Single-photon Detection at 1.55 µm with InGaAs APDs and via Frequency Upconversion

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Funded by: ARO MURI, NRO, MIT Lincoln Laboratory
Quantum Communication Architecture

Shapiro, New J. Phys. 4, 47 (02)

Quantum frequency translation

source of nondegenerate polarization-entangled photons

Polarization-entangled photons at 795 nm (s) and 1550 nm (i)

ARO MURI Program: MIT/NU collaboration
Detectors for Single Photons

Long-distance quantum communication protocol requires entangled photon pairs at:

- **Si photon counters**
  - Cooled, cw
  - High QE, low dark counts
  - No afterpulses

- **InGaAs/Ge photon counters**
  - Cooled, gated
  - Low QE, high dark counts
  - Severe afterpulsing

795 nm \(\rightarrow\) cw quantum-state frequency translation \(\rightarrow\) \(\sim 1550\) nm
Geiger-mode InGaAs APDs

Our Custom Detector

Wideband trace of photoelectron hit

- JDSU InGaAs APDs designed for linear-mode operation
- Overbiased in Geiger mode
- Gated-on, passively-quenched
- High-speed timing circuitry
- Entirely TE-cooled from -50 to -70°C
- Linear-mode performance not affected by severe cooling

- \( V_{\text{bias}} \sim 45 \text{ V DC} \)
- \( V_{\text{gate}} \sim 2-4 \text{ V} \)
- \( \tau_{\text{gate}} \sim 20 \text{ ns} \)
- \( \Phi_{\text{gate}} \sim 10-500 \text{ kHz} \)
- Sub-ns risetime
- Bias Tee circuit design
- Custom PCB for high-bandwidth operation
Detector Characterization

- Afterpulse contribution dominates at high gate rep. rate, low T
- Thermally generated dark counts increase exponentially with T
- Breakdown voltage increases linearly with T
- Photoelectron counts vary linearly with gate duration

Using weak cw light: 0.13 photons/20ns
QE ~ 20%

Gated-count Histogram

T = -60C
20 ns gate
Quantum Efficiency vs Dark Counts

- QE $\sim 20\%$
- $P_{dk} \sim 0.11\%$ per 20-ns gate
- Gate rep. rate $\sim 100$ kHz
- Negligible afterpulses at temperatures from -50 to -60 °C
Spontaneous Parametric Downconversion

- Energy conservation: \( E_p = E_s + E_i \) with \( E_s > E_i \)
- Momentum conservation: \( k_p = k_s + k_i \)
- Photon pairs are produced simultaneously in a single quantum event akin to photon fission
- The pairs of photons are correlated in time, momentum and polarization
Nondegenerate Photonic Entanglement

- cw 532-nm pump
- SPDC in 2-cm PPLN

~ 3.1% conditional detection probability limited by conjugate-mode coupling and QE


- InGaAs APD externally triggered by Si photon-counting module
- Demonstrated time coincidences between highly nondegenerate cw outputs at 1560 nm and 808 nm
- Wavelengths are temperature-tunable
- High-flux pair production rate of 1.4x10^7 pairs/s/mW
Frequency Upconversion

1064-nm cw pump (strong)

~ 1550 nm signal (weak)

PPLN $\chi^{(2)}$

SFG output 631 nm

- SFG intensity in low conversion limit (plane waves):

$$I_3(b_3,L) = \frac{2b_3^2d_{eff}^2}{n_1n_2n_3c^3b_o}L^2I_1I_2 \text{sinc}^2(\sqrt{2}KL / 2)$$

- Phasematching: $b_3 = b_1 + b_2$

- Required pump power for 100% conversion using Gaussian beams:

$$P_2 = \frac{n_1n_3b_1b_2b_3b_0c}{128d_{eff}^2Lh_m(B,b)}$$

Energy conservation:

$\square_3 = \square_1 + \square_2$
Periodically Poled Lithium Niobate Design

Compute desired grating period for phasematching

- Congruently grown lithium niobate
- z-cut, 0.5-mm-thick wafers
- Type-I, first order QPM
- $d_{\text{eff}} \sim 17 \ \text{pm/V}$
- Sum-frequency generation of 631 nm
- Inputs at 1550 nm (weak signal) and 1064 nm (strong pump)

- Uses bulk PPLN crystal for cw upconversion
- PPLN waveguide considered but not used because of high losses and max. power limitations
PPLN Fabrication

- Uses electric field poling of bulk lithium niobate
- First-order QPM nonlinear optical interactions:
  \[ k_3 = k_1 + k_2 \pm 2 \frac{\omega}{L} \]
- Non-critical (90°) phase matching:
  \[ k \approx 0 \quad sinc^2(\frac{kL}{2}) \approx 1 \]
- Collinear and co-polarized signal and idler outputs
- Temperature-tunable operation
Upconversion Results for 6 mm PPLN

- Temperature and wavelength phasematching curves have $sinc^2$ shape
- Upconverted signal varies linearly with pump power (no depletion)
- Single-pass conversion efficiency $\sim 0.65\%$ with 332 mW pump
- Weak-signal wavelength is temperature-tunable at $\sim 0.36$ nm/°C
Cavity-enhanced Upconversion

- Ring cavity resonant only for the 1.064 µm pump
- Single pass for probe and signal
- 1\textsuperscript{st} order QPM in 4 cm-long PPLN with measured $d_{\text{eff}} \sim 14$ pm/V
Cavity Resonance and Signal Output Trace

- 2.15% T coupler, measured cavity finesse ~ 200
- Cavity power enhancement factor ~ 100

Total scan time: 50 ms

Pump resonance and signal output

Output voltage (scaled + offset)

Total scan time: 50 ms
Cavity-enhanced Upconversion Results

- Maximum upconversion efficiency: 85%
- Data fit: $\sin^2\left(\frac{\sqrt{2}}{2} \frac{P}{P_{\text{max}}}^{1/2}\right)$ yields $P_{\text{max}}$ of 32 W
Summary

- Demonstrated 20%-efficient InGaAs Geiger-mode detection at 1.55 µm
- Experimental implementation of an 85%-efficient frequency upconverter from 1.55 to 0.63 µm

Future experiments:
- Optimization of cavity parameters to achieve near-100% upconversion
- Single-photon level upconversion
- Completely bypass InGaAs photon counters by using quantum-state upconversion followed by Si Geiger-mode detection (cw, high QE, very low dark counts)
- Combine efficient downconverter with quantum upconversion scheme for long-distance quantum communication
3D imaging w/ photon-counting APD arrays

- Silicon Geiger-mode APD array
- 532 nm Q-switched laser
- Coherent, monostatic, direct detection 3D laser radar

- Frequency upconversion will allow 3D imaging at covert/eye-safe wavelengths


Angle-angle-range Image
~ 2-3 cm range resolution