Quantum Imaging Technologies: Quantum Laser Radar

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Quantum Laser Radar

Classical or Quantum

Target
Glint / Speckle

Transmitter
Optical Pre-processing
Transmit Optics

Receiver
Optical Post-processing
Receive Optics

Atmospheric Turbulence

Quantum return severely degraded by loss → keep quantum local

Direct
Heterodyne
Homodyne

PIA
PSA
$\chi^{(2)}$
$\chi^{(3)}$

PIA = Phase Insensitive Amplifier
PSA = Phase Sensitive Amplifier
Pictorial View of Amplification of Coherent Input Light

\[ E = X + iY \]

\[ E = X \cos \omega t - Y \sin \omega t \]

Phase-sensitive

\[ \sigma_X^2 = g \sigma_{in}^2 \]
\[ \sigma_Y^2 = g^{-1} \sigma_{in}^2 \]

Phase-insensitive

\[ \sigma_{out}^2 = (2G -1) \sigma_{in}^2 \]
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)
  - \( \text{SNR}_{\text{IN}} = N_s \) (shot-noise limited signal)
  - \( \langle (\Delta N_s)^2 \rangle_\eta = \eta N_s \)
  - \( \text{SNR}_{\text{OUT}} = \eta N_s \)
  - \( \text{NF} = \frac{\text{SNR}_{\text{IN}}}{\text{SNR}_{\text{OUT}}} = \frac{1}{\eta} \)

- **For G > 1**
  - \( \text{SNR}_{\text{IN}} = N_s \) and \( \langle (\Delta N_s)^2 \rangle = N_s \)
  - Output = \( \eta GN_s \). Find \( \langle (\Delta N_s)^2 \rangle_{\eta G} \) from:
    - \( \text{NF} = \frac{\text{SNR}_{\text{IN}}}{\text{SNR}_{\text{OUT}}} = \frac{N_s}{[(\eta GN_s)^2 / \langle (\Delta N_s)^2 \rangle_{\eta G}]} \)
    - …or…
    - \( \langle (\Delta N_s)^2 \rangle_{\eta G} = \text{NF} (\eta GN_s)^2 / N_s = \frac{\langle (\Delta N_s)^2 \rangle_\eta \eta G^2 \text{NF}}{N_s} \)
Simulation of Preamplified Photodetection of Shot-Noise Limited Signals

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

- 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 \( \rightarrow \eta \left[1 + \frac{1 - \eta}{\eta G}\right] \langle (\Delta N_s)^2 \rangle_\eta \)
  - PIA \( \rightarrow \eta \left[2\left(1 - \frac{1}{G}\right) + \frac{1}{\eta G}\right] \langle (\Delta N_s)^2 \rangle_\eta \)
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 x 256 image

Add noise per spatial frequency:

\[
\langle (\Delta N_s)^2 \rangle_\eta \rightarrow \text{When } G = 1
\]

\[
\eta \left[ 1 + \frac{1 - \eta}{\eta G} \right] \langle (\Delta N_s)^2 \rangle_\eta \rightarrow \text{For PSA}
\]

\[
\eta \left[ 2(1 - 1/G) + \frac{1}{\eta G} \right] \langle (\Delta N_s)^2 \rangle_\eta \rightarrow \text{For PIA}
\]

Soft Gaussian Frequency Filter

FFT

+ 

\[\text{Add noise per spatial frequency:}\]

\[\text{When } G = 1\]

\[\text{For PSA}\]

\[\text{For PIA}\]

IFFT

Result
Results: Averaged over 100 Frames
\[ \eta = 0.8, \ G = 10 \text{ dB} \]

- Target (no average)
- No gain
- PSA gain
- PIA gain
- One frame after IFFT (no average)
Results: Averaged over 100 Frames
\[ \eta = 0.3, \; G = 10 \text{ dB} \]

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

\[ \text{NF}_{\text{ave}} \text{ (Anti-Stokes)} = (0.42 \pm 0.53) \text{ dB} \]

\[ \text{NF}_{\text{ave}} \text{ (Stokes)} = (0.68 \pm 0.59) \text{ dB} \]
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  

objects  
illumination  
PSA pump input  
phase-sensitive amplifier (PSA)  
detection  
illuminating light input
Experiment in Progress

Transmitter
Signal Generation

Source laser (CW 1559.8nm)

30GHz Double sideband modulation

modulated signal

EDFA Pre-Amplifier

Phase modulation
SBS suppression

EDFA

Phase-delay generator

Three-stage FBG sideband separator

PSA Output

PSA Based
Receiver

Phase-lock loop

HNLF with Faraday mirror terminal

Optical signal

Electrical signal

Test pattern

Free space testbed

Feed back

Circulator

PSA Output
PSA Schematic
PSA Attenuation Schematic

Polarization Beam Splitter

Half-wave Plate
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

One Dimensional Scan

Optical Power (W)

Distance (mm)

Input

Output

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.
Future Applications

Near-Field Scanning Optical Microscopy (NSOM)


Typical NSOM Setup

- Transmission
- Reflection
- Collection
- Illumination/Collection


www.nanonics.co.il
PSA Assisted NSOM
NSOM Examples

Fluorescence imaging of DNA

NSOM Examples

Photonic crystal nanocavities