Detector Tomography of Superconducting Single Photon Detectors

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Goal: investigate SSPD fundamentals

- Nanodetector
- Multiphoton excitations
- Detector tomography
Multiphoton excitations

- Observed in 2001 [1], but considered a curiosity
- We claim: important experimental tool:
  - Enhanced dynamic range
  - Probe with multiple energies in a single experiment

How to study multiphoton excitations?

• Exist in meander, but suppressed due to geometry

• Furthermore: meander has:
  – Bends
  – ‘Constrictions’

• Fundamental study, so efficiency not an issue
Our sample: nanodetector

- One active point, 150, 220 nm wide NbN on GaAs (5 nm)
- Simple geometry
- Few fabrication errors
- Several multiphoton processes at once
Detector tomography

- Method to measure strength of multiphoton processes
- Gives probability that detector responds to \( N \) photons

\[
P(\text{detection}|\text{Intensity}) = P(\text{detection}|\# \text{ photons})
\]

\[
P(\# \text{ photons}|\text{Intensity})
\]
Why detector tomography?

- Fundamentals: Agnostic description
- Applications: Complete description

SSPD modeling:
1) Efficiency
2) Dark counts
3) Constrictions
4) Varying efficiency over active area
5) Effects of cavity
6) ???
Why detector tomography?

- Fundamentals: Agnostic description
- Applications: Complete description

Detector tomography:

\[ \rho_i : \text{probability of click given } i \text{ photons} \]
How to do detector tomography

- Measure counts vs input intensity
- Response to $i$ photons given by $p_i$
- Treat linear efficiency separately, but as free parameter

$$R(N) = e^{-\eta N} \sum_i p_i \frac{(\eta N)^i}{i!}$$

Renema et al, Optics Express 2012
Detector Tomography

- Measure counts vs input intensity
- Response to $i$ photons given by $p_i$
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\[
R(N) = e^{-\eta N} \sum_i p_i \frac{(\eta N)^i}{i!}
\]

Renema et al, Optics Express 2012
Complete tomography

• 1, 2 photon processes present

\[ R(N) = e^{-\eta N} \sum \frac{(\eta N)^i}{i!} \]
Complete tomography

- 1, 2 photon processes present
- Usual method $R = (\eta N)^i$ restricted to $\eta N \ll 1$, lowest $i$
Now repeat this many times

- For each current, vary the input power
- From the power dependence, reconstruct which photon processes are present
Result from tomography

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig1}
\caption{Result from tomography graph.}
\end{figure}
We find: linear efficiency is independent of bias current.

This is a result, not an assumption (agnostic).

Number consistent with overlap x absorption.

Tomography code available, see also Renema et al, Optics Express 2012.
Result from tomography

• $P_i$ internal response of the detector

• Independent of absorption, independent of incoupling

• There is more going on than linear efficiency!

Tomography code available, see also Renema et al, Optics Express 2012
Multiple wavelengths

![Plot of multiple wavelengths](image-url)

- Detection probability
- Bias Current $I_b$ (uA)
- Wavelength (nm): 1500, 1300, 1000
- Photon number: 1, 2, 3, 4
Interchange energy/current

QP conversion is linear

- No dependence on initial number of photons, only energy
- Excitation insensitive to details of how you made it
- Detector is an energy detector

\[ \text{Renema et al, Phys Rev B 87, 174526 (2013)} \]
Universal curve

Detection probability $p_n$

Renormalized bias current $(I_b + 2.9(\mu A/eV) \times E)$
Universal curve

- $R(I, \lambda, N) = R(I + \gamma E)$ with $E = N^*hc/\lambda$
- Goes beyond measuring edge of the plateau region

Renema et al, Phys Rev B 87, 174526 (2013)
Universal curve

- Fluctuation-assisted scales in the same way as plateau response
- Challenge for theorists: explain this curve

Renema et al, Phys Rev B 87, 174526 (2013)
Result on 220 nm detector

![Graph showing bias current vs photon energy](graph_url)

- **Bias current $I_b$ (µA)**
- **Photon energy (eV)**

Legend:
- 1 photon
- 2 photons
- 3 photons
- 4 photons
- 5 photons
- 6 photons


Result on 220 nm detector

![Graph showing bias current vs photon energy for different photon counts](image)

- **Bias current** $I_b$ (µA)
- **Photon energy** (eV)

Legend:
- **1 photon**
- **2 photons**
- **3 photons**
- **4 photons**
- **5 photons**
- **6 photons**

Multiphoton-only region
Extreme dynamic range

- 10.8 eV: 
  \[ \lambda_{\text{eff}} = 115 \text{ nm} \]
- X-UV: not available with open-beam setup

![Graph showing bias current (\(I_b\)) vs. photon energy (\(E\)) with different data points for 1 to 6 photons.

- 1 photon
- 2 photons
- 3 photons
- 4 photons
- 5 photons
- 6 photons

Legend:
- 1 photon
- 2 photons
- 3 photons
- 4 photons
- 5 photons
- 6 photons

Extreme dynamic range

- Photon regimes overlap -> no stitching errors
Single experiment

- Within single experiment 50 nA errors
- Allows for extremely accurate comparison with theory
Comparison with theory

• We find: $I = I_0 + \gamma E$
• We find: $I_0 \neq I_c$
• $I_0 / I_c \sim 0.79 \pm 0.01$
• Very compatible with results of Engel et al arXiv: 1308:5781:
  $I_0 / I_c \sim 0.826$
Comparison with theory

- Accuracy sufficient to rule out alternatives to linear behaviour
  - Normal-code HS model
  - Time-dependent GL model (Zotova et al)
  - Bulaevskii model before Engel’s corrections
Comparison to theory

![Graph showing bias current I_b vs energy E (eV) with annotations for n = 1, 2, 3, 4.]

Comparison to theory

![Graph comparing theoretical and experimental data for different numbers of photons in excitation. The graph shows the residual Δσ for different models: Diffusion-based, Normal-core, Vortex crossing, and Vortex nucleation. The number of photons in excitation ranges from n=1 to n=4.]
Conclusions

- There is more in the detector than linear efficiency
- Quantum tomography studies inner workings of detector
  - Universal response curve
  - Linear behavior up to X-UV

\[\text{JR et al, OE 20, (2012)}\]
\[\text{JR et al, PRA 79, (2013)}\]
\[\text{JR et al, PRB 87, (2013)}\]