Providing reference standards and metrology for the photon counting community

Andrew Beaumont, Jessica Cheung, Christopher Chunnilall

National Physical Laboratory, Teddington, Middlesex, UK

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Overview

• Metrology
  – iMERA roadmap for optical radiation
  – NPL motivation

• Detector characterisation
  – Conventional technique
  – Correlated photons technique

• qu-candela
  – EU iMERA funded project
  – New measurement standards for the photon counting community
The present *Photonic Century* based on rapidly developing optical technology and photon devices especially applied in the field of secure communication and quantum computing requires optical metrology based on better standards and calibration chains including new optical quantum standards (“quantum candela”) also affecting fundamental metrology.

Key targets include:
- Low-cost, high-accuracy transfer standards
- Secure bit rate > $10^9$ Hz
- Certification of optical quantum based systems
- Establish quantum candela with self-consistency within $10^{-5}$

- Linking classical and quantum radiometry
- Utilization of single photon sources and detectors
- Non-linear characteristics of optical materials and devices
- Novel quantum optical devices and technology including nanofabrication and materials research
- New optical fibres (PCF) and WDM systems
- Progress in theory, quantum mechanics: entanglement, coding in non-commuting observables
- Single photon radiometry with photon quantum state characterisation
- Certified entangled photon states

http://www.euromet.org/projects/imera
Traceability: detector calibrations

Primary standard
Cryogenic radiometry

Characterisation at discrete laser wavelengths (210 nm to 11 μm)

Calibrate transfer secondary standards at different wavelengths

UV: PtSi, GaN, GaAsP
VIS: Si trap detectors
IR: InGaAs
Far-IR: 20 μm

Cavity pyroelectric detectors

Dissemination to laboratories and industry

Photodiodes, thermal detectors, thermal imagers, photon counters, power meters

Fundamental constants

0.002%
0.005%
Detector and instrumentation characterisation capabilities

- Spectral range: 200 nm to ~ 30 μm
- Solid state and thermal
- Photon counting ~ 5000 pht s\(^{-1}\) (upwards)
- Single elements through to linear and 2D arrays
  - Individual pixels and intra-pixel
- Optical instruments – spectrometers, cameras VIS and IR
- Spectral response, linearity, spatial uniformity, response time, noise

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Photon counting motivation

- bioluminescence
- single molecule detection
- fluorescence
- lighting
- displays
- entertainment
- robust imaging devices
- IR detectors
- neutrino / Cherenkov / dark matter detection
- detector calibration
- hyper spectral imaging
- primary radiometric scales
- quantum standards
- Quantum Information Processing
- medical / non intrusive imaging
- quantum cryptography
- quantum computing
- single photon sources
- Medical Physics
- radioactive techniques
- nuclear detection
- Meteorology
- remote sensing lidar
- environmental monitoring

few photon science
Single Photon metrology: Motivation

• Develop measurement infrastructure and reference standards for validating single photon sources and detectors for the ‘few photon science’ community
• Input into definition and implementation of standards for the QIP industry – e.g. certification
• NMIs to be the ‘honest brokers’ to enable the acceptance of new technology by the user community
• Meet the targets of the iMERA roadmap
Conventional calibration

Top view

Integrating sphere

Photon counter

gain
photo-diode

moving stage

pinhole

Photon counter

Side view

Band pass filter
Neutral density filter
Broad band source

\[ P = N h \nu \]

Reference trap detector\(^1\) provides link to the primary standard, the cryogenic radiometer

100 % Divergent beam of light entering the trap

0.4% Back-reflection from trap

Hamamatsu S1337 Photodiode
30 % reflectance

Absolute detector characterisation using SPDC photons

- Coincidence measurements using nuclear decay, Geiger and Marsden 1910 [1].
- Two photon production via atomic cascade, Brannen et al 1955. [2].
- Non linear process: Spontaneous parametric downconversion first predicted in 1961 by Louisell et al. [3].
- First detection efficiency measurement carried out on PMT 1970. [4]
- Rigorous application of technique to measure quantum efficiency, Rarity et al. 1987 [5], Migdall et al. 1995 [6].
- Recent validation of technique, Migdall and Polyakov – 2007 [7].
- Technique offers an alternative and direct method of measuring detection efficiency of photon counting detectors and realising primary radiometric scales.

References
Detector characterisation

$N$: number of photon pairs

$N_C$: number of coincidences

$$\eta_A = \frac{N_C}{N_B}$$

$\eta$ is the detection efficiency

A is DUT channel, B is trigger channel

No external standards required!

Non-degenerate wavelengths

IR calibrated against visible telecom wavelengths

Key sources of uncertainty

• Measurement of $N_C$ and $N_B$

• Losses in channel A: $t_A$

• Optical elements can be placed in the trigger path B

• Alignment – optimisation, stability, reproducibility

$$\eta_A = \frac{(N_C - A_C)}{[t_A (N_B - D_B)]}$$

Measurement of coincidence counts

$$\eta_A = \frac{N_C - A_C}{T_s (N_B - D_B)}$$

- $N_C$ area under curve in region B between P and Q
- $A_C$ accidental count rate in region B between P and Q
- $N_B$ trigger count rate during downconversion
- $D_B$ trigger count rate downconversion OFF

Region C detectors and counting electronics deadtime
Region D occurs after dead-time

Small peak in region D, after pulse events (0.4% of coincidences in region B)
After-pulsing, dead-time

Decompose coincidences into single, double and triple stop events.
Characterising optical components

[\eta_A = \frac{(N_C - A_C)}{(N_B - D_B)}] \]

- \( t_d \) = transmittance of the downconversion crystal
- \( t_f \) = transmittance of focussing optics \(^\text{[1]}\)
- \( t_\lambda \) = transmittance of the band pass filter
- \( t_g \) = geometric losses

Each value is determined through separate in-house measurements

<table>
<thead>
<tr>
<th>( t )</th>
<th>Value</th>
<th>Absolute uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_d )</td>
<td>0.93</td>
<td>0.0012</td>
</tr>
<tr>
<td>( t_f )</td>
<td>0.97</td>
<td>0.0002</td>
</tr>
<tr>
<td>( t_\lambda )</td>
<td>0.53</td>
<td>0.0010</td>
</tr>
<tr>
<td>( t_g )</td>
<td>0.99</td>
<td>0.0053</td>
</tr>
<tr>
<td>Ts</td>
<td>0.47</td>
<td>0.0026 (k=1)</td>
</tr>
</tbody>
</table>

Results so far!

Comparison:
SPDC measurement:
0.0147 ± 0.00005 (k=1) (0.35% rel)
(upper bound 0.5% relative)

Conventional measurement:
0.0145 ± 0.0001 (k=1) (0.7% rel)
(upper bound 1% relative)

Difference: 0.0002 (1.6% relative)

Uncertainty (k=2): 0.00022

Hence difference between measurements just within uncertainty bound of 2 standard deviations

Target 0.1%

Issues:
Spatial uniformity of DUT: 0.1% variation over 3 mm
Matched beam profile
Reproducibility
A quantum candela?

Candela – S I unit:
The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency $540 \times 10^{12}$ hertz and that has a radiant intensity in that direction of $1/683$ watt per steradian.

Realised in terms of electrical units

Natural unit is in terms of numbers of ‘photons’: $E = nh\nu$

Quantum candela – a proposed re-definition:
The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency $540 \times 10^{12}$ hertz at a rate of $4.092 \times 10^{15}$ photons per second per steradian in that direction.

Candela: Towards quantum photon-based standards

Implementation

Converting metrology to the counting of natural units: photons

CMI, Czech Republic
INRIM, Italy
JV, Norway
AS Metrosert, Estonia
PTB Germany
MIKES, Finland

Courtesy of iNRIM, Italy
Linkage to SI

Radiometer / PQED\textsuperscript{[1]} $\quad 100 \ \mu\text{W}$

\nodal{PQED \ / \ SPAD $\quad \sim 10^5$ attenuator $\quad 1 \ \text{nW} \ / \ \sim 10^9$ photons/s}

SPAD / TES $\quad 10^3$ photons/s

TES (PNRD) $\quad 1$ photon/s

\textsuperscript{[1]} Geist, Brida, Rastello, Metrologia \textbf{40}, S132, 2003
Current & future

• qu-candela
• Improve uncertainties in correlated photon technique – target uncertainty 0.1%
• Development of photon counting and photon number resolving detectors
• Metrology requirements for the photon counting community
• Measurement requirements specific to QIP and single photon metrology
Announcements

- Photon counting resource web page: www.photoncount.com
  - Launched in 2005 at the NPL single photon workshop
  - Promote knowledge transfer between different communities working with photon counting detectors
  - Over 150 international members
  - Over 1000 visits this month
  - Registration is free

Thank you!

For more information about our work please visit:
www.npl.co.uk/photonics
jessica.cheung@npl.co.uk

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Cryogenic radiometry

- Pioneered at NPL, late 1970’s
- Primary standard – thermal detector
- Basis of realisation of the SI unit of luminous intensity, the candela
- Links optical heating to electrical effect – electrical SI units (Electrical Substitution)
- Underpins optical radiation source and detector scales
- Optical power 0.005% accuracy

\[ \Delta T_{\text{opt}} = \Delta T_{\text{elec}} \]
\[ P_{\text{opt}} = P_{\text{elec}} \]
Beam profile

XYmap28112007-001, z = -2000

X stage position (microns)

Number of coincidences

Data
Fitted

NPL
National Physical Laboratory