Using Quantum Entangled Photons to Measure the Absolute PDE of a Multi-Pixel SiPM Array

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Aims and Motivation

• Determining the photodetection efficiency is critical

• How to calculate relative PDE?
  – Comparing detector output to another detector

• How to calculate absolute PDE?
  – Calibrated laser diode and photodiode, compare responses
  – Entangled photons…

• Can we use entangled photons to calculate absolute PDE?

• Eventually….could it become the basis for a new lab-based calibration tool?
Outline

- Quantum Entanglement and Absolute PDE
- Using a Multi Pixel Array
- The Target Module for CHEC
- Monte Carlo Simulations
- Experimental Results
- What Next?
- Conclusions
Quantum Entangled Photons

- Incident photons can be down-converted using non-linear crystals
  - e.g. beta barium borate (BBO), potassium titanyl phosphate (KTP), LiNbO$_3$
- Photon strikes non-linear crystal, generates two lower energy photons through spontaneous parametric downconversion (SPDC)
- Photons are entangled: what happens to one happens to the other
- For BBO, SPDC photon emission rate is 4 in $10^6$
- Emission at different angles depending on each photon energy
- Different types of entanglement, whether or not the emitted photons are ordinarily or extraordinarily polarised
Quantum Entanglement and Absolute PDE

- Proposed by Ware + Migdall (2004)
- Entangled photons, N, strikes both detectors
- Both detectors should detect the photons → PDE limits the response
- Ratio of the number of coincident events to trigger-only events gives the PDE
- Need individual outputs from two separate detectors
- This can be achieved with a single, multi-pixel array

\[ N_{\text{Detector}} = \eta_{\text{Detector}}N \]
\[ N_{\text{Coinc}} = \eta_{\text{DUT}}\eta_{\text{Trigger}}N \]
\[ \eta_{\text{DUT}} = \frac{N_{\text{Coinc}}}{N_{\text{Trigger}}} \]
Using a Multi-Pixel Array

• Count the number of events observed on both pixels simultaneously

• Count the number of events observed only on the trigger pixel

• Ratio gives the PDE → $\eta_{DUT} = \frac{N_{Coinc}}{N_{Trigger}}$

UV photon ~ 405nm from pulsed laser source

Non-linear crystal (BBO)
  • Downconverts photon to two photons with energy that total initial photon
  • Crystal operates in given frequency range

Photon pair generated at angle relative to photon energies
  • Symmetric position on array about a central pixel gives photon energy

Band pass filter → photon striking photon is the required energy

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Quantum Entangled Photons

- Photon strikes crystal
- Daughter photons emitted at angles $\theta, \phi$ relative to incident photon
- Photon momentum related to the angle and frequency dependent refractive index, etc
- Relationship between $\theta$ and $\phi$ found via conservation of momentum
Quantum Entangled Photons

- BBO generates a ring
- BiBO generates an oval

Guilbert 2015

- BBO easier to identify where a downconverted photon should be
Target Module

- Developed for the CHEC camera for the Cherenkov Telescope Array

- Silicon Photomultiplier detectors
  - Hamamatsu S12642 SiPM array
  - 64 6mm x 6mm pixels
  - Each pixel is four 3mm x 3mm pixels coupled together

- Output from SiPM arrays goes to 64 channel digitiser based on TARGET ASIC, designed for fast timing and coincidence measurements
  - GHz sampling

- For more information about TARGET module AIV and testing, please speak to J Lapington or C Duffy
Monte Carlo Simulation

- Tested with a Monte Carlo simulation
- Pick a random angle $\theta$
- Work out corresponding energy of downconverted photons
- Does it pass the band pass filter of $E/2 \pm \sigma$?
  - $E$ is energy of initial photon, $\sigma$ is the width of the band pass filter
- Generates ring on multi-pixel array
Monte Carlo Simulation

- How does distance and band pass filter width affect which pixel the photon strikes?
  - Increase distance, test pixels further from central pixel
  - Reduced number of counts with band pass filter
Experimental Requirements

- Single PE resolution
- Pulse Height – Charge calibration
- Choose pulse heights of 2-7mV only
Experimental Requirements

- Window the peak between ~30-40ns
Experimental Setup

TARGET module
SiPM array in cooled holder. Operating at 14.5 degrees C
810nm bandpass filter
5mm diameter SPDC BBO crystal
Optical Iris
Photek LPG-1 405nm Pulsed Laser
Experimental Results

- Run of ~30000 events

- Count the number of events with a peak between 30 and 40ns and 2-8mV

- Dead pixel due to damaged silicon - output turned off

- Central pixel: residual blue photons that pass through bandpass filter

- Visible ring

- **CHALLENGE:** the BBO crystal we purchased had an opening angle of 3°. It also has an SPDC cut at 10°, which is what our results suggest
Estimating the Absolute PDE

- Calculate coincident events in opposite pixels
- Treat one as DUT, one as trigger
- Count number events coincident in DUT and trigger
Experimental Results

- Count number of instances where events are coincident
- Take the ratio of number of coincident events to DUT-only events
- Tested for different pulse width
  - ~1% for 100ps pw
  - ~3% for 450ps pw
  - ~4% for 850ps pw
- CHALLENGE: What causes the apparently difference in absolute PDE regarding the pulse width?
Experimental Results

• Why do we see PDE variation with laser pulse width?

Each bin is a nanosecond wide
  – Currently: Looking for synchronicity within 1ns
  – Need to: interpolate timing → improved synchronicity

Lack of timing synchronisation between TARGET electronics and pulsed laser trigger
  – Need to: determine and correct for skew
    → removes effect of electronics → incident time on detector
Experimental Results

- Skew correction for peak:
  - Average waveform for each pixel over 10000 events, relative to average waveform from entire array
    - -2.5 to +1ns skew, subtracted from timing

- Quintic interpolation of waveform peak
  - Peak found of initial waveform
  - Signal maximum and ±2ns around nanosecond (5 bins) used
  - Interpolate 500 points within this sector
  - Find the new peak

- Window of peak ±200ps used
Experimental Results

- With updated data analysis…
- Absolute PDE drops ~ factor 2
  - Removing false positive coincident events
- 450ps and 850ps measurements in better agreement
  - Removes discrepancy seen earlier
- 100ps pulse width estimate still significantly lower
  - Why?
Experimental Results

Number of Coincident Events vs. Pulse Width (ps)

- Left plot: Coincidence window
- Right plot: Coincidence window

Number of Trigger Events vs. Pulse Width (ps)
How do we compare?

- Bias $V = 67.5V \sim 1-1.5V$ overvoltage

Hamamatsu S12642 silicon array:
scaled QE<10% @3V overvols

Hamamatsu S13360:
PDE ~7% @ 810nm @ 4V overvols

- Initial estimate $\sim 1-2\% @810nm$
  @ 1-1.5V overvols

Otte 2014
Requirements for this technique

- Individual pixel outputs
  - Achieved using TARGET ASIC

- Fast timing
  - 1GHz sampling via TARGET
  - Interpolated quintic binning used ±200ps

- Discrimination between 810nm and 405nm photons
  - Needed to prevent false positive correlation
  - Use narrowband 810nm band pass filters (10^-4 405nm pass through)

- Count and test each pixel

- Can be achieved with current TARGET electronics + SiPM detector array
Verification, Issues and Possible Resolution

• Verification
  – Imaging ring with SLR camera on a long integration time
    → Nothing spotted with 30s integration → near IR filter causing a problem?

• Possible Issues/Challenges
  – Timing and Apparent pulse width variation
    Resolution: Improved skew characterisation of electronics
    Resolution: optimisation of coincidence windows
  – Observed ring appears wider than expected
    - Resolution: test on bigger camera, further out to ensure this is the only ring seen
  - Achieving other wavelengths
    - Currently limited to narrowband SPDC (e.g. 405\text{\textendash}810)
Summary

• PDE needs to be characterised for different detectors
• Absolute PDE calibration using a calibrated photodiode
• Technique from ~2004 used to calibrate a pixel PDE using quantum entangled photons
• Applying this technique to a SiPM array used for CHEC camera module being developed for the Cherenkov Telescope Array
• Ring observed from individual pixel outputs due to BBO crystal
• Absolute PDE estimated ~1-2% at 810nm for 1-1.5V overvoltage
  – Correct order of magnitude for the silicon
• Some issues with timing, sizing, pulse width variation that need rectifying
  – Routes identified to achieve this
• Arrangement could lead to a small, cheap, versatile method of testing absolute PDE
Thanks for listening. Any questions?