Quantum Imaging Technologies: Quantum Laser Radar

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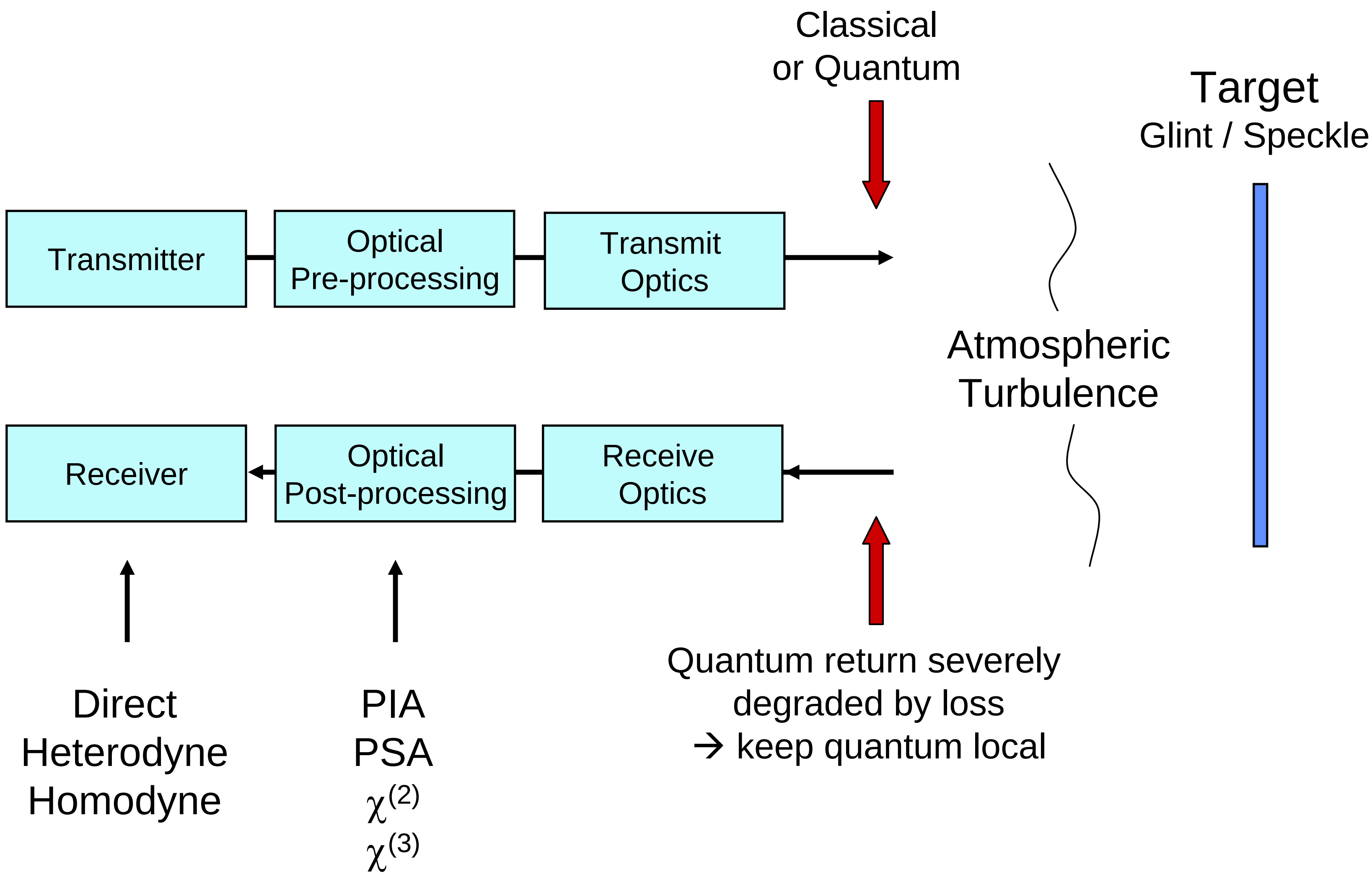
Support: U. S. Army Research Office Multidisciplinary University Research Initiative Grant No W911NF-05-1-0197

Quantum Laser Radar

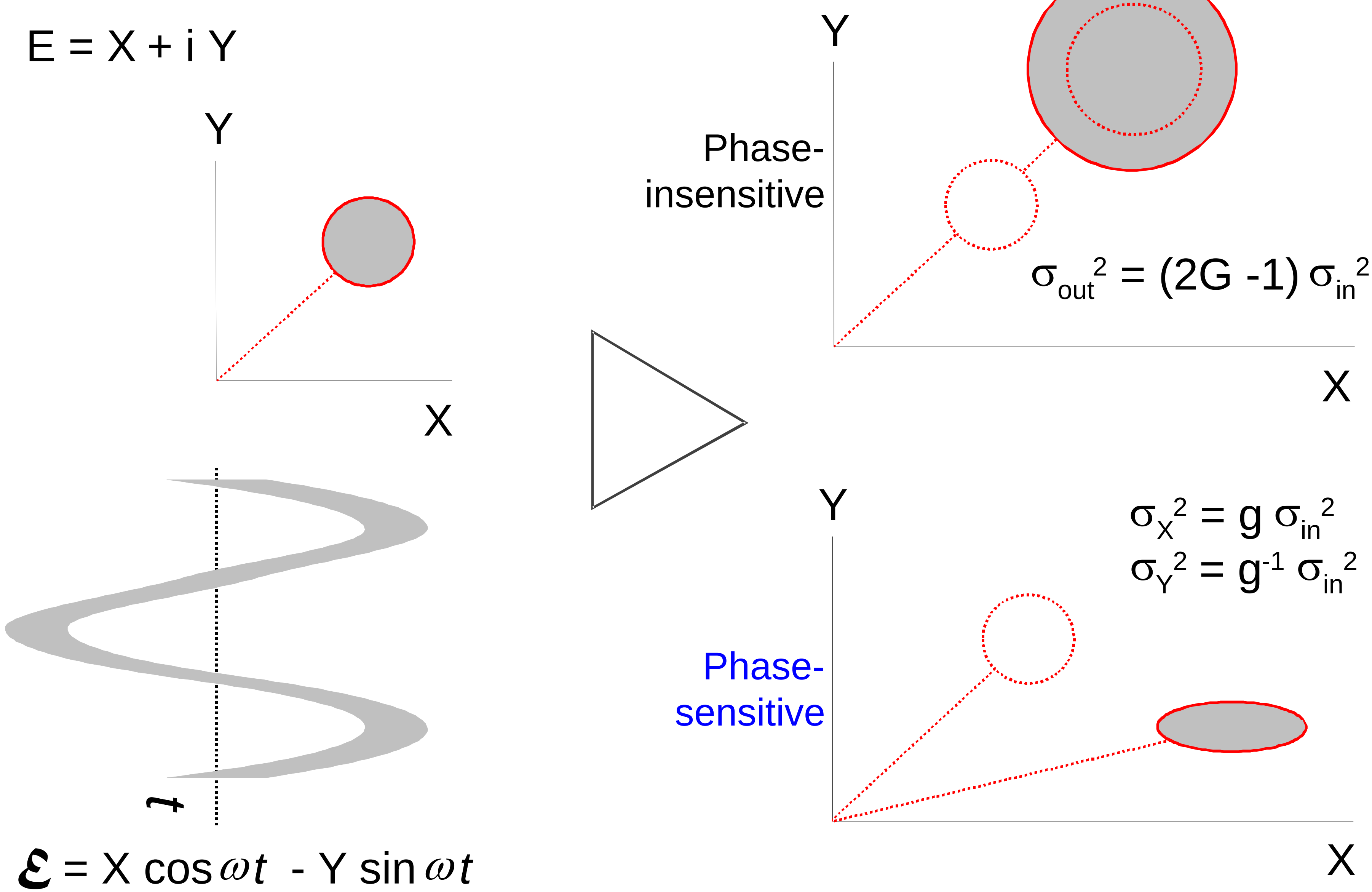


PIA = Phase Insensitive Amplifier

PSA = Phase Sensitive Amplifier

Pictorial View of Amplification of Coherent Input Light

$E = X + i Y$



$\sigma_{out}^2 = (2G - 1)\,\sigma_{in}^2$

$\sigma_X^2 = g\,\sigma_{in}^2$

$\sigma_Y^2 = g^{-1}\,\sigma_{in}^2$

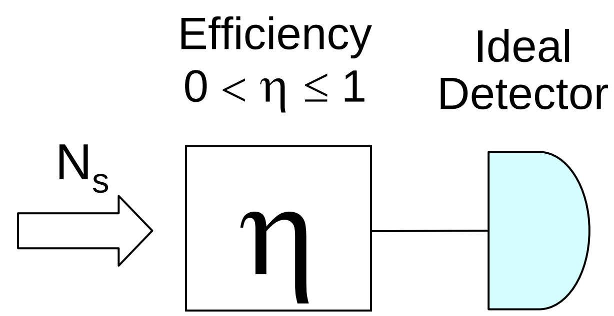
$\mathcal{E} = X \cos \omega t - Y \sin \omega t$

Simulation of Preamplified Photodetection of Shot-Noise Limited Signals

- Simulation of the amplification of a gray-scale image in the shot-noise limited regime
- Random zero-mean Gaussian noise is added to represent detector noise
  - A valid model when the received signal photon number per pulse or per inverse bandwidth is not too small
- Photocurrents in the unamplified and amplified cases are scaled appropriately for fair comparison.

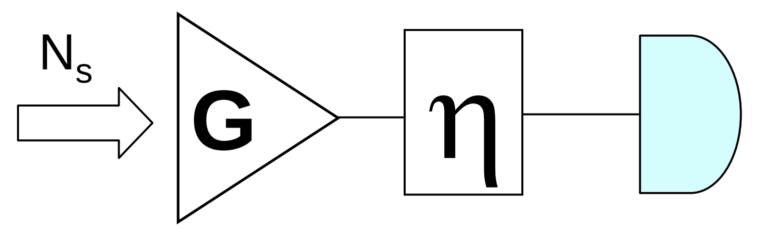
Simulation of Preamplified Photodetection of Shot-Noise Limited Signals

- For $G = 1$ (no preamplification)
  - $SNR_{IN} = N_s$ (shot-noise limited signal)
  - $\langle(\Delta N_s)^2\rangle_\eta = \eta N_s$, $SNR_{OUT} = \eta N_s$
  - $NF = SNR_{IN} / SNR_{OUT} = 1/\eta$



- For $G > 1$
  - $SNR_{IN} = N_s$ and $\langle(\Delta N_s)^2\rangle = N_s$
  - Output = $\eta G N_s$. Find $\langle(\Delta N_s)^2\rangle_{\eta G}$ from:
  - $NF = SNR_{IN} / SNR_{OUT} = N_s / [(\eta G N_s)^2 / \langle(\Delta N_s)^2\rangle_{\eta G}]$

    …or…
  - $\langle(\Delta N_s)^2\rangle_{\eta G} = NF\,(\eta G N_s)^2 / N_s = \boxed{\langle(\Delta N_s)^2\rangle_\eta\, \eta G^2\, NF}$



Simulation of Preamplified Photodetection of Shot-Noise Limited Signals

- Noise Figure (NF): [PRL 83 (10), pp.1938-1941, Choi, Vasilyev & Kumar]
  - $NF_{tot} = NF_{amp} + (1 - \eta) / (\eta G)$
  - $NF_{PSA} = 1 \rightarrow (NF^{PSA})_{tot} = 1 + (1 - \eta) / (\eta G)$
  - $NF_{PIA} = 2 – 1/G \rightarrow (NF^{PIA})_{tot} = 2 (1 – 1/G) + 1 / (\eta G)$

- Also, the detected signal in each case is different. So, we scale PSA & PIA noise by G^2 in order to fairly compare the photo-current between the three cases.

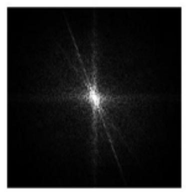
- Therefore, added noise:
  - No gain $\rightarrow \langle(\Delta N_s)^2\rangle_\eta$
  - PSA $\rightarrow \eta\, [1 + (1 - \eta) / (\eta G)]\, \langle(\Delta N_s)^2\rangle_\eta$
  - PIA $\rightarrow \eta\, [2(1 – 1/G) + 1/(\eta G)]\, \langle(\Delta N_s)^2\rangle_\eta$

Simulation of Potential Advantage

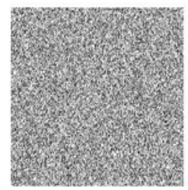
Although shown here for a spatially broadband case, our goal in the MURI is to do proof-of-principle experiments with raster scanning of the image with use of a fiber-based PSA.

Start w/ 256 × 256 image

FFT

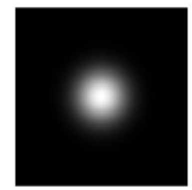


+



×

Soft Gaussian Frequency Filter



Add noise per spatial frequency:

$\langle(\Delta N_s)^2\rangle_\eta \rightarrow$ When G = 1

$\eta\,[1 + (1-\eta)/(\eta G)]\,\langle(\Delta N_s)^2\rangle_\eta \rightarrow$ For PSA

$\eta\,[\,2(1 - 1/G) + 1/(\eta G)]\,\langle(\Delta N_s)^2\rangle_\eta \rightarrow$ For PIA

IFFT

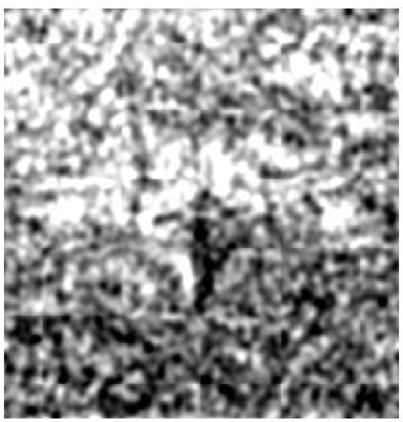
Result

Results: Averaged over 100 Frames
η = 0.8, G = 10 dB

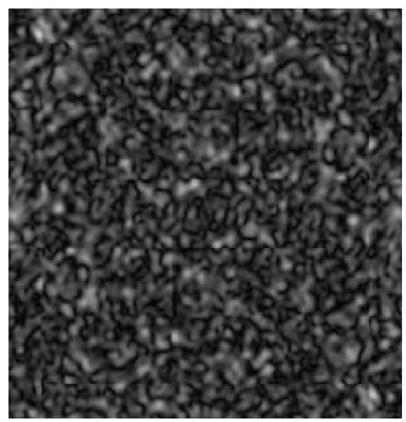
Target (no average)

No gain

PSA gain



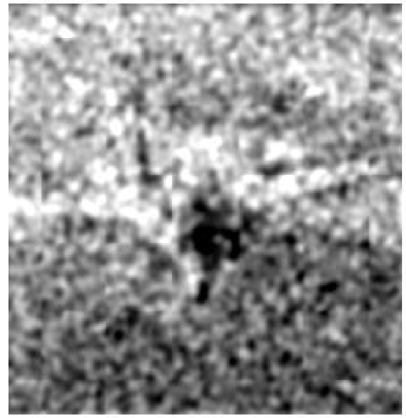
PIA gain



One frame after
IFFT (no average)

Results: Averaged over 100 Frames
η = 0.3, G = 10 dB

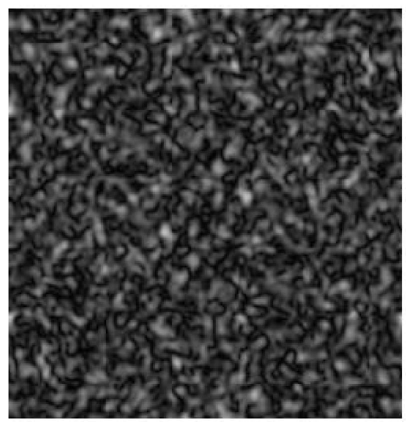
Target (no average)



No gain

PSA gain

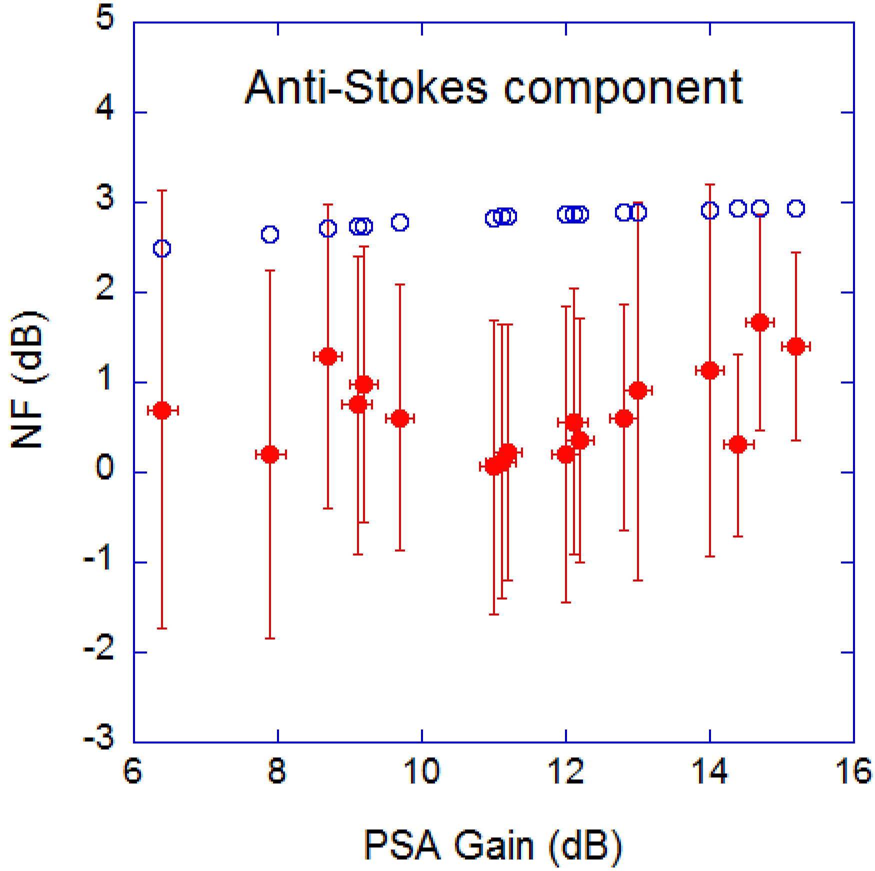
PIA gain

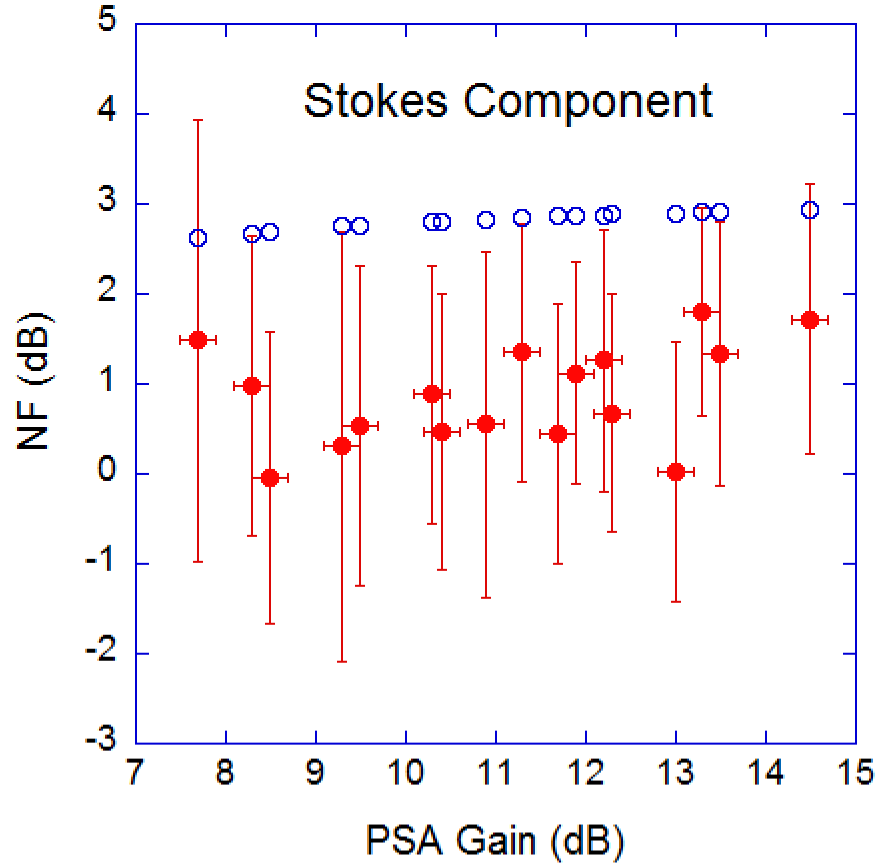


One frame after
IFFT (no average)

Noise Figure Measurement of the Fiber PSA

Lim, Grigoryan, Shin, & Kumar, OFC'2008





NF_{ave} (Anti-Stokes) = (0.42 ± 0.53) dB

NF_{ave} (Stokes) = (0.68 ± 0.59) dB

Proposed Proof-of-Principle Experiment

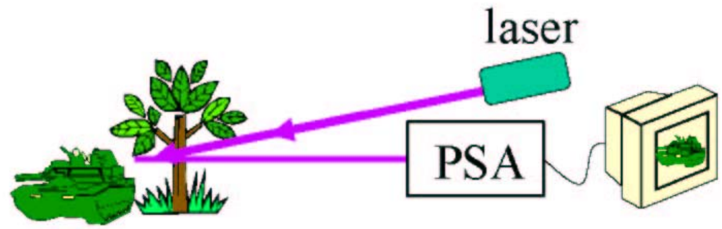
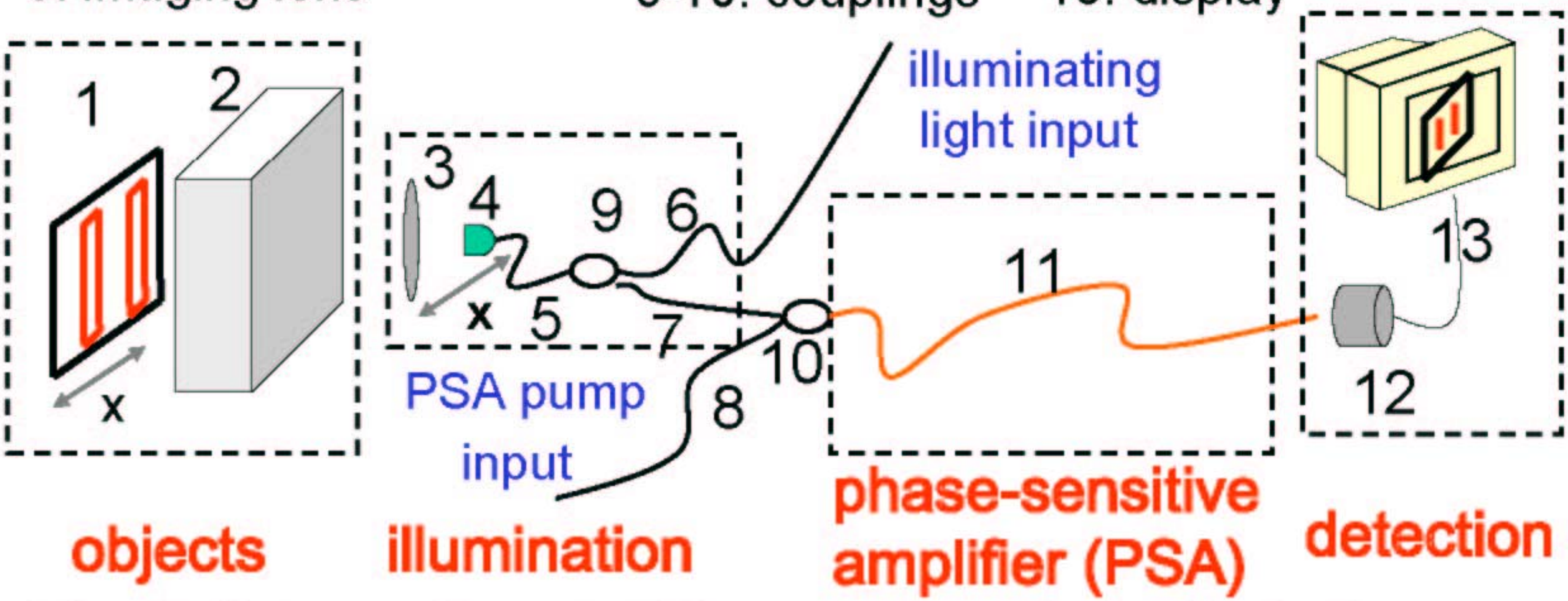
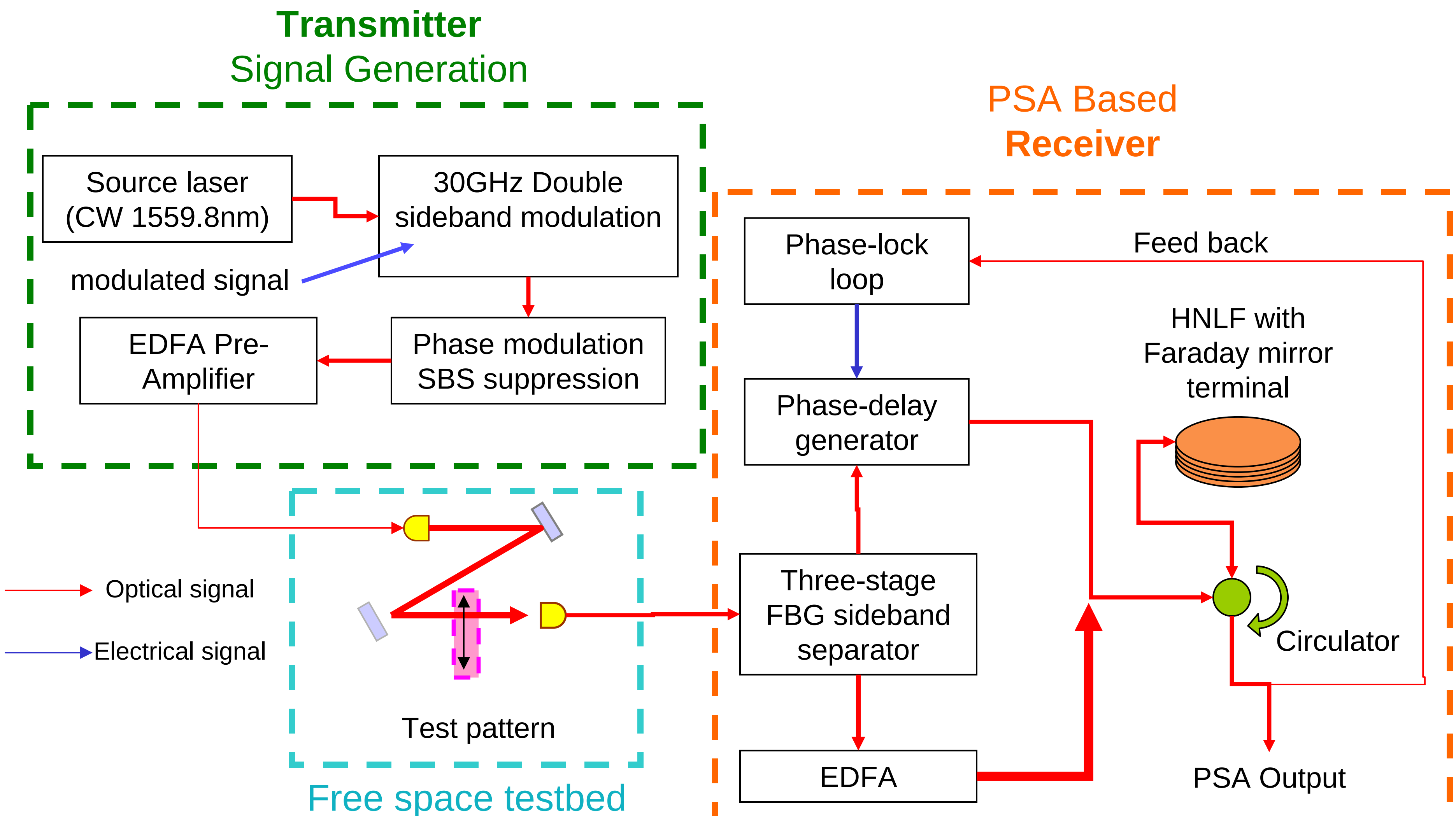


Fig. 1 Cartoon illustrating the real situations where PSA finds useful applications.

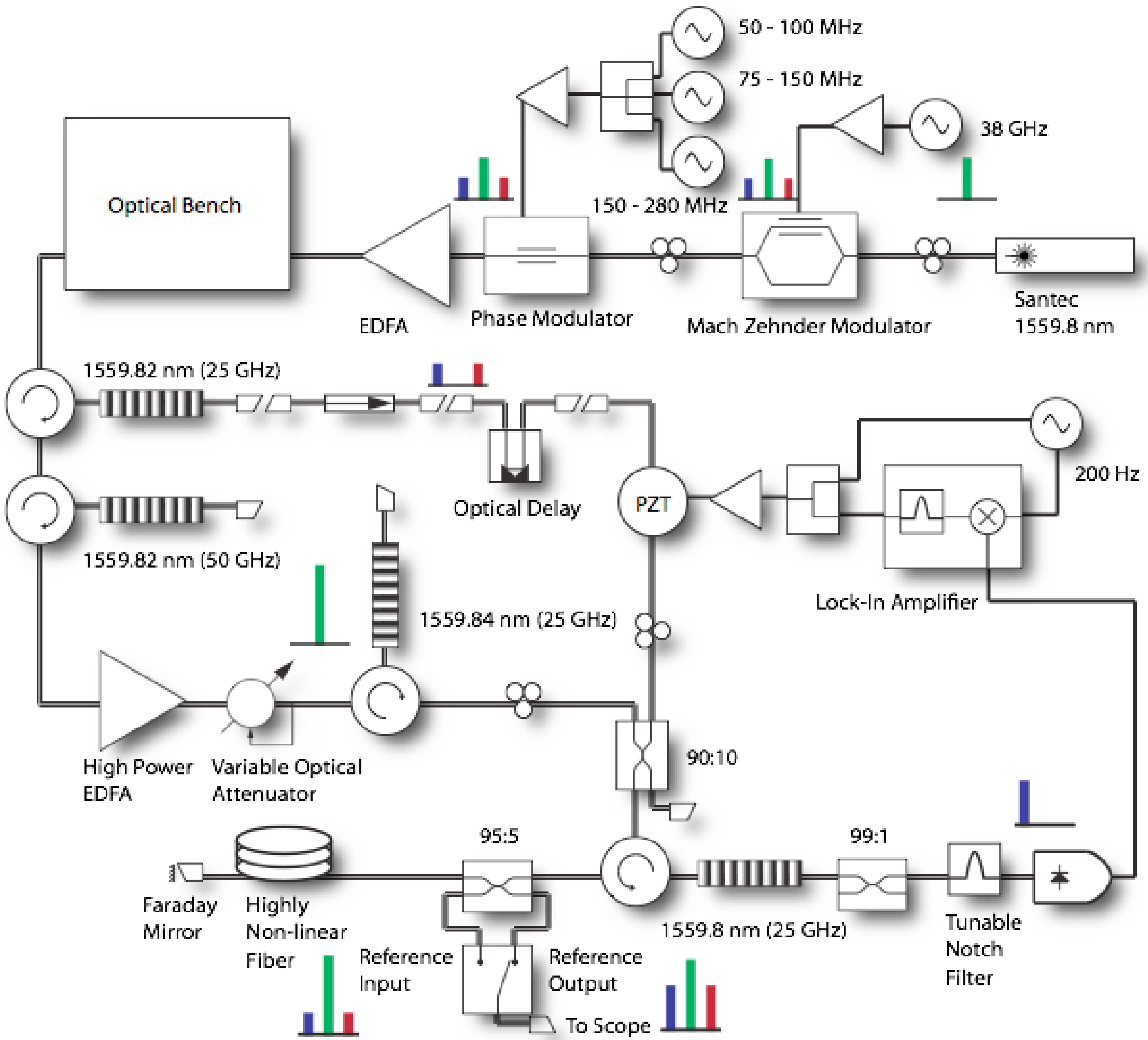
1: object patterns
2: light scattering material
3: imaging lens
4: fiber collimator
5-8: fibers
9-10: couplings
11: PSA fiber
12: photo-detector
13: display



Experiment in Progress

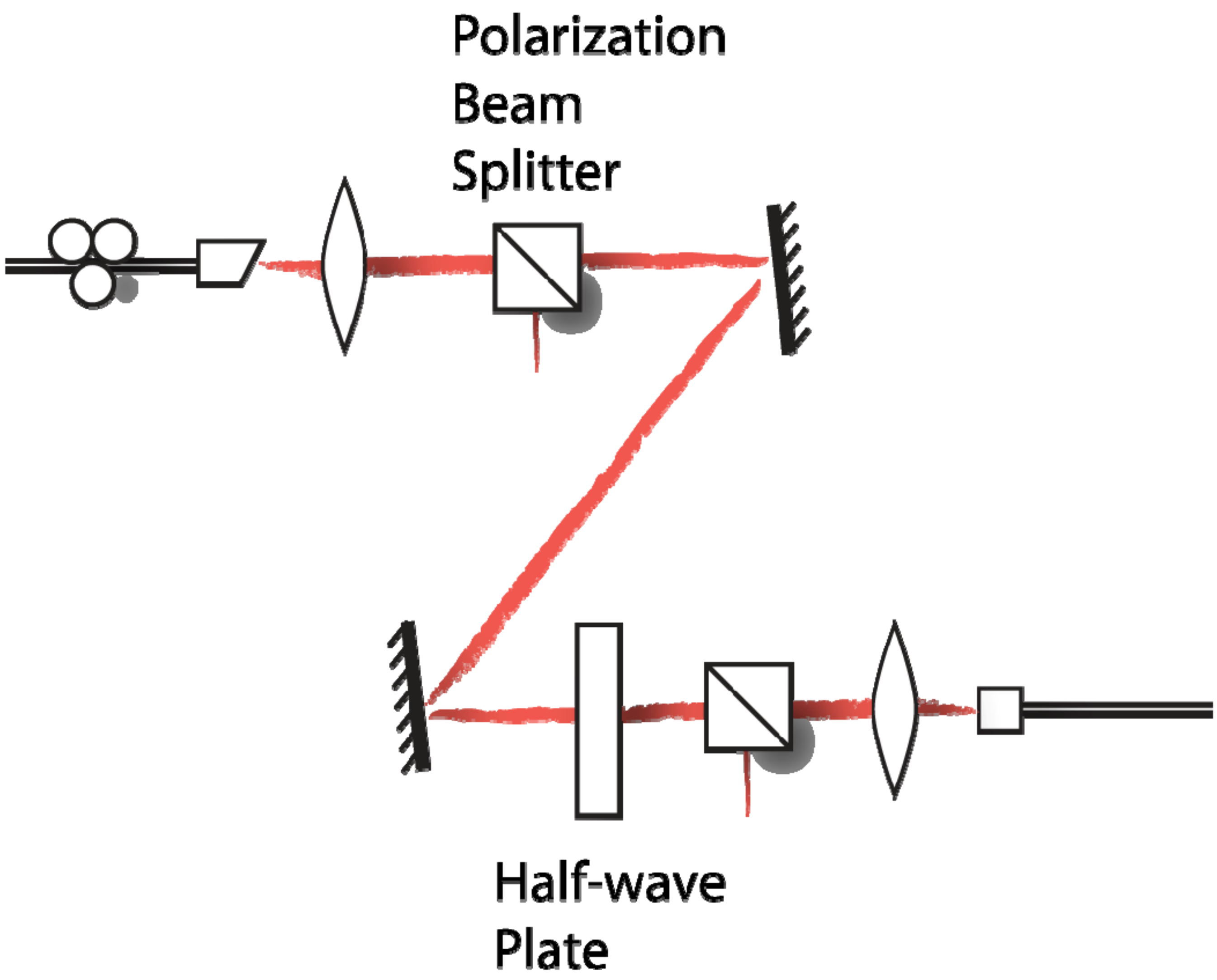


PSA Schematic

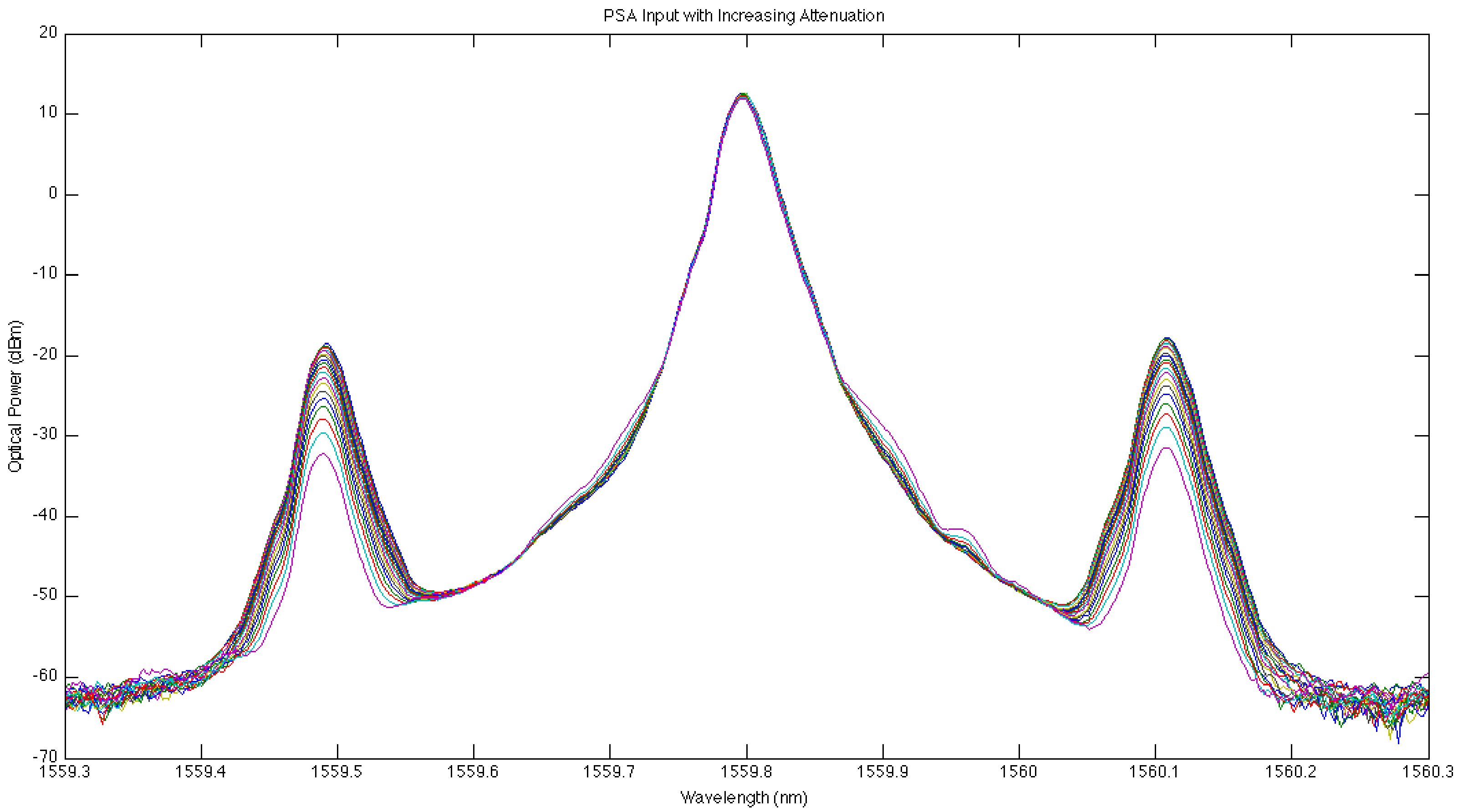


PSA Laboratory

PSA Attenuation Schematic

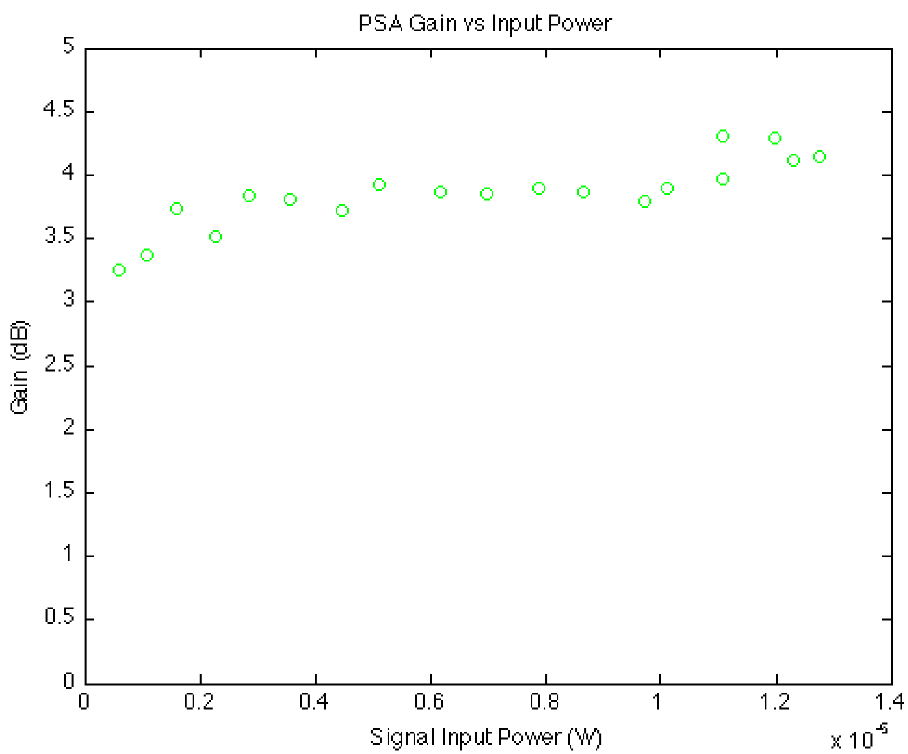


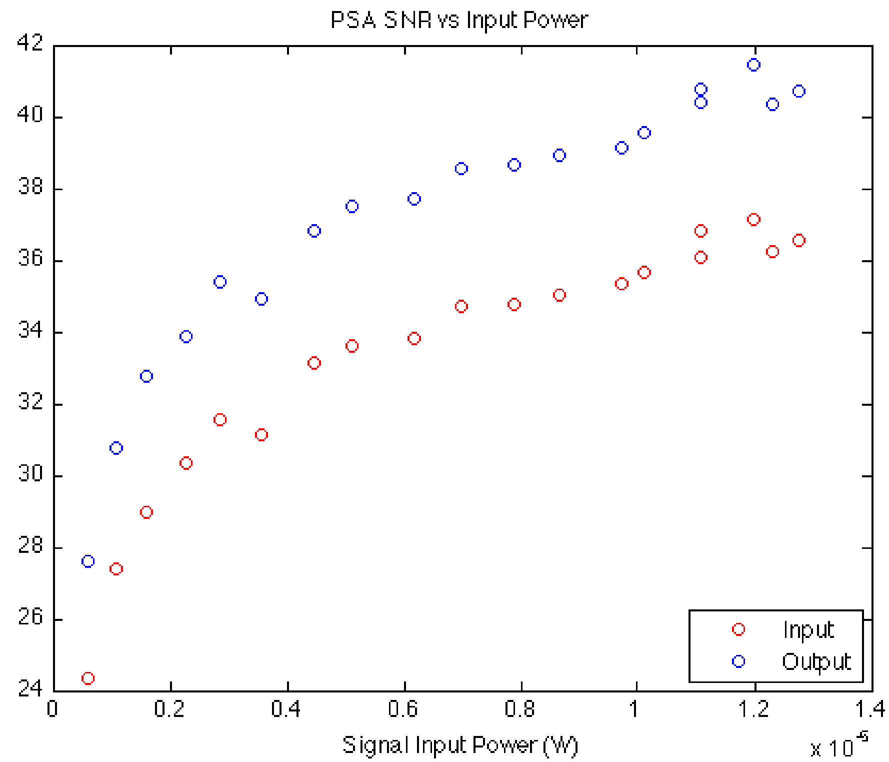
PSA Attenuation Results



- Half-wave plate rotated to achieve 15 dB of attenuation in the signal and idler.
- Pump stays at constant level due to variable optical attenuator.

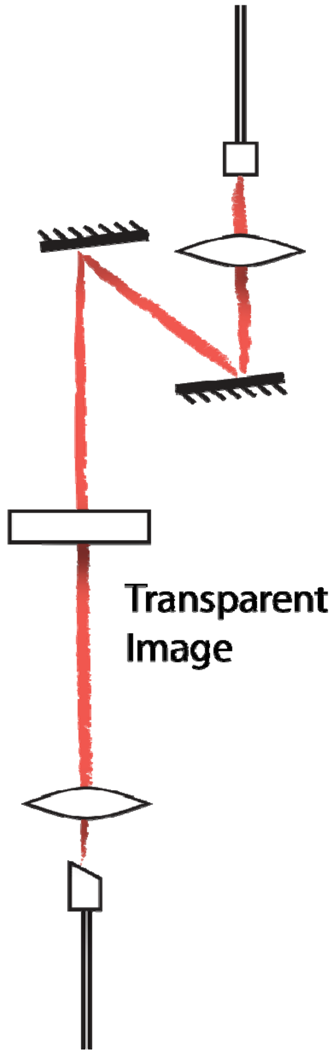
PSA Attenuation Results

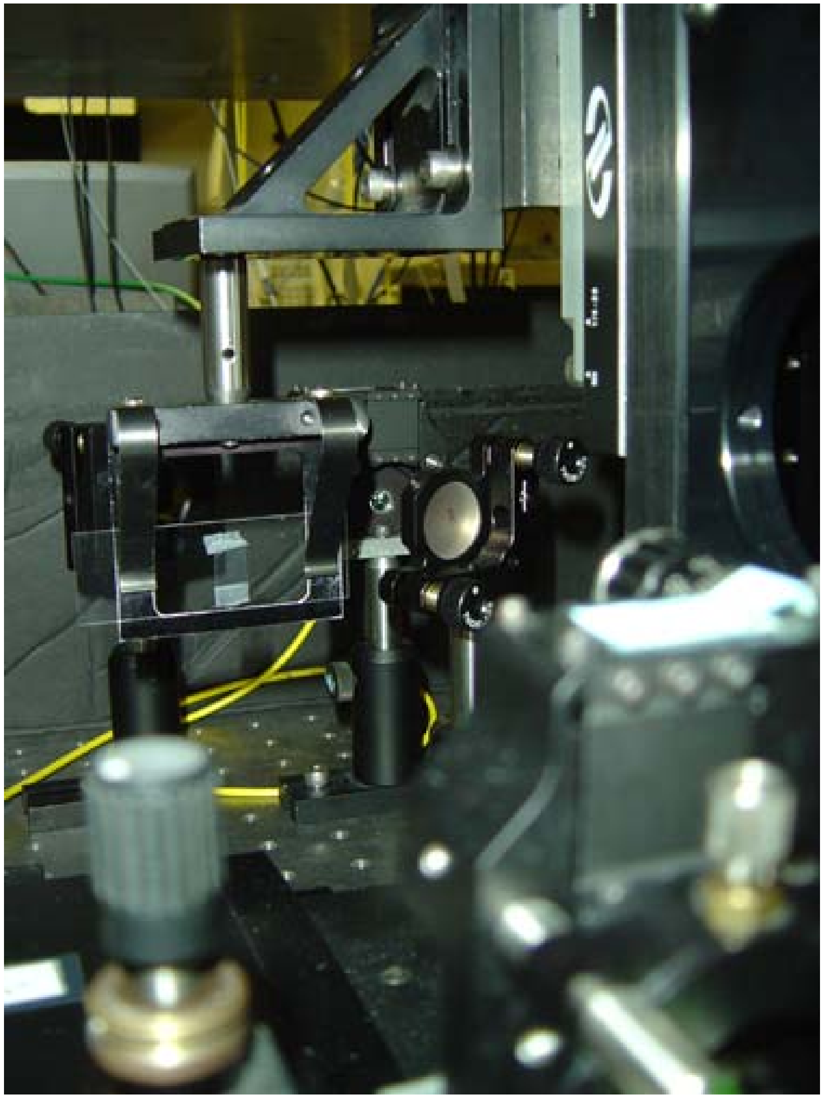




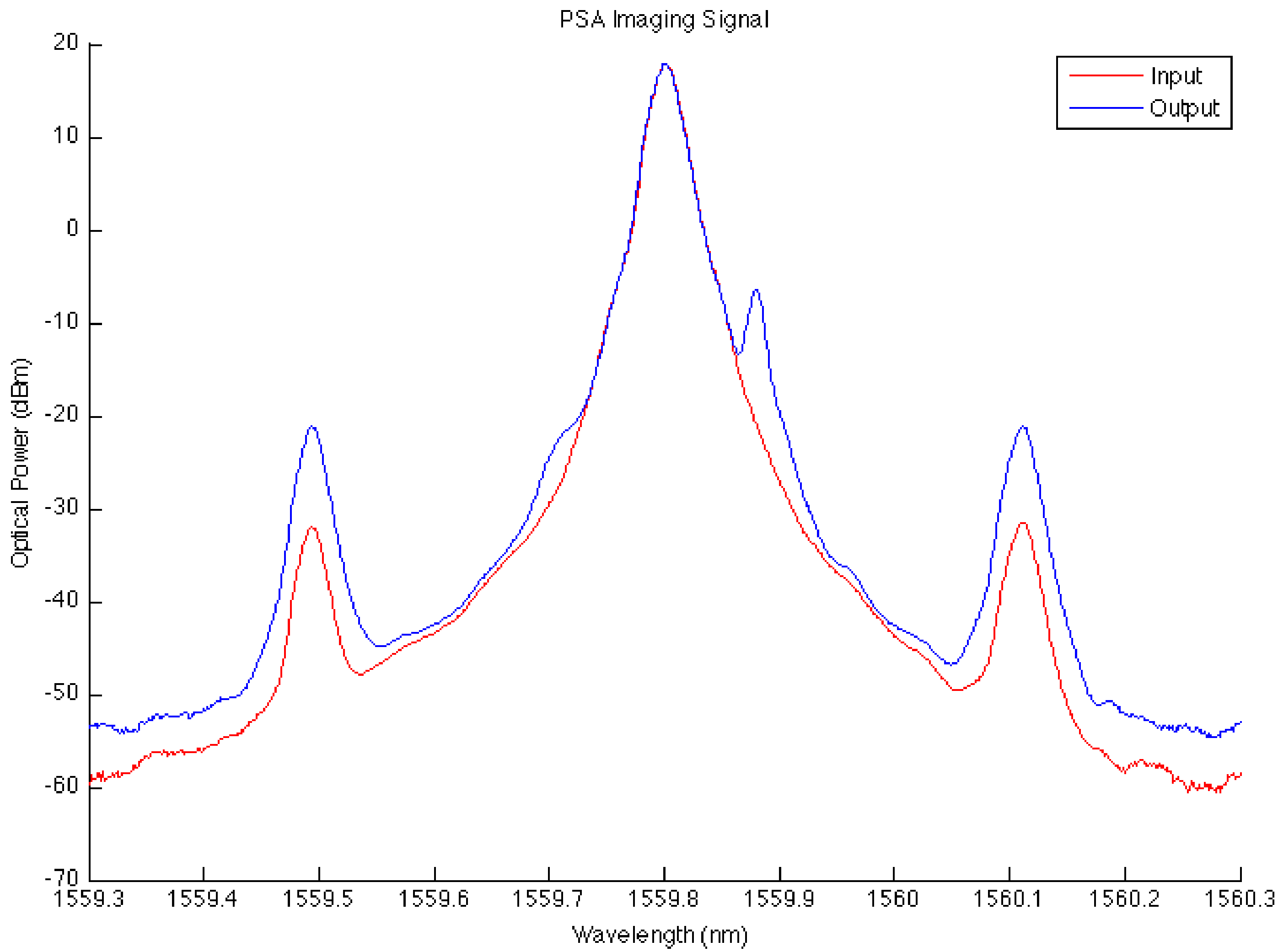
- Gain stays relatively constant over the range of attenuation.
- SNR ratio decreases with increased attenuation.

PSA Imaging Schematic



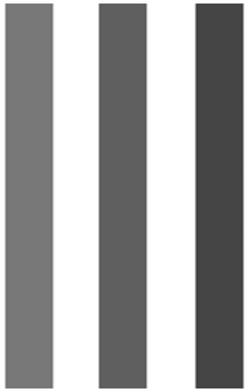


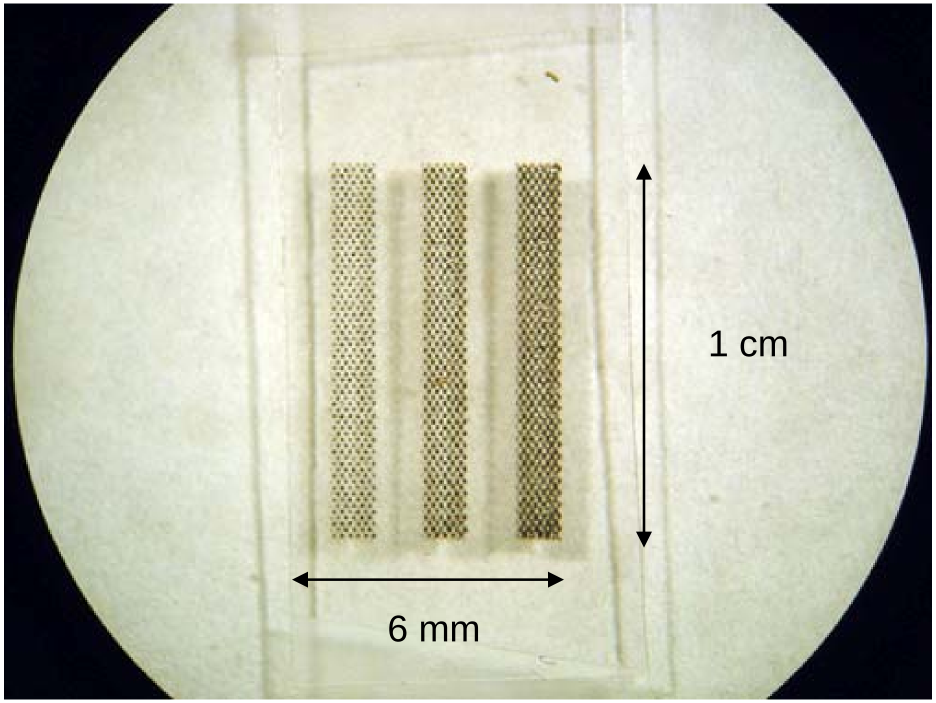
PSA Imaging Signal



- 10 dB Signal Gain
- 20 dB SNR

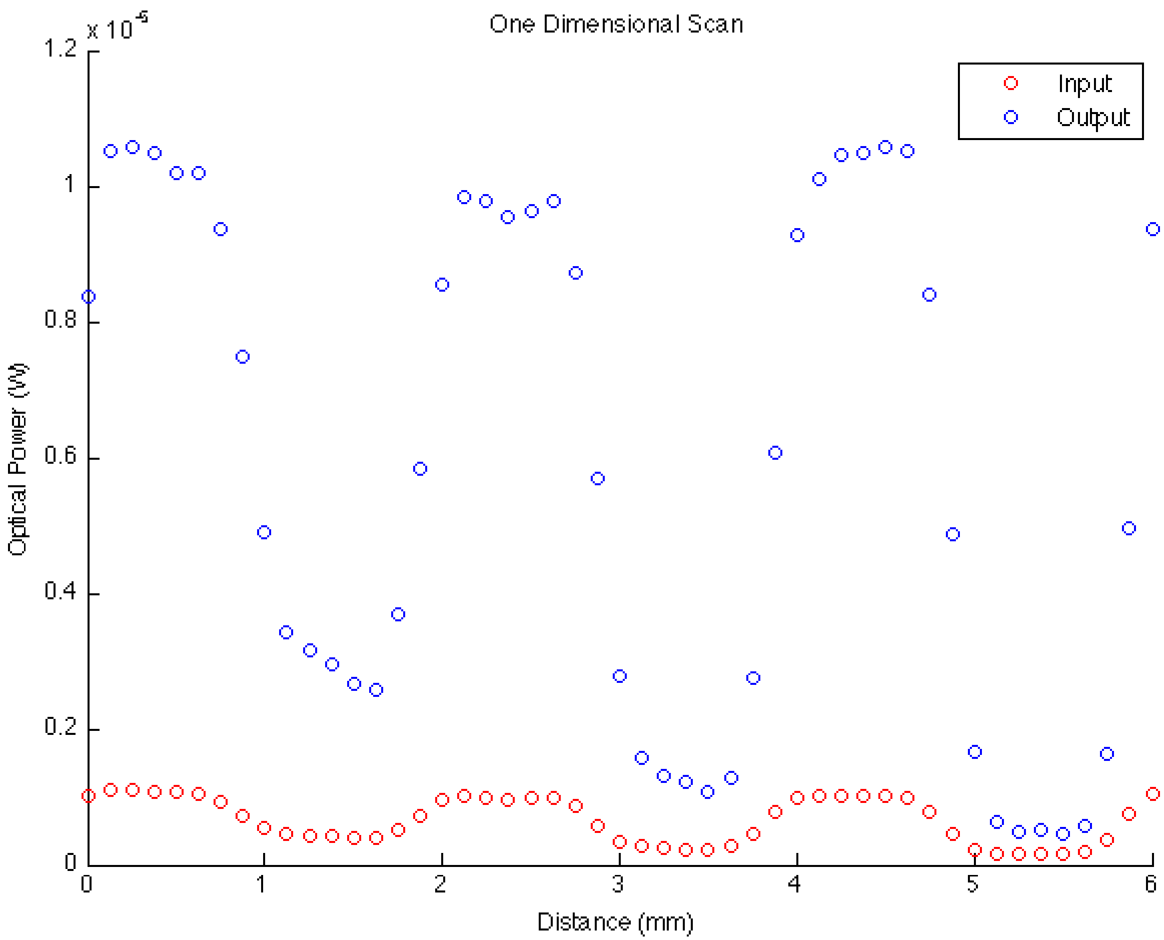
One Dimensional Scan

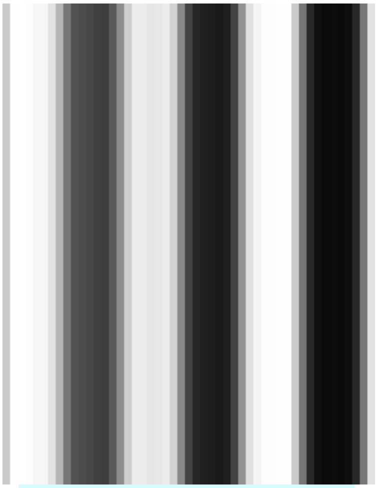




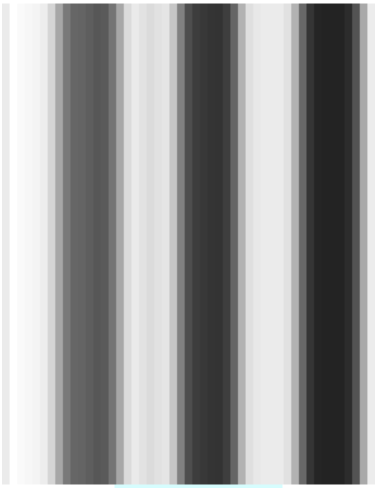
- Three gray bars printed on transparency at 1200 dpi.
- 60%, 70%, 80% gray bars with transparent background.
- Transparency taped and sandwiched between two glass slides.

One Dimensional Scan Results



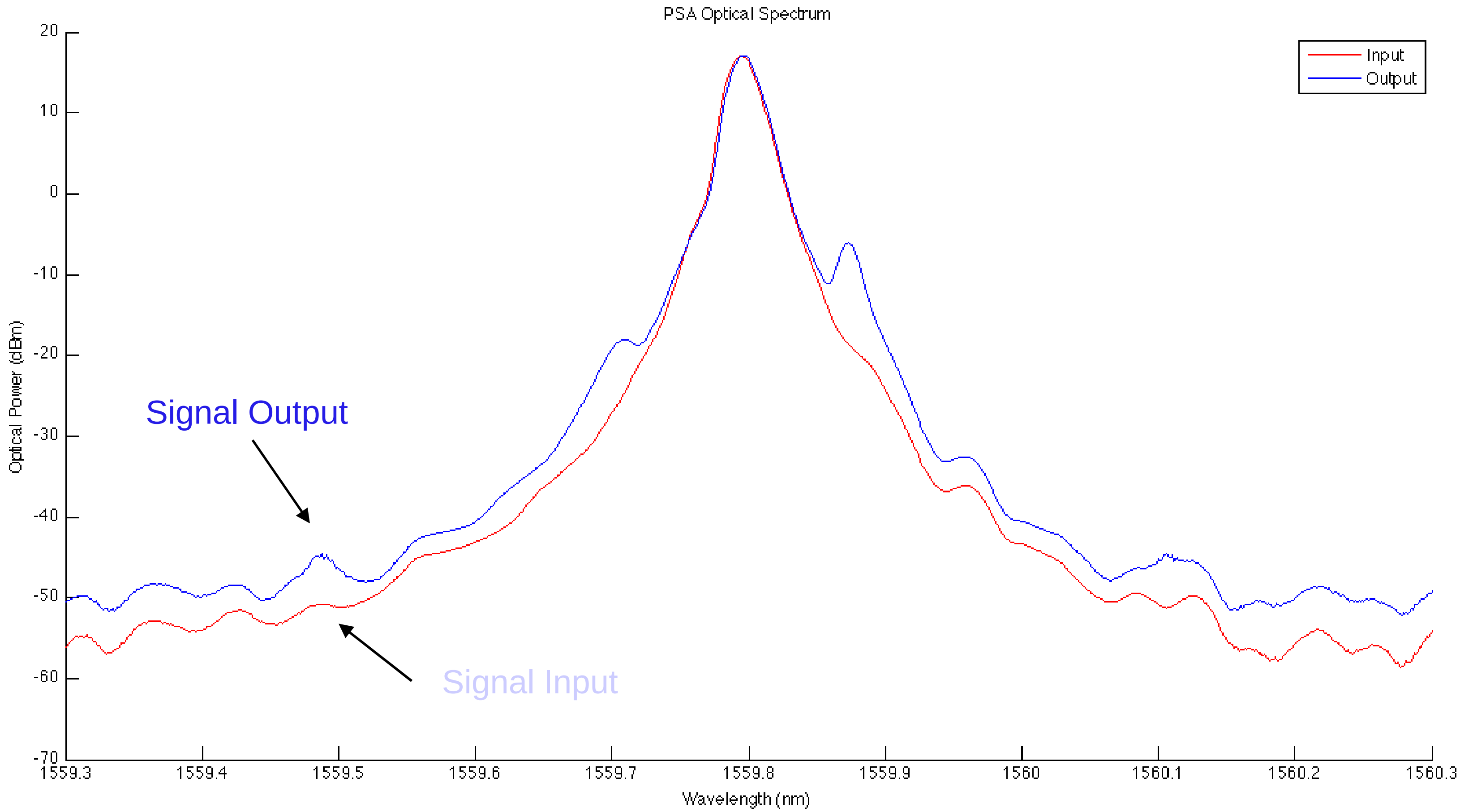


PSA Output



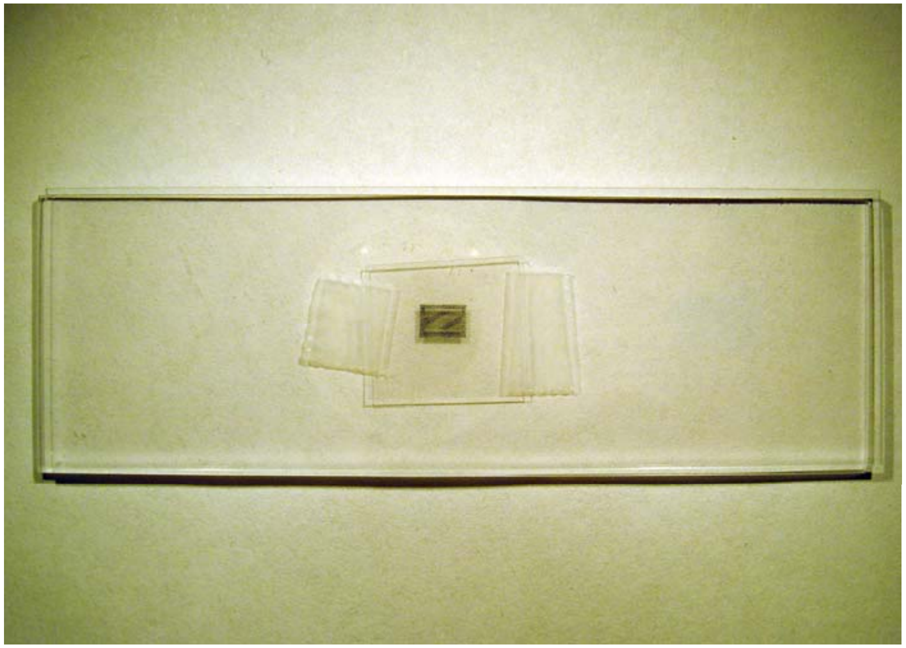
Input

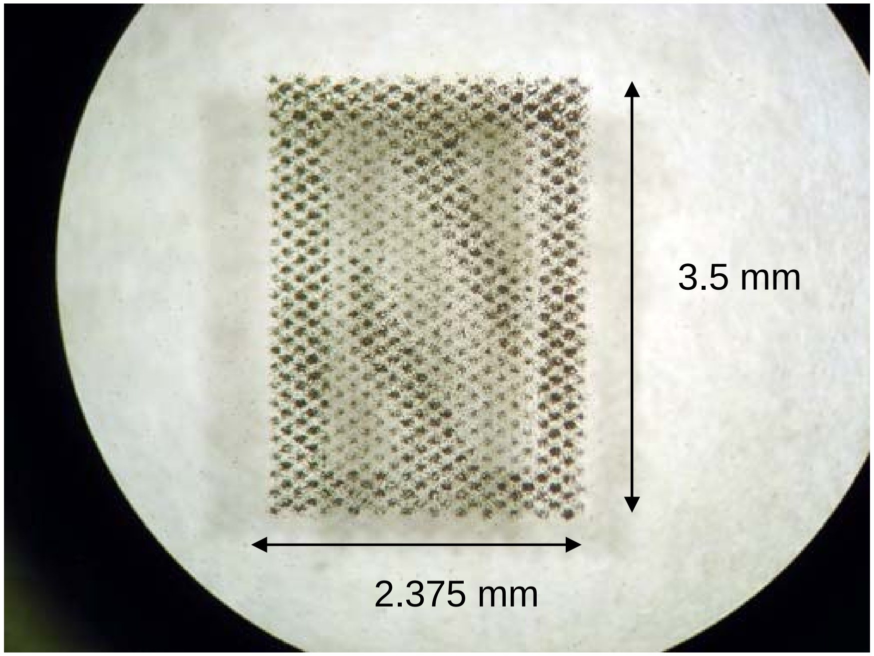
PSA Imaging Decreased Signal



- Low light imaging of target.
- 6 dB Signal Gain
- 1 dB SNR

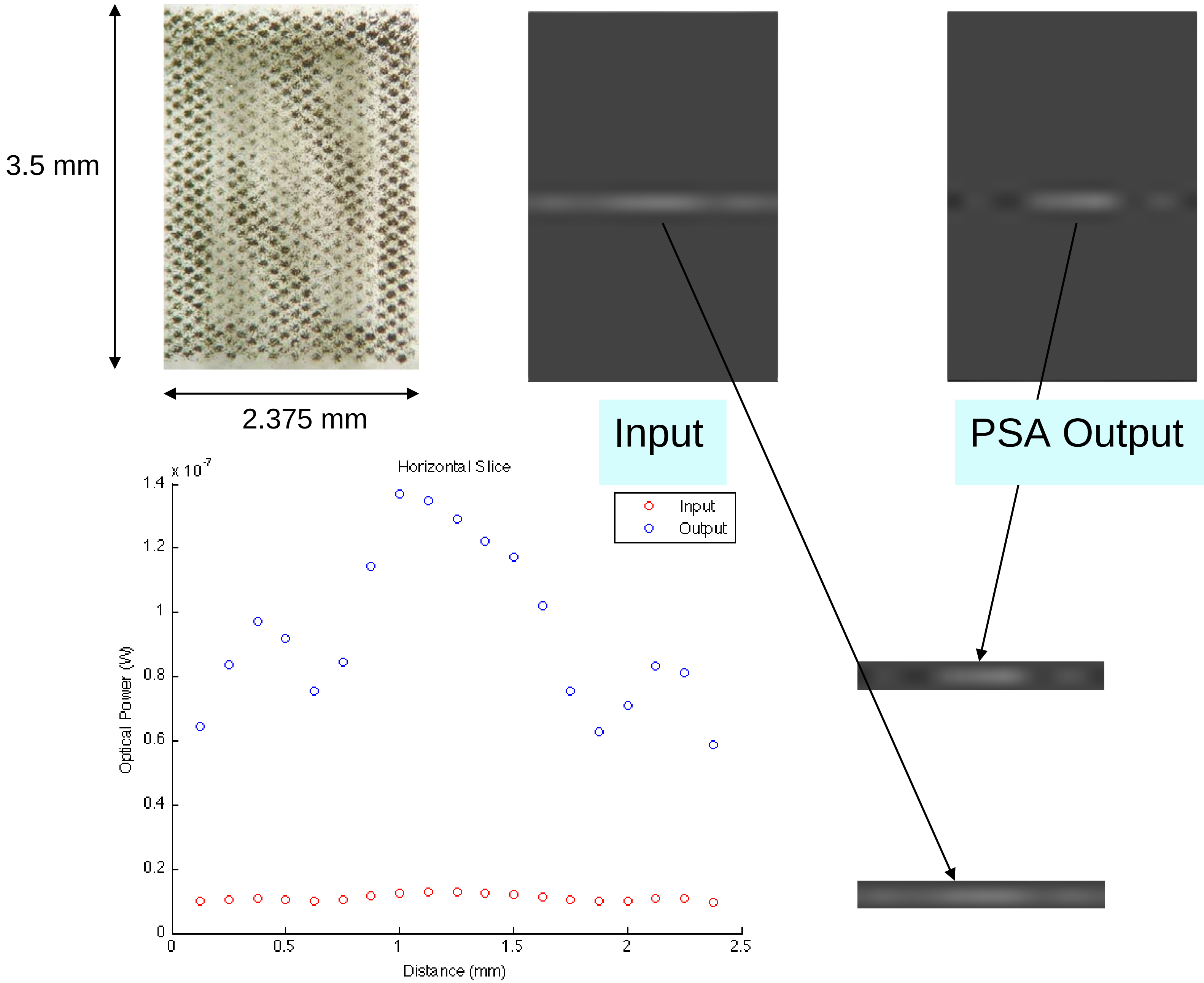
Northwestern 'N' Raster Scan





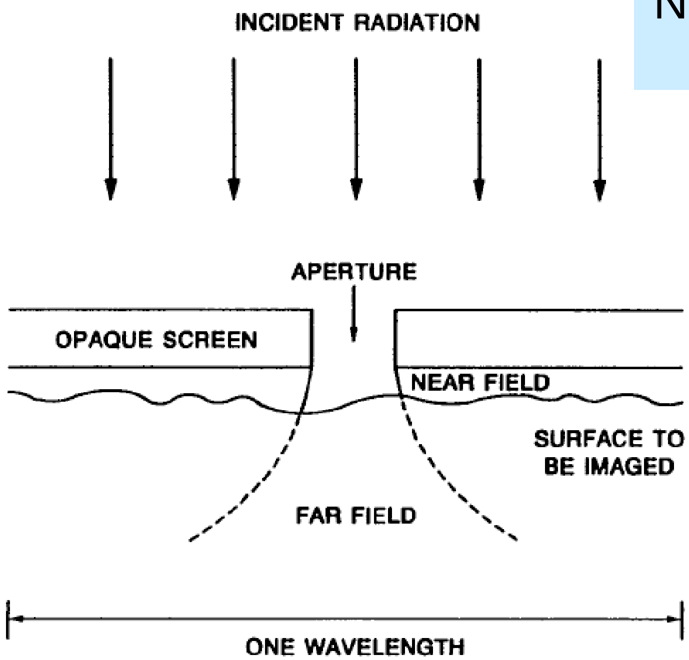
- Northwestern 'N' printed on transparency at 1200 dpi.
- 70% gray scale background with 60% gray scale letter.
- Transparency taped and sandwiched between two glass slides.

Northwestern 'N' Imaging Results

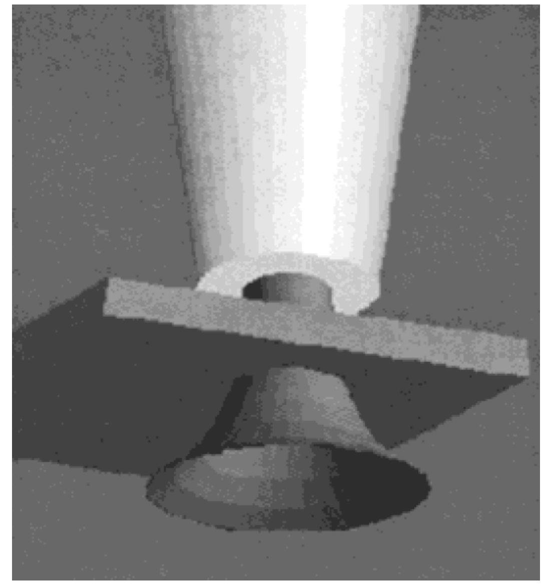


Future Applications

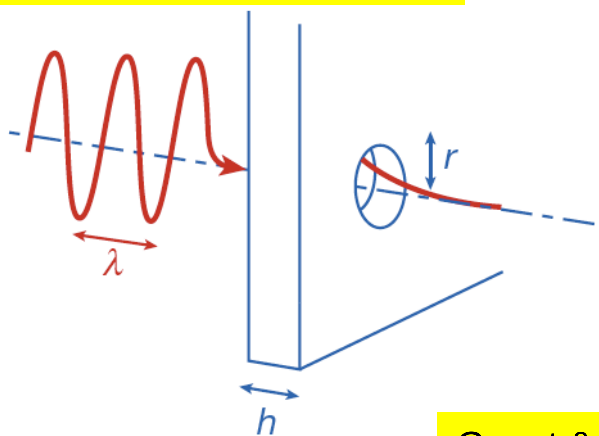
Near-Field Scanning Optical Microscopy (NSOM)

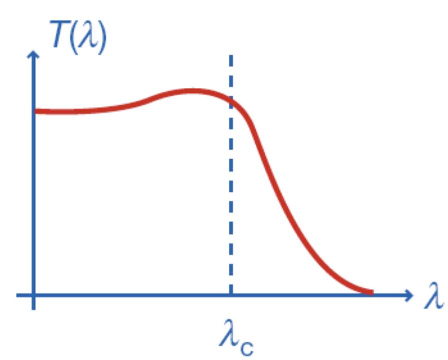


Betzig & Trautman, *Science* **257** pp. 189-195



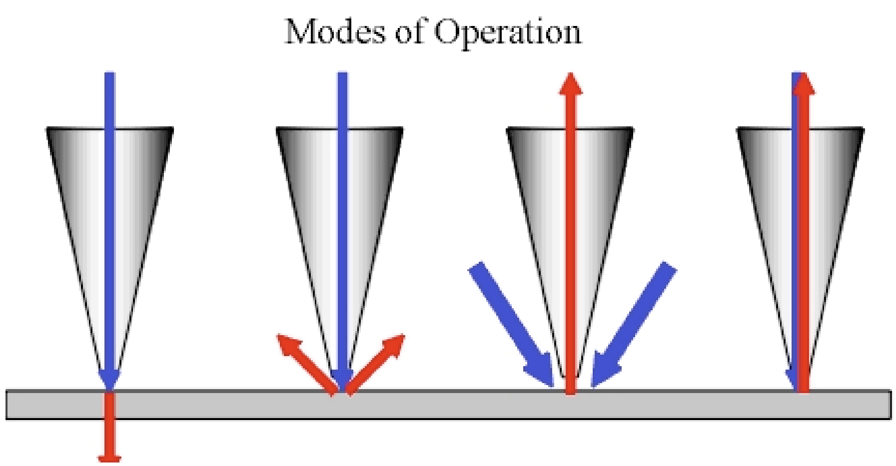
Dunn, *Chem. Rev.* **99** pp. 2891-2927





Genet & Ebbesen, *Nature* **445** pp. 39-45

Typical NSOM Setup



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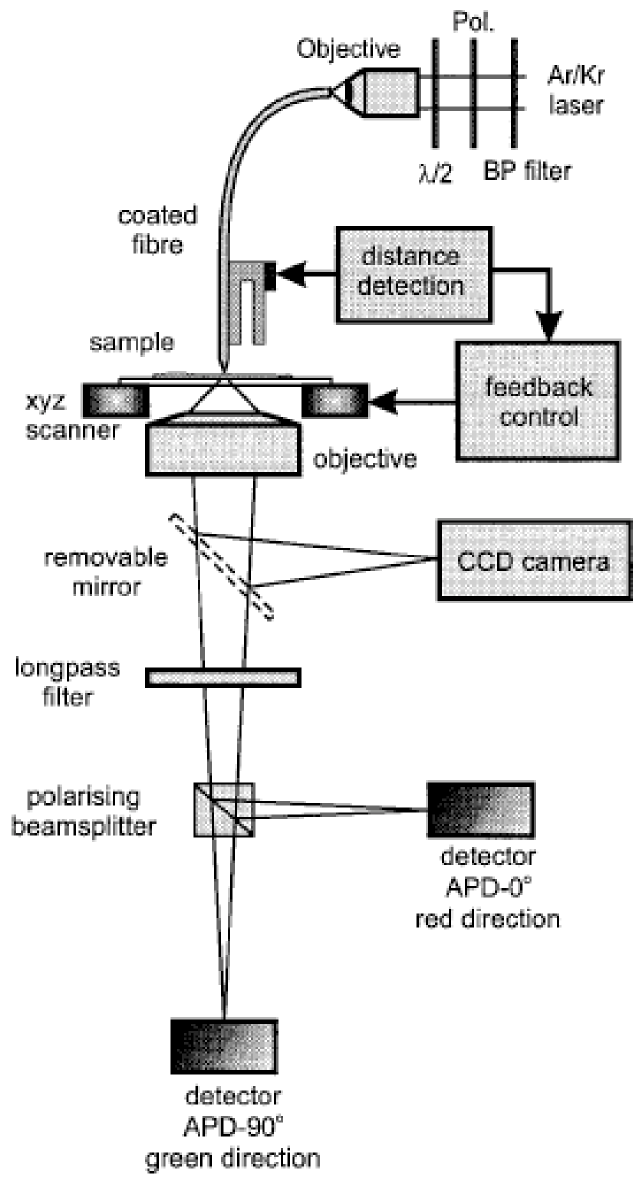
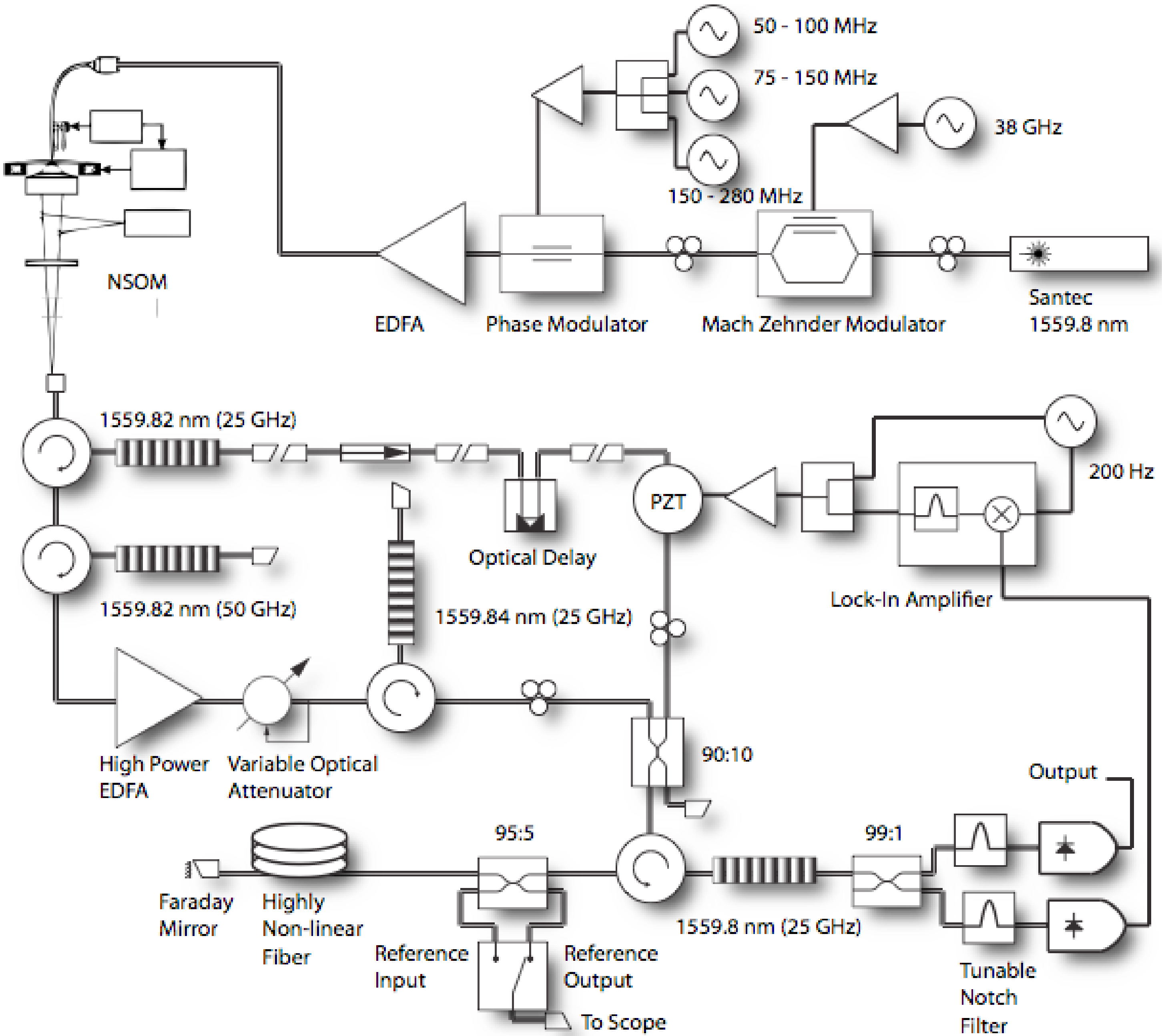
- Transmission
- Reflection
- Collection
- Illumination/Collection



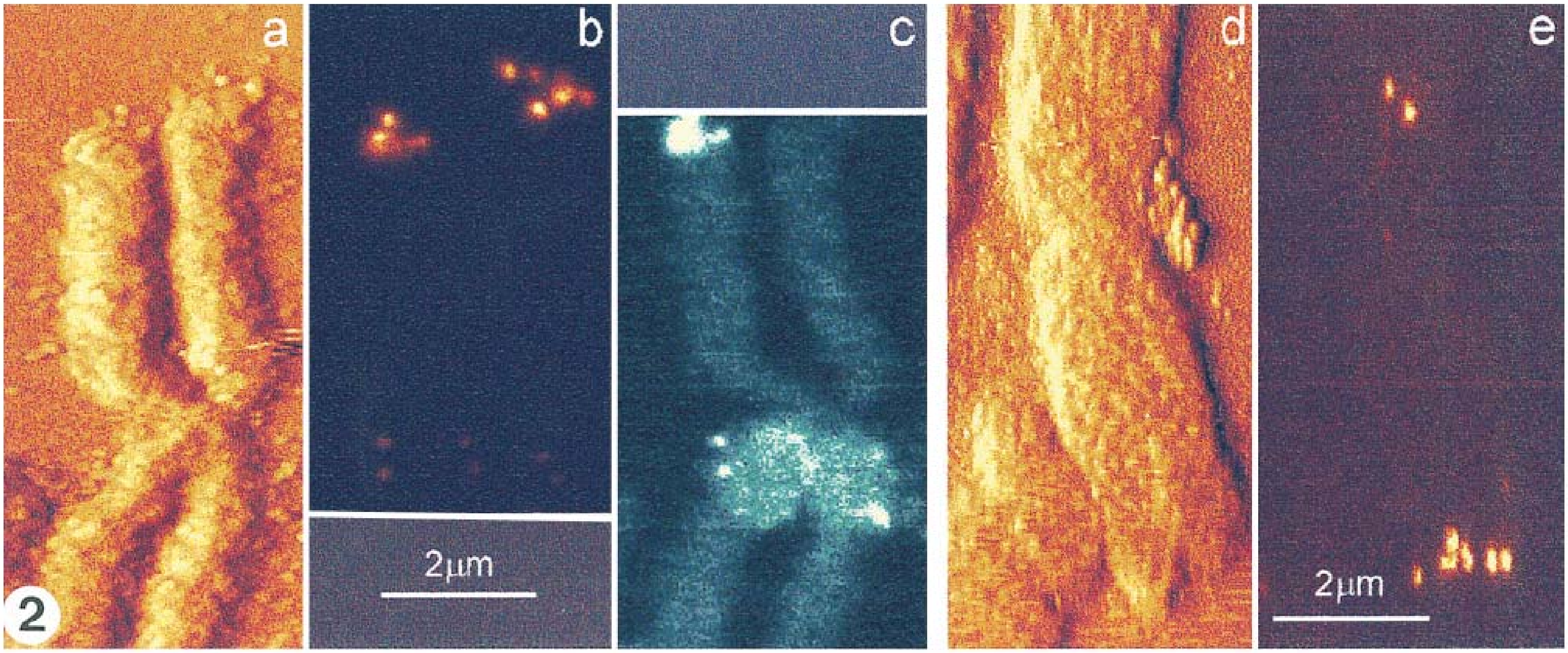
van Hulst, et al. *J. Stuct. Biol.* **119** pp. 222-231

PSA Assisted NSOM



NSOM Examples

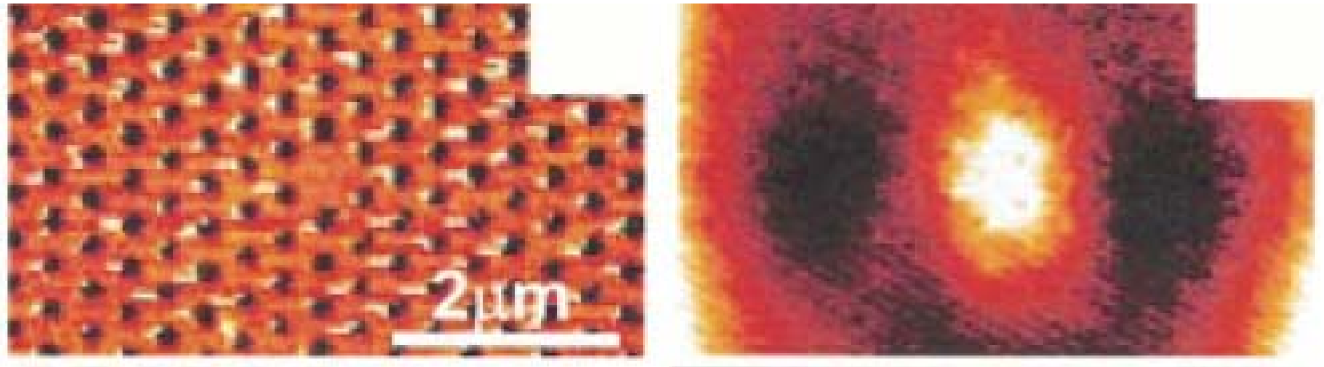
Fluorescence imaging of DNA



van Hulst, et al. *J. Stuct. Biol.* **119** pp. 222-231

NSOM Examples

Photonic crystal nanocavities



Okamoto, et al. *Appl. Phys. Lett.* **82** pp. 1676-1678