe out

Conjugate out





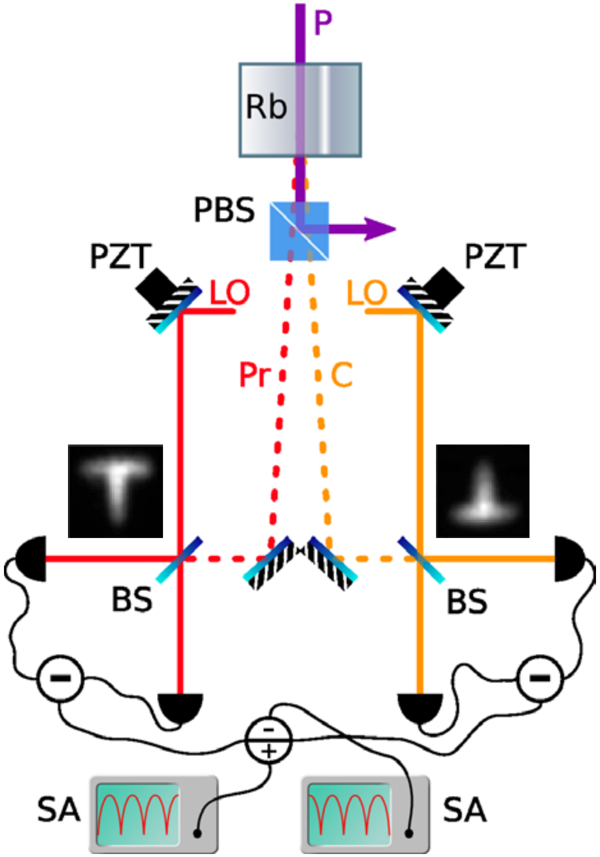
- Intensity-difference squeezing at 3.5 MHz:
  - "N T": -5.4 dB
  - "N": -5.1 dB
  - "T": -5.2 dB

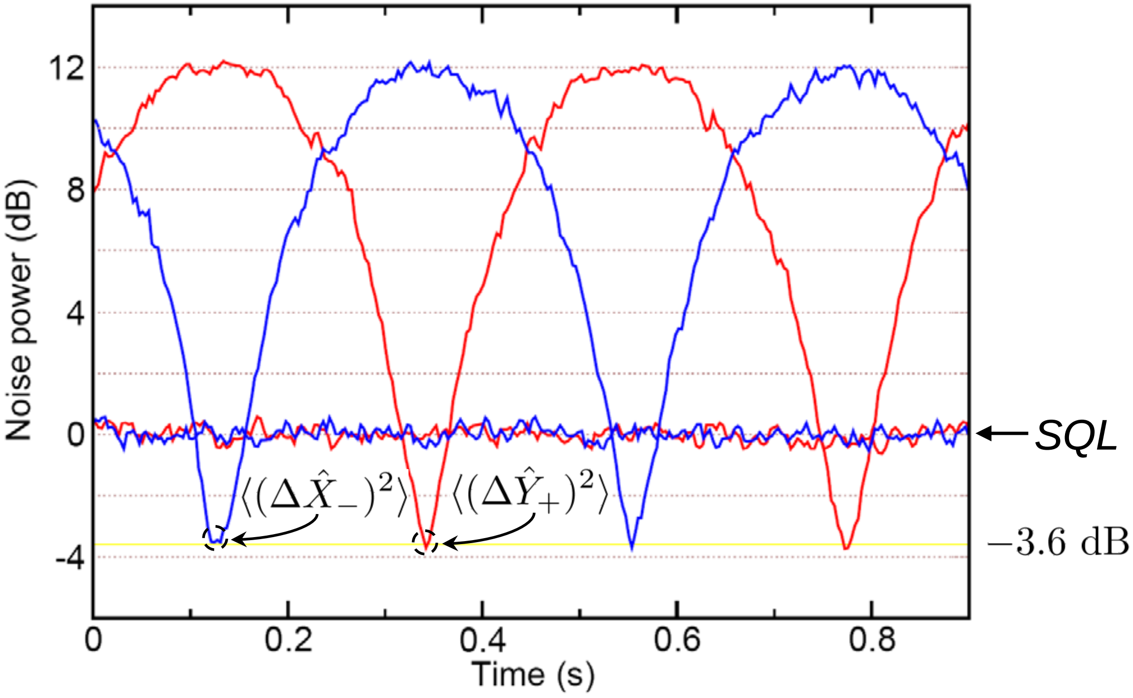
- Independence of spatial regions is a hallmark of spatial quantum correlations.

- V. Boyer, A.M. Marino and P.D. Lett, *PRL* **100**, 143601 (2008).

Entangled Images

- The local oscillator selects the “shape” of the beam that is measured by the homodyne detection.

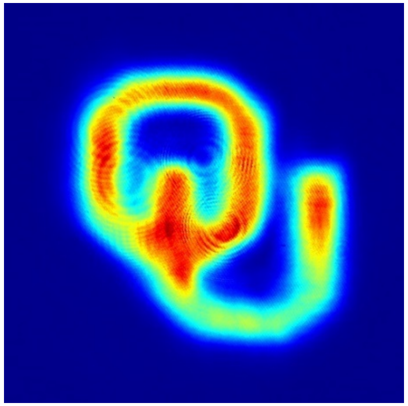




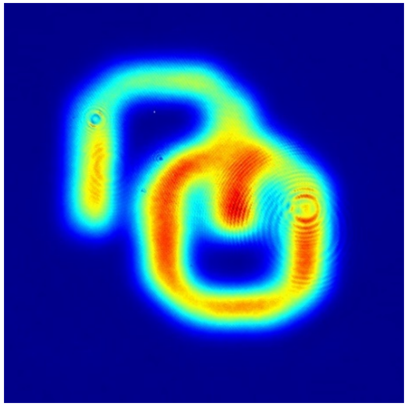
$$\mathcal{I} = 0.87 < 2$$

• V. Boyer, A.M. Marino, R.C. Pooser, and P.D. Lett, *Science* **321**, 544 (2008).

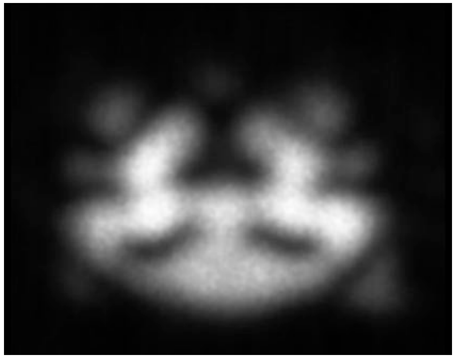
Entangled Images



Probe



Conjugate

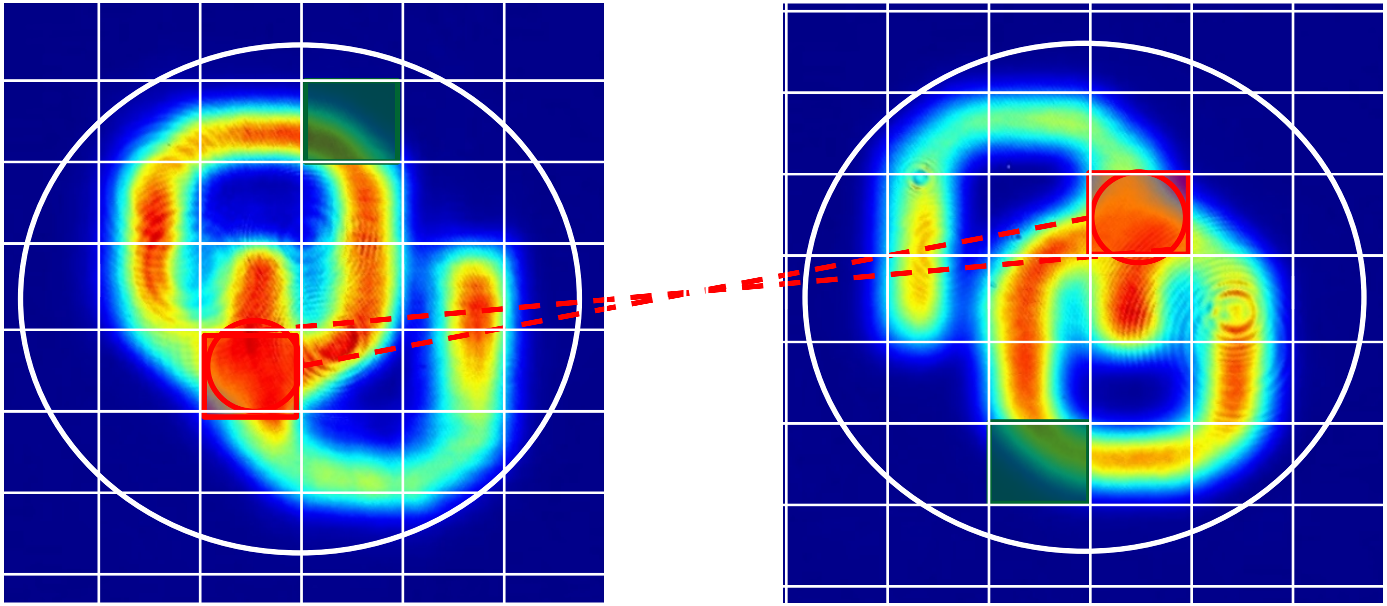


$\mathcal{I} \approx 1.6 < 2$

Intensity-difference squeezing:

-4.5 dB

Properties of Entangled Images

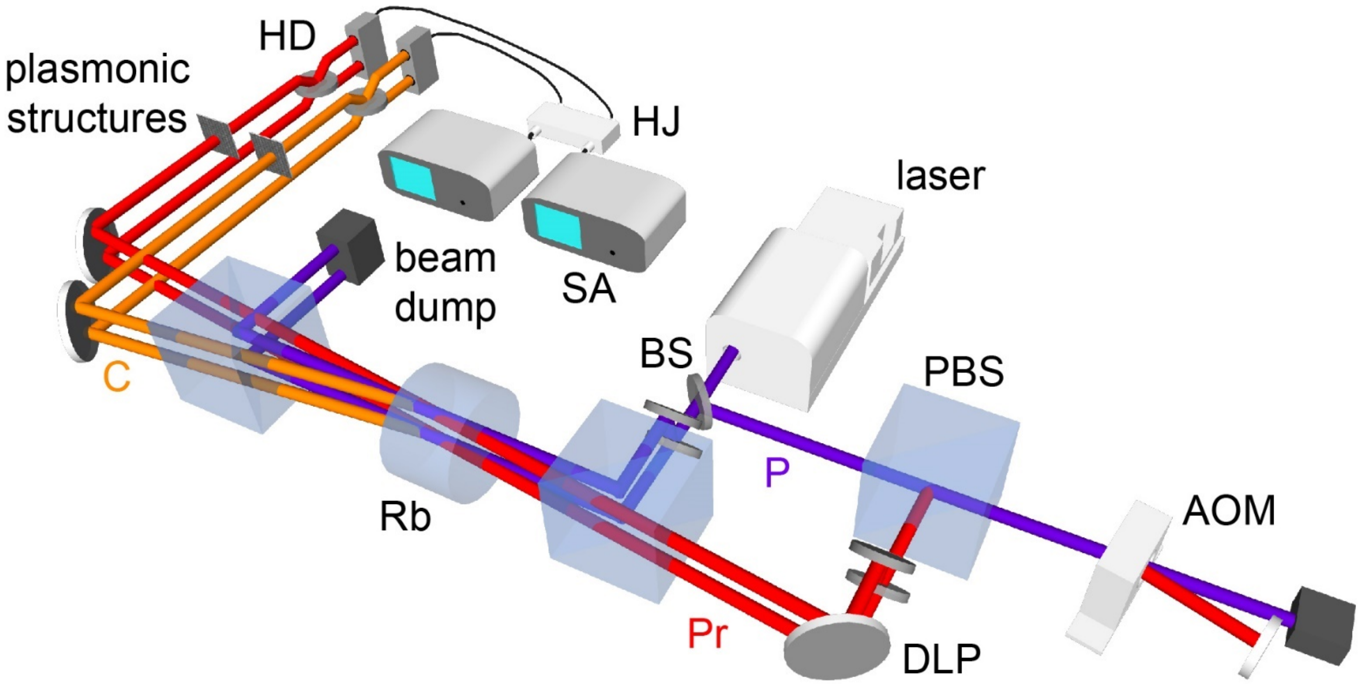


- Minimum size of the correlation area known as the coherence area and can be seen as a “pixel”.
- “Pixel” in one images is only correlated with corresponding pixel in other image.
- Can think of each of “pixel” as an independent channel to probe a sensor.

INTERFACE WITH PLASMONIC STRUCTURES

Experimental Setup

- Study if plasmonic structure maintain quantum properties of entangled images.

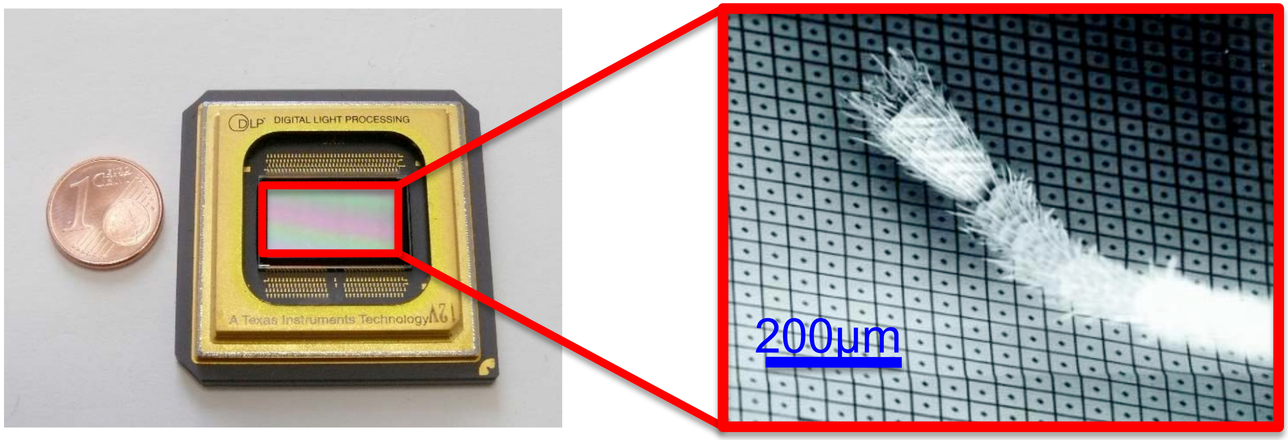


- In transduction, entanglement transferred from photons to plasmons and back to photons.

• M.W. Holtfrerich et. al, *Optica* **3**, 985 (2016).

Beam Shaping of Probe

- Use DLP (digital light processor) to shape input probe.



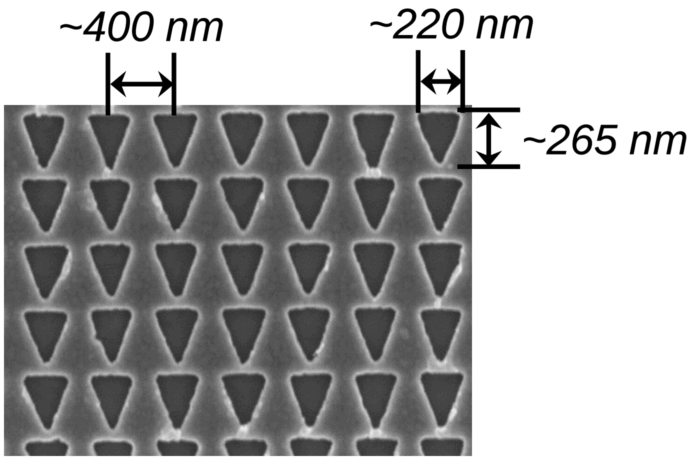
- Lightcrafter module:
  - Only on-off position for each pixel
  - Binary amplitude control
  - 608 x 684 pixels
  - ~ 25% total transmission

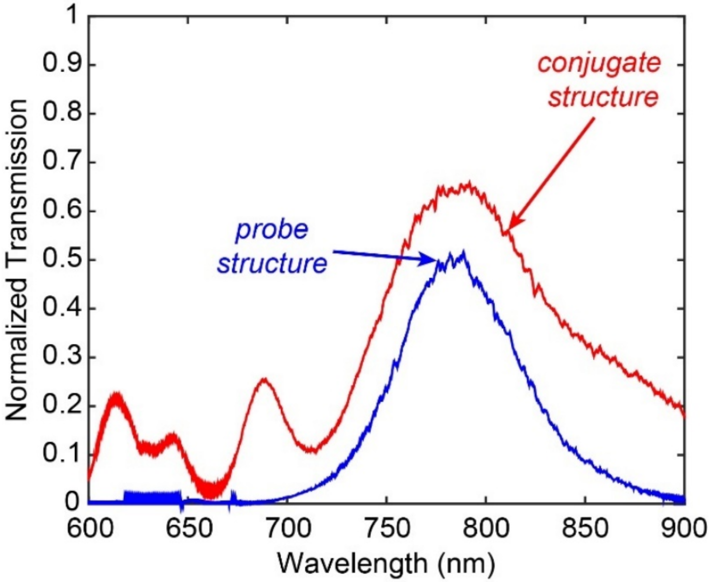
Plasmonic Structures

- Array of nanoholes in a thin silver film (100 nm thickness).
- Use triangular structures.
- Incident field at 795 nm excites localized surface plasmons, which lead to EOT (extraordinary optical transmission).
- Array of nanoholes leads to resonance.
- Use two independent plasmonic structures (one for probe and one for conjugate).

Conjugate structure ~ 65 %

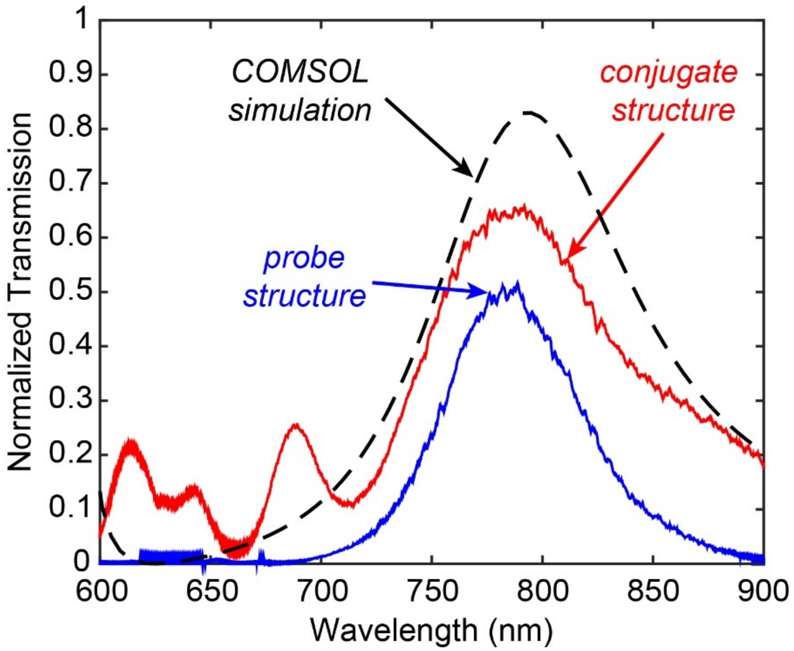
Probe structure ~ 50 %

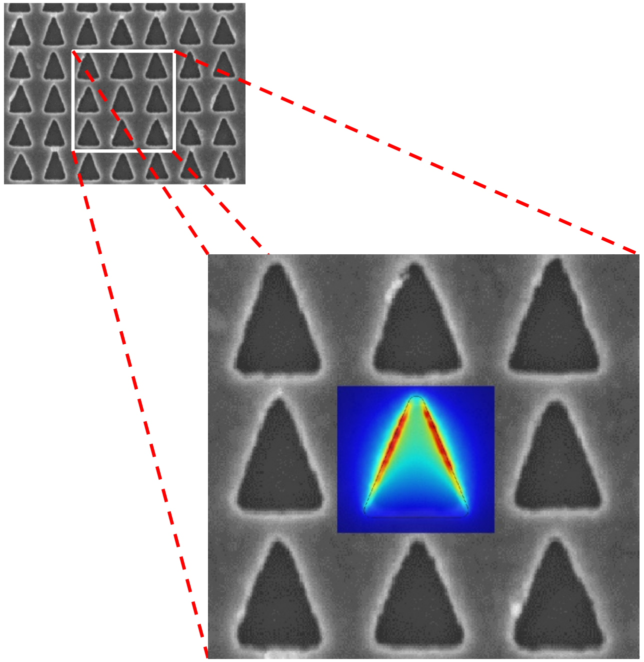




Modeling of Plasmonic Structures

- Use COMSOL to model properties of plasmonic structures.



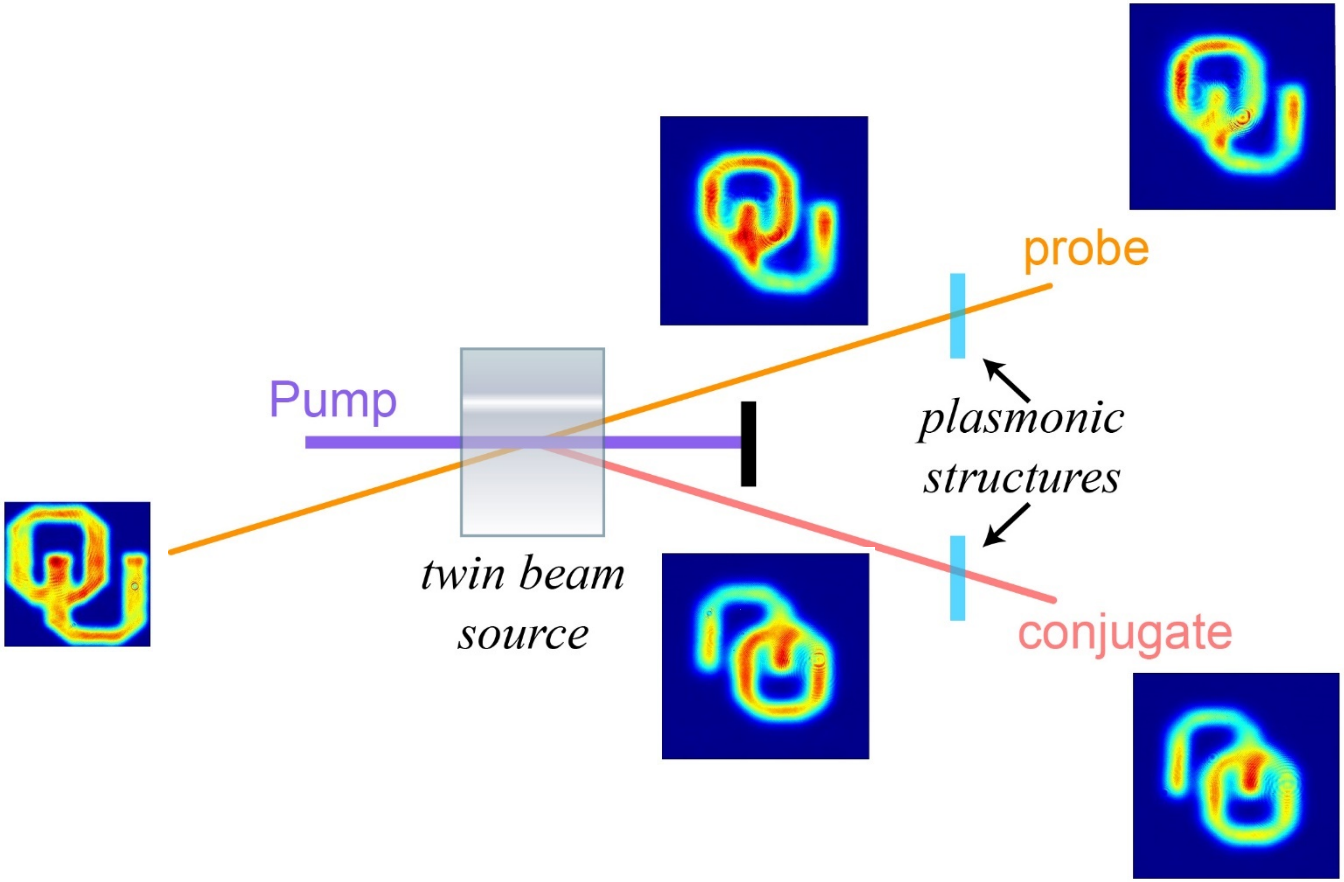


- Modeling shows profile is localized around the edges of apertures.

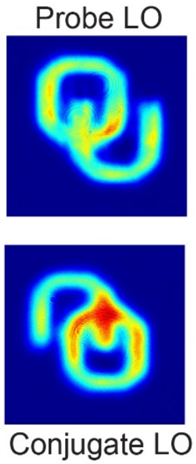
→ Localized surface plasmons (LSP)

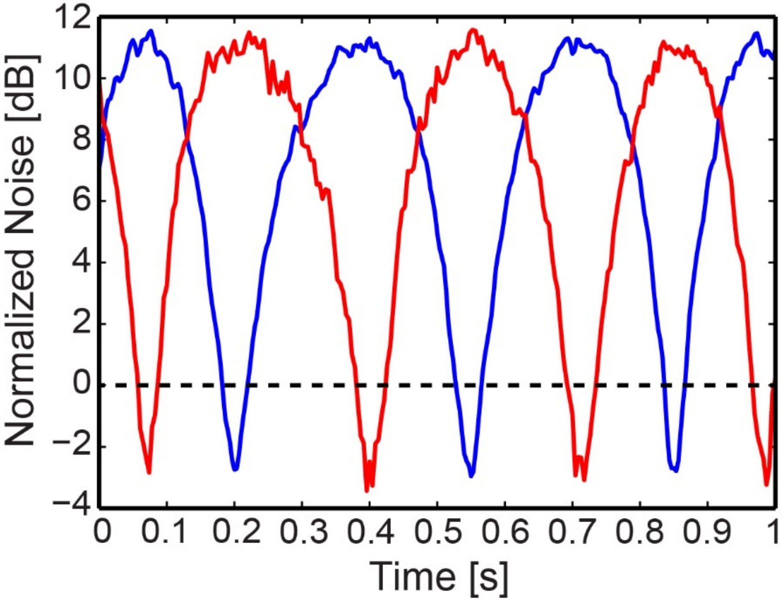
Spatial Properties

- A large number of *k*-vectors can coupled to LSPs [*PRL* ***110**, 156802 (2013)*].

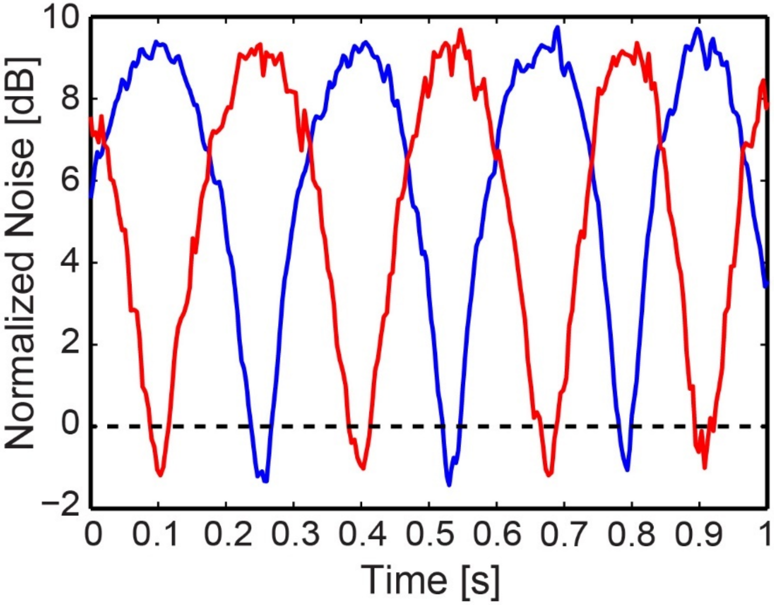


Entanglement Properties




without plasmonic structure

$$\mathcal{I} = 1.05 < 2$$


with plasmonic structure

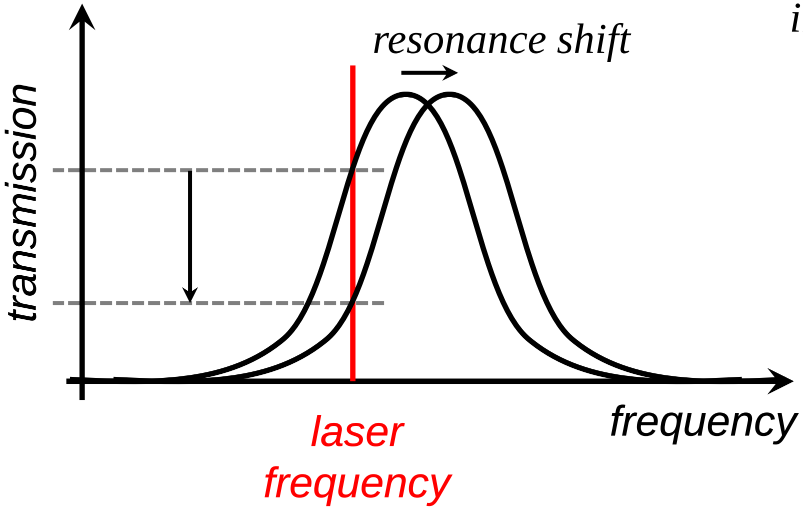
$$\mathcal{I} = 1.55 < 2$$

- Loss of entanglement consistent with losses introduced by plasmonic structures.

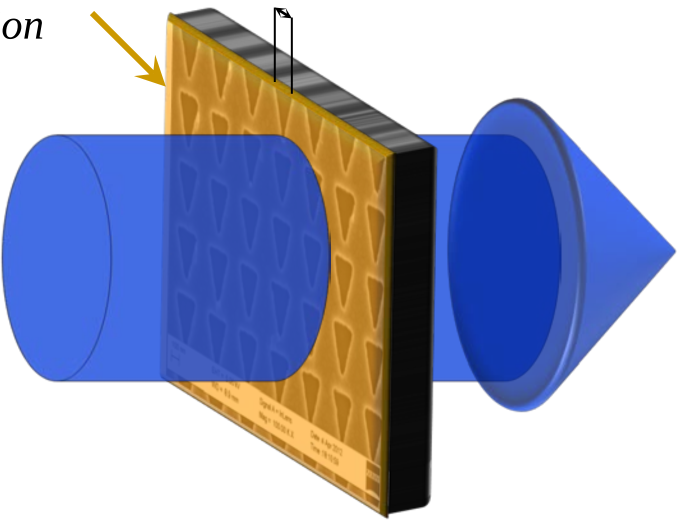
QUANTUM ENHANCED PLASMONIC SENSORS

Plasmonic Structures as Sensors

- Operation based on two principles:
  - Extraordinary optical transmission (EOT).
  - Array of nanoholes leads to a resonance as a function of frequency [surface plasmon resonance (SPR) sensors].



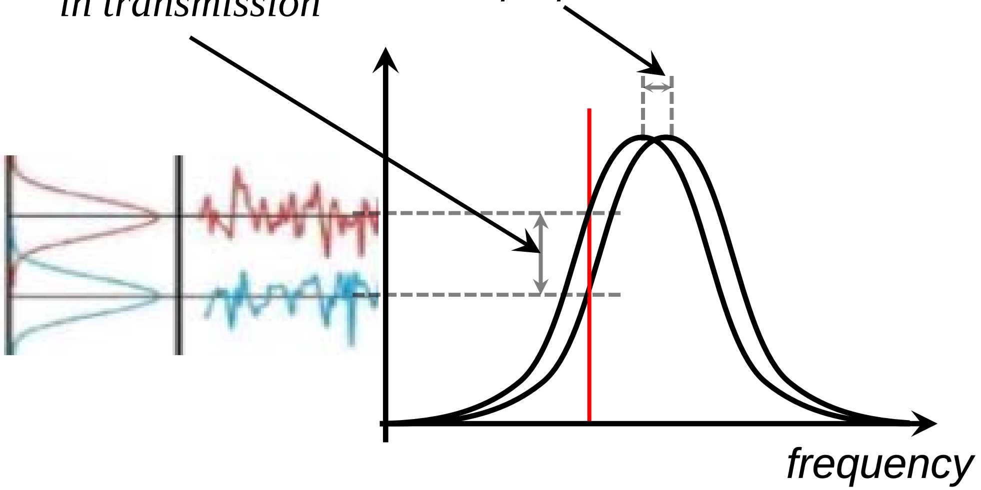
substance of interest induces local changes in index of refraction



Sensitivity Enhancement

resulting change in transmission

resonance shift due to change in index of refraction



Uncertainty in index of refraction estimation:

measurement noise

$$\Delta n_{est}^2 = \frac{\Delta T^2}{|\partial T/\partial n|^2}$$

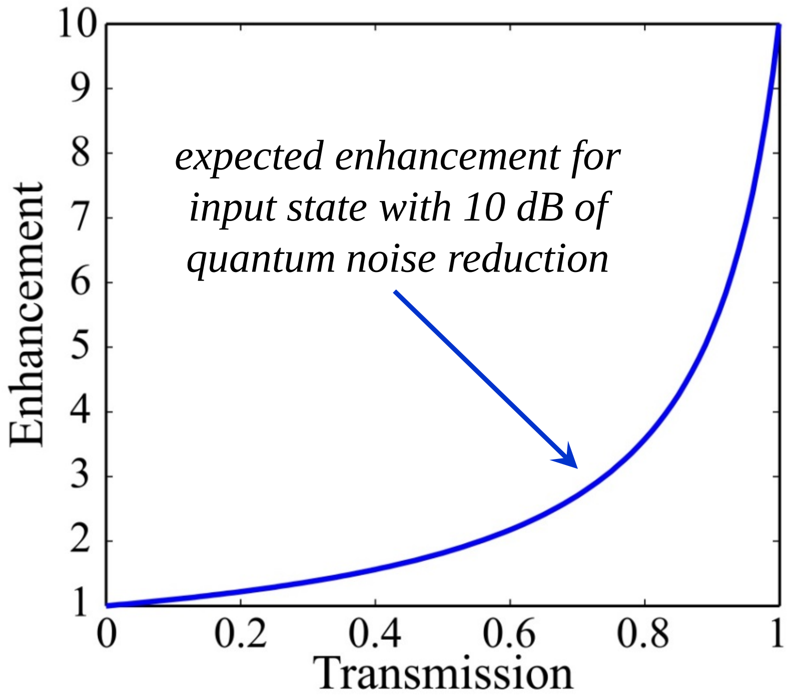
lower uncertainty
=
enhanced sensitivity

change in transmission for change in index of refraction

- Sensitivity Enhancement:
  - ➢ Reduced noise (current devices limited by quantum noise)
    - ➢ Use quantum states of light
  - ➢ Increased slope (reduce resonance width and increase transmission)

Expected Enhancement

- For large transmissions sensitivity enhancement given by degree of quantum noise reduction.



expected enhancement for input state with 10 dB of quantum noise reduction

Enhancement:

uncertainty in estimation of index of refraction with classical resources

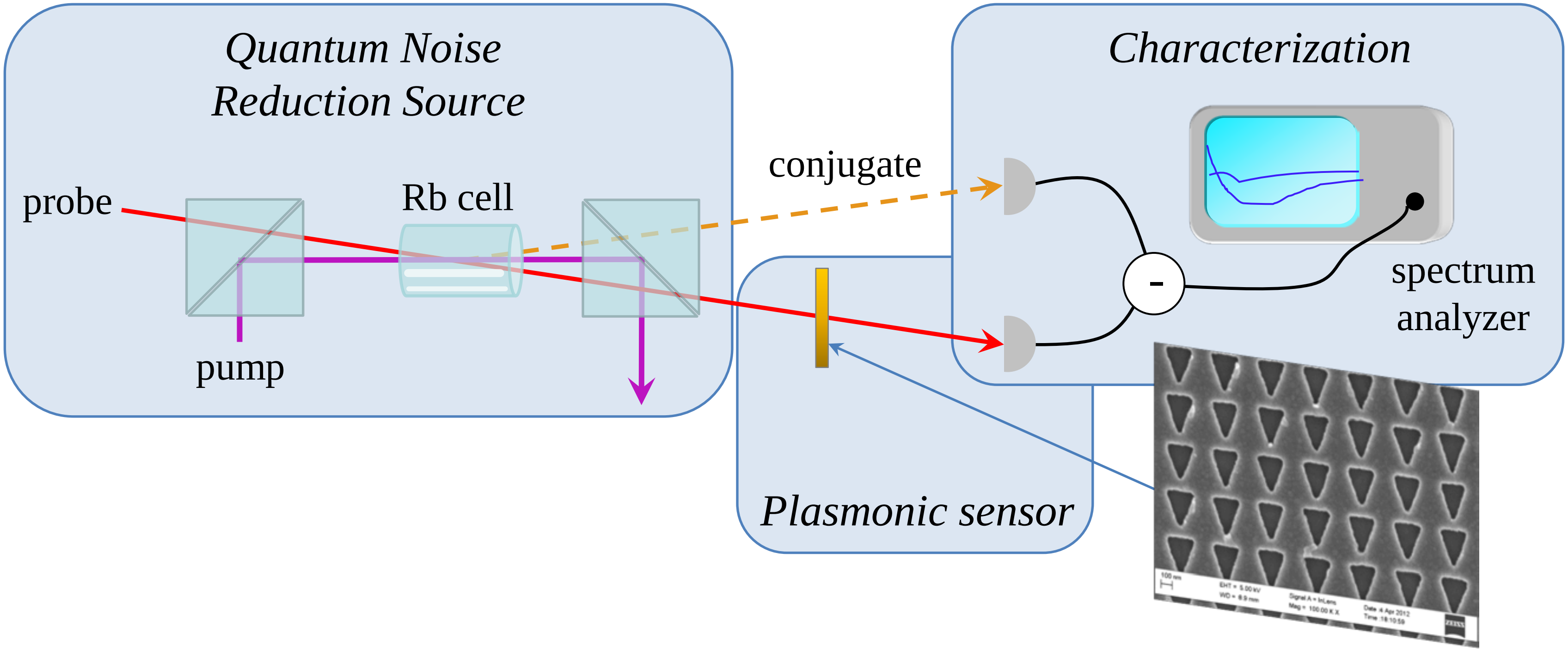
$$\frac{\Delta n_c^2}{\Delta n_q^2} = \frac{\Delta T_c^2}{\Delta T_q^2}$$

uncertainty in estimation of index of refraction with TMSS

- *Main technical challenge*: quantum states are very fragile to sources of loss.

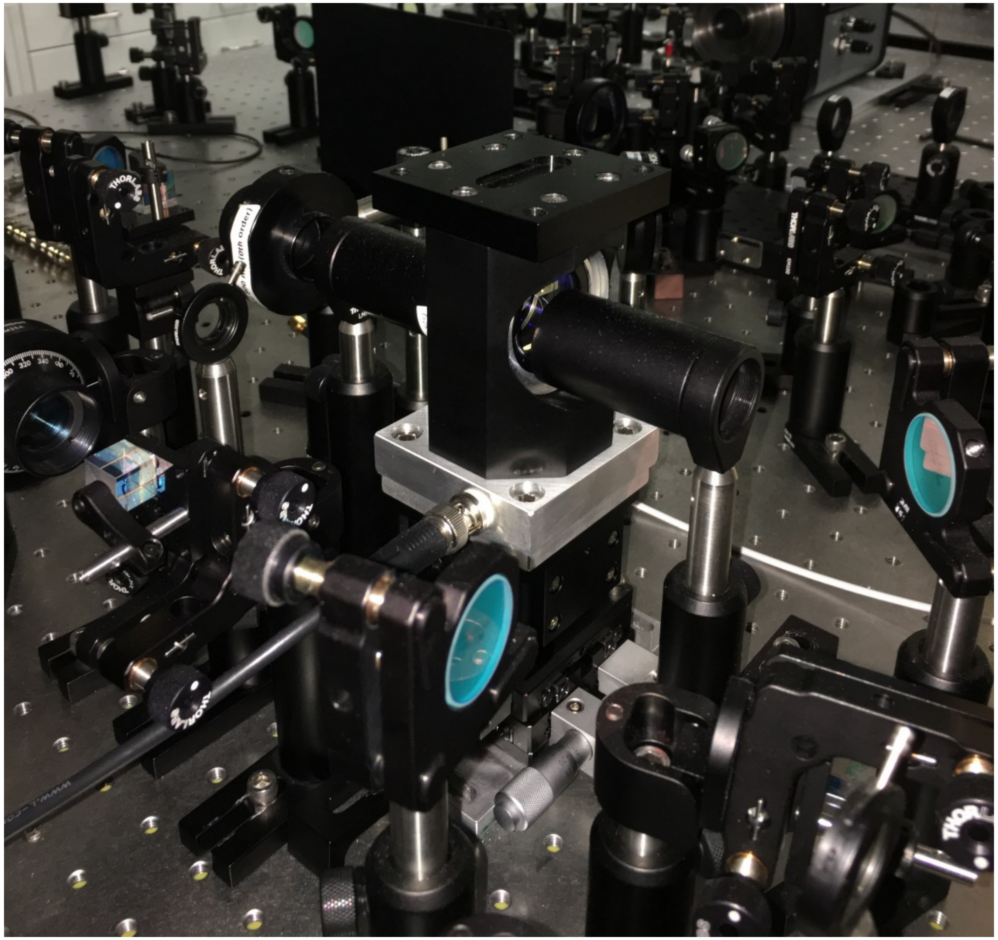
Experimental Setup

- Probe beam used to probe plasmonic sensor.
- Conjugate beam serves as a “reference” beam.



- Plasmonic sensor placed in controlled environment to control change in index of refraction and perform precision measurements.

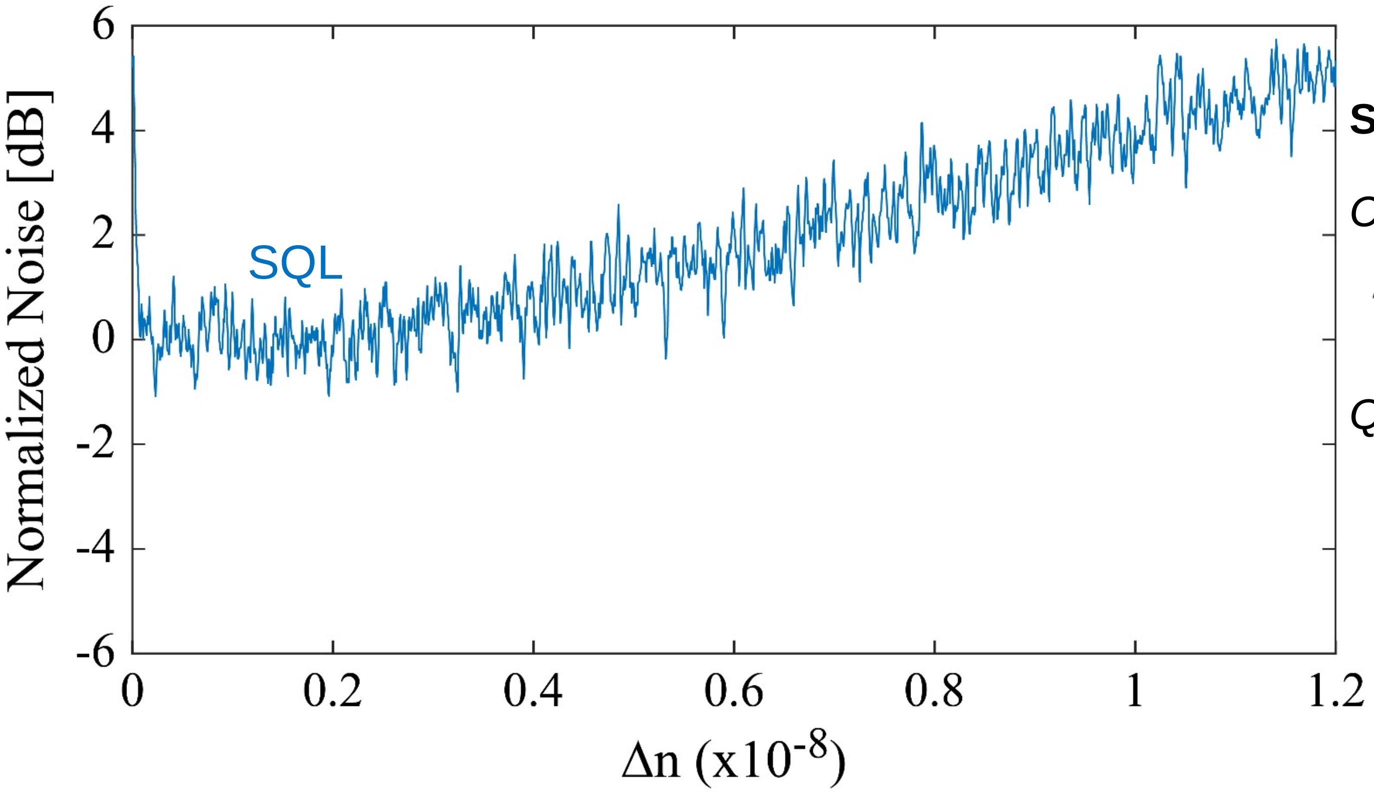
Characterization of Sensor



- Pressure controlled chamber allows precise control of index of refraction.
- Modulation of index provides measure of sensitivity.
- Change in index of refraction calibrated with an interferometer.

Quantum Enhanced Plasmonic Sensor

- Test plasmonic structure as sensor (preliminary results).



Sensitivity:

Classical States:

$\Delta n \sim 9 \times 10^{-10}\ \mathrm{RIU}/\sqrt{\mathrm{Hz}}$

Quantum States:

$\Delta n \sim 5 \times 10^{-10}\ \mathrm{RIU}/\sqrt{\mathrm{Hz}}$

Measurement bandwidth: 100 Hz

Outlook

- Use the multi-mode nature of entangled beams to probe plasmonic sensor in parallel.

- Design alternative structures to allow with higher transmissions and narrower resonances.

  ➡ Further enhancements in sensitivity

- Test plasmonic sensors in more realistic configuration.

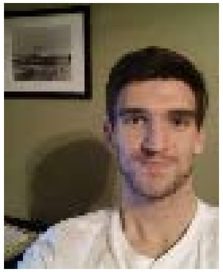
- Possible imaging applications?

Acknowledgements

- University of Oklahoma team:

Students

Javad Dowran



Matt Holtfrerich

Postdoc

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- ORNL team:

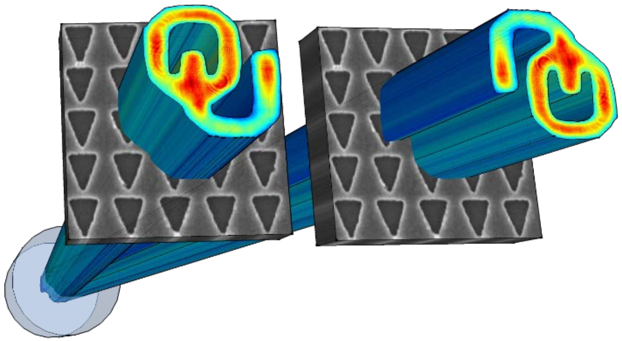
Raphael Pooser

Ben Lawrie

Roderick Davidson

Conclusions

- Four-wave mixing used to generate entangled images.
- Transduction through plasmonic structures preserves entanglement and spatial properties of entangled images.
- Enhancement of plasmonic sensors.



Postdoctoral position available.
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