Metrology for Quantum Communications

M. L. Rastello, Varenna, July 20, 2012
Contents of the presentation

Part 1
• What are photons?
• How do we produce photons?

Part 2
• How do we measure photons?

M. L. Rastello, Vareenna, July 20, 2012
Contents of the presentation

Part 1

• What are photons?
• How do we produce photons?

Part 2

• How do we measure photons?
Six years ago…

Why photons at the Varenna School on Metrology?

*Tomorrow will be today very soon*

The present *Photonic Century* is based on rapidly developing optical technology and photon devices especially applied in the field of secure communication and quantum computing.

This technology requires optical metrology based on better standards and calibration chains including new optical quantum standards also affecting fundamental metrology.
The first quantum revolution gave us new rules that govern physical reality, the “second quantum revolution” take these rules and use them to develop new technologies and standards.

The second quantum revolution is and will be responsible for most of the key physical technological advances, namely quantum technology (QT) specifically Quantum Information Technology (QIT), allowing us to control and engineer the components of a complex system governed by the laws of quantum mechanics.

Successful technologies are predicted on precise engineering, which in turn requires high-precision measurements for validation. QIT will thus require us to develop quantum metrology.
Quantum Metrology = Intrinsically absolute ultra sensitive measurement techniques
• To provide highest precision standards
• To Validate performances of single components in QIT devices

QIT = precise design and engineering of devices and communication channels according to the quantum information requirements

Relationship Between Quantum Metrology and QIT

Quantum Information Processing
Quantum Optics
Quantum Resources
Quantum Information
Quantum Atomics
Quantum Mechanical Systems
Quantum Metrology

Quantum Information technology (QIT)
Coherent Quantum Electronics
Quantum Optics
Quantum Resources
Quantum Atomics
Quantum Mechanical Systems
Quantum Metrology
Quantum Information Processing
Coherent Quantum Electronics

1. Quantum Information
2. Quantum Resources
3. Quantum Atomics
4. Quantum Mechanical Systems
5. Quantum Metrology
6. Coherent Quantum Electronics
7. Quantum Optics
8. Quantum Information Processing

Quantum metrology means to provide the highest precision standards and validate the performance of single components in QIT devices.
Towards quantum photon-based standards for optical radiation

Field of secure communication and quantum computing requires optical metrology based on better standards and calibration chains including new optical quantum standards also affecting fundamental metrology.

Certification of optical quantum based systems

- Single-photon radiometry with photon quantum state characterization
- Linking classical radiometry 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 sources, detectors and materials
- New optical fibers (photonic crystals) and WDM systems
- Progress in theory, quantum mechanics: entanglement, coding in non-commuting observables

Enabling science and technology

Metrological application of basic science and technology

Experimental realization

Targets

Triggers
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 also affecting fundamental metrology.

Towards quantum photon-based standards for optical radiation

- **Triggers**
- **Targets**
- **Experimental realisation**
- **Metrological application of basic science and technology**
- **Enabling science and technology**

**Certification of optical quantum based systems**

**Single-photon radiometry with photon quantum state characterization**

- Non-linear characteristics of optical materials and devices
- Novel quantum optical devices and technology including nanofabrication and materials research
- New sources, detectors and materials
- New optical fibers (photonic crystals) and WDM systems
- Progress in theory, quantum mechanics: entanglement, coding in non-commuting observables

- 2005
- 2010
- 2015
- 2020
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 also affecting fundamental metrology.

**Triggers**

**Certification of optical quantum based systems**

**Targets**

**Towards quantum photon-based standards for optical radiation**

**Experimental realisation**

**Metrological application of basic science and technology**

**Enabling science and technology**

**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 sources, detectors and materials**
- **New optical fibers (photonic crystals) and WDM systems**
- **Progress in theory, quantum mechanics: entanglement, coding in non-commuting observables**
- **Certified entangled photon states**

**Towards quantum photon-based standards for optical radiation**
What are photons?

I therefore take the liberty of proposing for this hypothetical new atom, which is not light but plays an essential part in every process of radiation, the name PHOTON”

What?

A photon is a state of the e.m. field with the following properties:

1) frequency \( \nu \) and wave vector \( k \)
2) energy \( E = h\nu \) and momentum \( p = hk \) satisfying

\[
E = c |p|
\]

3) spin 1
A photon has two states of polarisation, because of:

2) energy $E = h\nu$ and momentum $p = hk$
   satisfying $E = c|p|$

3) spin 1
A simple experiment

- a light source, shining on the projector screen
- three polaroids (polarization filters) that can be picked up at any camera supply store.

Filters A, B, and C are polarized horizontally, at 45°, and vertically, respectively, and can be placed so as to intersect the beam of light.
Insert filter A.

Assuming the incoming light is randomly polarized, the intensity of the output will have half of the intensity of the incoming light.

The outgoing photons are now all horizontally polarized.
The function of filter A cannot be explained as a “sieve” that only lets those photons pass that happen to be already horizontally polarized.

If that were the case, few of the randomly polarized incoming photons would be horizontally polarized, so we would expect a much larger attenuation of the light as it passes through the filter.
Next, insert filter C.

The intensity of the output drops to zero. None of the horizontally polarized photons can pass through the vertical filter.

A sieve model could explain this behavior.
Finally, insert filter B between A and C.

A small amount of light will be visible on the screen, exactly one eighth of the original amount of light.
A photon’s polarization state can be modeled by a unit vector pointing in the appropriate direction.

Any arbitrary polarization can be expressed as a linear combination

\[ a(\uparrow) + b(\rightarrow) \]

of the two basis vectors

(\rightarrow)  (horizontal polarization)

(\uparrow)  (vertical polarization).
We are only interested in the direction of the polarization. The notion of “magnitude” is not meaningful, and so the state vector will be a unit vector, i.e.,

\[ |a|^2 + |b|^2 = 1. \]

In general, the polarization of a photon can be expressed as

\[ a(\uparrow) + b(\rightarrow) \]

where \( a \) and \( b \) are complex numbers such that

\[ |a|^2 + |b|^2 = 1. \]

Note, the choice of basis for this representation is completely arbitrary: any two orthogonal unit vectors will do.
The measurement postulate of quantum mechanics

Any device measuring a 2-dimensional system has an associated orthonormal basis with respect to which the quantum measurement takes place.

Measurement of a state transforms the state into one of the measuring device’s associated basis vectors.
The probability that the state is measured as basis vector \((u)\) is the square of the norm of the amplitude of the component of the original state in the direction of the basis vector \((u)\).

**Example:** given a device for measuring the polarization of photons with associated basis \{\((\uparrow), (\rightarrow)\)\}, the state \(\psi = a(\uparrow) + b(\rightarrow)\) is measured as \((\uparrow)\) with probability \(a^2\) and as \((\rightarrow)\) with probability \(b^2\)
Note that

• different measuring devices have different associated basis, and
• measurements using these devices will have different outcomes.
• measurement of the quantum state will change the state to the result of the measurement.
measurement of the quantum state will change the state to the result of the measurement.

That is, if measurement of
\[ \psi = a(\uparrow) + b(\rightarrow) \]
results in \( \uparrow \),

then the state \( \psi \) changes to \( \uparrow \) and a second measurement with respect to the same basis will return \( \uparrow \) with probability 1.
Quantum mechanics can explain the experiment:

A polaroid measures the quantum state of photons with respect to the basis consisting of the vector corresponding to its polarization together with a vector orthogonal to its polarization.

The photons which, after being measured by the filter, match the filter’s polarization are let through.

The others are reflected and now have a polarization perpendicular to that of the filter.
For example, filter A measures the photon polarization with respect to the basis vector (→), corresponding to its polarization. The photons that pass through filter A all have polarization (→).

Assuming that the light source produces photons with random polarization, filter A will measure 50% of all photons as horizontally polarized. These photons will pass through the filter and their state will be (→).
Filter A will measure 50% of all photons as horizontally polarized. These photons will pass through the filter and their state will be (→).

Filter C will measure these photons with respect to (↑). But the state (→) = 0(↑) + 1(→) will be projected onto (↑) with probability 0 and no photons will pass filter C.
Finally, filter B measures the quantum state with respect to the basis

\[ \{ \frac{1}{\sqrt{2}} \left[ (\uparrow) + (\rightarrow) \right], \frac{1}{\sqrt{2}} \left[ (\uparrow) - (\rightarrow) \right] \} \]

Photons passing through A with state \( (\rightarrow) \) will be measured by B with probability 1/2 and so 50% of the photons passing will pass through B.
As before, these photons will be measured by filter C as (↑) with probability \(1/2\).

Thus only one eighth of the original photons manage to pass through the sequence of filters A, B, and C.
The single photon

“Photons interfere with themselves”

This is not always true but is a reminder of the importance of superposition.

An object is identified by a unique set of attribute (height, weight, shoe size,....), each of them with a well definite value.

On the contrary, the single photon can, in some sense, take on multiple directions, energies and polarizations.

Single photon spatial interference requires superposition of these quantum descriptors for single photons
The single photon

“Photons interfere with themselves”

The single photon should not be thought of as like a simple plane wave having a unique direction, frequency and polarisation. Such states are rare special cases. Rather the superposition state for single photons is the common situation. Upon detection light appear as if discrete and indivisible possessing well definite attributes.
Some counterintuitive concepts of quantum mechanics can be illustrated through an experiment.

They seem counterintuitive because everyday phenomenons are governed by classical physics, not quantum mechanics -- which takes over at the atomic level.
A light source emits a photon along a path towards a halfsilvered mirror. This mirror splits the light, reflecting half vertically towards detector A and transmitting half toward detector B.
The beam splitter experiment

Our intuition would say that the photon leaves the mirror either towards A or B with equal probability since it cannot be split.
The fact that a photon cannot split have been verified through detecting a signal at only one detector. This means that photons will be detected 50% of the time at each of the two detectors. So far, the quantum physical prediction agrees with the classical one.
The beam splitter experiment

This piece of information is misleading since it might lead us to think that the photon leaves either towards A or towards B. However, quantum mechanics predicts, through the effect known as single-particle interference, that the photon actually travels along both paths simultaneously, collapsing down to one path only upon measurement. The following experiment illustrates the last effect.
The beam splitter experiment

Let us introduce a fully silvered mirror instead of each detector of the first experiment such that the two paths will encounter a halfsilvered mirror before reaching detectors A and B.
Once a photon will reach the last half-silvered mirror, along either one of the two paths, one might think that the photon will reach the detectors A or B with a probability of 50% each. However here, the detector A or the detector B will register a hit 100% of the time whereas the other one will never be triggered.
Our classical intuition based on the conditional probability doesn’t predict such outcome. We cannot explain this conclusion based on a comparison with the first experiment. This phenomenon is known as single-particle interference.

Actually, quantum physics states that the photon traveled both paths simultaneously; creating interference at the point of intersection that canceled the possibility of the photon to reach the other
If we cancel out the effect of quantum interference by placing an absorbing screen on one of the paths, both detectors will register 50% hits similar to the first experiment. Those potential paths taken by the photon represent the superposition of the possible photon states.
Those special characteristics as the superposition of different states and interference give the quantum computer the potential to be incredible powerful computational devices.

Therefore, quantum computers are not seen as continuity of classical computers but as an entirely new branch of thoughts.
More than one photon

Bose-Einstein statistics

Two conventional objects and two properties $R$ and $G$

Classically four combinations $\text{RR} \quad \text{GG} \quad \text{RG} \quad \text{GR}$

The two objects have different locations and are distinct
More than one photon

**Bose-Einstein statistics**

Photons obey Bose-Einstein Statistics, as spin one particles.

Two photons and two properties $R$ and $G$

As required by Bose-Einstein statistics, the states available to the two photons are those that are symmetric states under exchange:

$$RR, GG, \frac{1}{2}(RG+GR)$$

The states $RG, GR$, and $\frac{1}{2}(RG-GR)$ are not suitable.
More than one photon

**Bose-Einstein statistics**

Photons are defined by three quantum numbers associated with momentum, energy, and polarisation.

Position and time do not enter into consideration.

If two photons possess the same three values for these quantum numbers, they are indistinguishable from one another.
More than one photon

**Bose-Einstein statistics**

As bosons, any number of photons can occupy the same state. They do not obey the Pauli Exclusion Principle and this fact is at the foundations of laser theory because laser operation requires many photons to occupy a single mode of the radiation field.
The task of counting photons

The past decade has seen a dramatic increase in interest in new single-photon detector technologies. A major cause of this trend has undoubtedly been the push towards optical quantum information applications such as quantum key distribution.
The task of counting photons

These new applications place extreme demands on detector performance that go beyond the capabilities of established single-photon detectors.

There has been considerable effort to improve conventional photon-counting detectors and to transform new device concepts into workable technologies for optical quantum information applications.
The task of counting photons

One of Einstein’s key contributions to modern science was to recognize that light is fundamentally composed of individual packets of energy, now referred to as photons. Although photons are often described as “particles” of light, one should not imagine them as little round balls or geometric points.
The task of counting photons

As with all denizens of the quantum world, photons have no native shape: their distribution in space is determined by their environment and interactions.

To the extent that photons have a shape, it is the shape of the optical mode they occupy.
The task of counting photons

The concept of a photon occupying an optical mode that is a solution of Maxwell’s equations is very similar to the idea of an electron occupying an orbital in an atom or molecule that is a solution of the Schroedinger’s equation.
The task of counting photons

One distinction is that photons are **bosons**, so an indefinite number of photons can occupy the same state, while electrons obey the Pauli’s exclusion principle.

Non-localised radiation and free space photon modes also exist, and are analogous to unbound electron states.
The task of counting photons

From the viewpoint of optical measurement:

• a single photon is the smallest amount of energy that can be extracted from the electromagnetic field; hence,

• a single photon is the smallest amount of light that can be detected by absorption
The task of counting photons

Of course, even relatively strong optical signals can be decomposed into a stream of single photons when viewed on a short time scale

- 1 W beam of 580 nm yellow light delivers one photon every $3.4 \cdot 10^{-19}$ s on average, but, ............,
The task of counting photons

but, technologically speaking,

• no detector responds on such a short time scale, so

• the granular nature of strong optical signals manifests itself as **shot noise on a continuous signal** rather than discrete pulsing of the signal itself
The task of counting photons

Only in the limit of weak signals

- 300 pW at 580 nm corresponds to an average of one photon every 1,14 ns

- one can speak of a detector “counting” the arrival of individual photons
The task of counting photons

Extremely weak signals on this order are characteristic of

• Laser radar returns from distant target
• Fluorescence of rarified species in spectroscopic experiments
• Data in certain quantum information applications
The task of counting photons

The energy of a single photon in the visible or near-infrared range is around

$10^{-19} \text{ Joule}$

A single-photon detector is an extremely sensitive device capable of registering these quantum objects.
The task of counting photons

Modern applications, like advanced QI technologies, place stringent demands on optical components such as single-photon detectors.

Significant improvements are required in terms of their signal-to-noise ratio, detection efficiency, spectral range and ability to resolve photon number (the number of photons reaching the detector simultaneously).
The task of counting photons

Scientists and engineers around the world have taken up this challenge.

Their efforts have led to considerable improvements in conventional single-photon detectors and to the emergence of new photon-counting technologies.
The task of counting photons

Single-photon detectors now support and enable a host of applications at the frontiers of science and engineering.
MIQC is a metrology framework that will foster development and market take up of quantum communication technologies aimed at achieving maximum impact for the European industry in this area.
MIQC is focussed on Quantum Key Distribution technologies, the most advanced towards practical application. Quantum key distribution is a way of sending cryptographic keys with absolute security. It does this by exploiting the ability to encode photons with quantum states that are noticeably disturbed if an eavesdropper is present in the channel.
QKD kits are available commercially and in that respect the EU is a world lead.

There are currently no independent measurement standards and definitions for this industry and MIQC aims to address this.
A QKD system is composed of

- quantum physical devices (quantum sources, quantum channels and quantum detectors) and
- classical (and well-established) information technology.
Photon Emitters

Photon Sources Characterisation

Quantum Channels

Optical Fiber Link Characterisation
State-(D)Encoding Devices Characterisation
In-Line Measurement Devices

Photon Receivers

Photon Detectors Characterisation
Contents of the presentation

Part 1
• What are photons?
• How do we produce photons?

Part 2
• How do we measure photons?

M. L. Rastello, Varenna, July 20, 2012
Metrology Source Standards

Black Body

Synchrotron

Single Photon or “Heralded” Source
Absolute Light Source

Output characteristics:
- photon # ➔ known
- photon timing ➔ known
- wavelength ➔ known
- direction ➔ known
- polarization ➔ known
Given a path of potential applications for quantum information processing, how can it be achieved in real physical systems? …

… a major difficulty has been producing single photons on demand;

experimentalists have instead opted to use schemes which produce single photons ‘every now and then’, at random, and wait for such an event to occur. “

M. Nielsen & I. Chuang, “Quantum Computation and Quantum Information”

Not single photon or Not on-demand
How do you make a source of single photons on demand?

**Scheme**
- Faint laser
- Downconversion
- Quantum dots
- Single fluorescent molecule
- N vacancy in diamond

**Trick**
- Pulsed pump + low photon rates
- Single quantum systems
Faint laser source

Laser pulses

< 1 photon/pulse

attenuator
Deterministic Single Photon Source

Classical (laser) source → Poisson photon number distribution

Number of photons

Probability
Stastical recostruction of quantum optical states

**Coherent state**
(attenuated He-Ne laser)

**Single photon states**

G. Zambra, A. Andreoni, M. Bondani, M. Gramegna, M. Genovese, G. Brida, A. Rossi, and M. G. A. Paris,
Target efficiencies

Compare to a classical pulsed laser

- 37% maximum probability of making one photon
- 18% probability of making two photons

Current technology

- 70% probability of making one photon
- 3% probability of making two photons
- 10 kHz rate

Stage 2 technology (multiple attempts method)

- 90% probability of making one photon
- 1.8% probability of making two photons
- 50 kHz rate

Future technology (more efficient detectors, lasers, electrooptics)

- 95% probability of making one photon
- <1% probability of making two photons
- 10 MHz rate
What is Parametric Down-Conversion?

Pump Beam

Linear Crystal

Output Beam

$\hbar \nu_{\text{pump}}$
Parametric Down-Conversion (PDC)

Pump Beam

Non-linear Crystal

\[ h\nu_{\text{pump}} \rightarrow h\nu_1 \rightarrow h\nu_2 \]

Correlated Photons

\[ k_{\text{pump}} = k_1 + k_2 \]

\[ \nu_{\text{pump}} = \nu_1 + \nu_2 \]
Parametric Downconversion
\[ \mathbf{K}_0 = \mathbf{K}_1 + \mathbf{K}_2 \]

\[ \omega_0 = \omega_1 + \omega_2 \]
Different Crystal Tilts Produce Different Output Patterns
Single Photon On-Demand?

Faint Laser Source

Laser

Attenuator

Heralded Photon Source

Creation is random &
P(1 phot.) > 0 implies
P(2 photon) > 0

Not Really Single Photon & Not Really On Demand!
First step to On-Demand production

Pulsed Laser

Single Photons only during pulse, but still not really On-Demand
Single Photons via Multiplexed Downconverters

Pulsed Pump Laser

~ 10% produce photon pair

Optical Cross Connects & Delays

Train of Single Photons

Separate P(1) from P(>1)

System requirements - fast switching < 10 ns low losses < 5%
Array of crystal downconverters each with the potential of producing a pair or pairs of photons. Each downconverter is shown with its own trigger detector. The information about which trigger detectors have fired is sent to the optical switching circuit to control which incoming
Experimental results showing multiplexed PDC Single Photon Generation
To realize a **SINGLE PHOTON SOURCE** we consider two key issues:

- **EFFICIENT PHOTON PAIR PRODUCTION**
  - Use of *periodically poled* crystals: Not yet used in metrology applications
  - Advantage of high pump conversion efficiency
  - What about the other characteristics?
  - Background fluorescence can limit the uncertainty achievable

- **COLLECTION OF THE HERALDED PHOTON IN A SINGLE-MODE FIBER**
  - Understanding and modelling the two-photon process
  - Detection of one photon of a PDC pair in a well defined **spatial** and **spectral** mode

And for commercial applications the **SINGLE PHOTON SOURCE** has to be *@ TELECOM wavelengths*
Periodically poled crystals: (PPLN)

**Ferroelectric domains periodically inverted**

Pump beam → Down converted photons

PDC in microstructures:

**Periodically poled wave guide**

Pump beam → Down converted photons
Experimental configuration

setup to herald single photons from CW PDC source from a PPLN crystal operating in a slightly noncollinear geometry

Laser source: CW Coherent VERDI
Pump Beam Power at crystal $\approx 350 \text{mW}$
$L_p$ with $f=1 \text{m}$
$w_p \approx 144 \text{mm}$

PPLN (MgO 5%) grating used = 7.36 $\mu\text{m}$
$T_{OVEN} = 131^\circ \text{C}$
$F_1$ centered at 810nm with FWHM = 10nm
$L_1$ and $L_2$ with $f=8 \text{mm}$
Zoom on experimental set-up

\( \lambda = 532 \text{nm} \)

oven with PPLN

dichroic mirror

pump cut-off

heralding \( \lambda = 810 \text{nm} \) 

1°

heralded \( \lambda = 1550 \text{nm} \) 

2°

data analysis
WORK IN PROGRESS ON...

- @810 nm
- @1550 nm

non degenerate case

- @1550 nm
- @1550 nm

degenerate case