Novel Designs for Single Photon Detection Based on Quantum and Nanoscale Systems

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Single Photon Detection is a Critical Enabling Technology

- Rare event detection (e.g., dark matter, neutrinos, electron-proton decay)
- Quantum Key Distribution
  Secure communications
- Single Photon LIDAR
  3D terrain and infrastructure mapping
- Biological imaging
  Neuronal processes mouse brain

Vallone et al, PRL 2015
Castello et al, Nat. Methods 2019
Exquisite Performance for Single Photon Detection

Superconducting Nanowire

Avalanche Photodiode

Photomultiplier tubes

What are the fundamental limits to single photon detection?

Are there inherent trade-offs?

What is the best architecture, and how do we design it?
Plan for Presentation

- New general modeling framework
- Novel designs for Photon Number Resolution
- Experiments with molecular and nanoscale systems
- Novel designs for Energy Resolving Detectors
General Modeling Framework from Quantum Optics

- Framework can handle...
  - General light field
    - Multiple photons
    - Multiple modes
    - Multiple profiles
    - Different types of materials
      - Atoms
      - Molecules
      - Solids
  - Complex intermediate states
    - Multiple states
    - Coherent and incoherent
    - Broad range of amplification processes

- Generates performance metrics
- Is practical

General Modeling Framework

\[ \Pi(t) = \text{Tr}_\text{LIGHT} [\mathcal{K}(t, t_0) \hat{\rho}_\text{LIGHT}(t_0)] \]

Measurement outcome (e.g. probability)

Depends on detector configuration

Incoming field state

From this, can get performance metrics:

**Efficiency:** \( \Pi(t) \)

**Dark count rate:**
\[
\frac{\Pi(0; t_m)}{t_m} + \frac{1}{2t_m} \text{erf}\left(2\sqrt{kt_m\Delta I_{hit}}\right)
\]

**Jitter:**
\[
\frac{d\Pi(t)}{dt}
\]
General Modeling Framework

\[ \Pi(t) = \text{Tr}_{\text{LIGHT}} \left[ \mathcal{K}(t, t_0) \hat{\rho}_{\text{LIGHT}}(t_0) \right] \]

How to get this?

Stochastic quantum master equation for density matrix

\[ \dot{\rho}(t) = \nu_{\text{sys}} + \nu_{l-m} + \nu_{\text{amp}} \]

\[ \hat{\rho}_{\text{MATTER}}(t) = \text{Tr}_{\text{LIGHT}} \left[ \mathcal{P}(t, t_0) \hat{\rho}_{\text{TOT}}(t_0) \right] \]

System Architecture

\[ I \sim \int \hat{\rho}_{\text{MATTER}}(t) dt \quad \text{Measurement outcome} \quad \Pi(t) \]
Fully Quantum Coherent Detector

- Measurement backaction quenches absorption
- Detector has limited performance

Important Result

When \[ \gamma = \Gamma \] and \[ \gamma^2 + \Gamma^2 \gg 1/\sigma_E \]

Perfect detection can exist: 100\% efficiency, no additional jitter

Extended Systems

New condition for ideal detection: \( \gamma = \Gamma + \zeta \)

Photon Number Resolution

Simple array: 
(\text{efficiency})^N 
(0.95)^{10} = 60\%

Even worse than this because two photons can hit the same pixel

New approach:

(1) Collective interaction of nanosensors with photon field

(2) Designed energetics and kinetic pathways

Significant improvement by structuring the system
Forster energy transfer
~ picoseconds
~ 100% efficiency

Experiments Towards Novel Designs

Devices with CNT arrays

Devices with individual CNT

Bergemann & Léonard, Small (2018)
Bio-Inspired Design

Retinal molecule

Cis

Trans

Retinal molecule

13.18 D

11.60 D

1

0

Γ

C

χ
Functionalized Carbon Nanotube Transistors

Gain $> 10^4$ at room temperature
$C_{60}/\text{CNT}$ System Achieves Ultrahigh Gain at Room Temperature

$C_{60}$/CNT System Achieves Ultrahigh Gain at Room Temperature

- Responsivity $> 10^8$ A/W
- Gain $> 10^8$
- Sensitive to UV, visible, and IR

Detection of 40-50 photons per CNT at room temperature

Response to Weak Light Pulse

Device with only one CNT

Detection of 200 photons at room temperature

Bergemann & Léonard, Small (2018)
**P3HT/CNT System Even More Sensitive**

Gain > $10^9$ at room temperature
Detection of 8-13 photons/CNT

Frequency-Resolving Single Photon Detection

Example applications for high-energy physics

Reconstruction of photon trajectories in liquid scintillator detectors

Cosmology: resolving emission lines from galaxies

The DESI Experiment Part II: Instrument Design

High Efficiency
Low jitter
High Frequency resolution
Subwavelength Elements Collectively Interacting with Photon Field

Existing approaches:

MUSE integral field spectrograph
European Southern Observatory

SNSPDs

New approach:

100% efficiency, minimal jitter

Must still account for collective interaction – the number/optical couplings of elements must be tuned together to ensure efficiency at each frequency
Frequency-Resolving Single Photon Detection

- High efficiency
- Low jitter
- High frequency resolution

Young, Saroar, Léonard, *arXiv*. 
Summary

• New modeling framework allows evaluation and design of photodetectors
• Novel designs emerge with improved performance
• Testing of these designs has already led to ultrahigh gain at room temperature

Future Work

• Develop approaches to reduce noise in experimental systems
• Test new molecule/nanotube combinations
• Integrate with CMOS