Measuring photon quantities in the International System of Units

M. L. Rastello
INRIM, Turin, Italy

Abstract. Advances in nanotechnology, biotechnology and quantum communication need access to even more accurate photon measurements traceable to the SI, from one hand, and open up the possibility of counting and controlling photons one by one, on the other, affecting photometry and present realizations at the National Metrology Institutes. This paper deals with this technological revolution.

Introduction

The optical domain provides great richness and potential given the latest engineering demonstrations and design of novel states of light either in their photon squeezing properties or at the single photon level. Photon metrology can complement and strengthen the results of quantum optical technology (QOT) research in two ways: increasing its practicability/application and therefore its social and industrial impact, and feeding it with new scientific stimula.

This paper deals with the development of metrological tools for promoting QOT, as well as establishing new photon standards to cover existing and future requirements in the wider realms of metrology. The fundamental scientific nature, the breadth of the approach, the wide variety of materials and techniques used, as well as the range of operating wavelengths of the resulting "single-photon devices", are key features to success.

The core of photon metrology is formed by the design and realization of efficient single-photon sources, and the integration and application of novel single-photon detectors. This paper will discuss these techniques offering improved uncertainties in photon counting regime. The detectors and sources considered in this paper may, in turn, prove to be suitable reference standards that can be used to calibrate detectors and sources in the industrial environment. Furthermore, they can result in a step towards the goal of a redefinition of the relevant SI unit, the candela. It is possible to scale such a realization from the photon-counting to the macroscopic level required for other applications and thus act as an independent verification of existing high level standards.

Photon quantities and units

This paper addresses firstly the question about what units are the more appropriate to photon metrology, as quantities related to counts, like the number of photons, will have an increasing importance as technology proceeds into counting photons one by one.

Light can be treated as a wave or a particle, depending on the application. The present definition of the photometric units links any photometric quantity to the corresponding radiometric quantity at one wavelength, under a wave scheme for radiation. It gives no indication as to how realize them, so that new techniques can be adopted without changing the definition of the base unit. Today, NMIs realize the candela by cryogenic radiometry with uncertainties around the 0.005 to 0.001 % level. The detector and source scales are established at discrete wavelengths in the 0.1 mW – 1 mW regime. In scaling down to the photon counting regime there is an unavoidable degradation in accuracy.

In principle, there might be no difficulty in counting the number of photons in a light beam. However, the number of photons per second in, say, a lumen of a monochromatic beam is extremely large and virtually uncountable using current techniques. It is sufficiently large that no essential information is lost in considering photon number to be a continuous quantity. Instead of counting the number of photons per second in a lumen, for the SI it can be compared with whatever the number of atoms is in 12 gram of carbon-12, i.e. the number called mole.

In that respect, please note that, in the 1979 definition of the candela, the value 683 was chosen to minimize the changes in the mean representations of the photometric units as maintained by NMIs. Its theoretical value based on T(Pt)= 2042 K was 682, whereas experimental values obtained by relating photometric and radiometric units by NMIs lie within the range 673 to 687. By changing 683 into 681, the candela could be nicely defined in both radiometric and photon terms, as spectral radiometric quantities can easily be described in terms of photons. In other words, any radiometric spectral quantity $X_{e,v}$ being described in terms of the corresponding photon quantity $X_{p,v}$ as $X_{e,v} = hv\ X_{p,v}$, one could have in radiometric terms that *the candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 10^{12} hertz and that has a radiant intensity in that direction of 1/681 watt per steradian,* and, in terms of photons, that *the candela is the luminous intensity, in a given direction, of a source that emits photons of frequency 540 x 10^{12} hertz and that has a photon intensity in that direction of 681 10^{11} mole per second per steradian.*

The non trivial relationship between counting and measuring was already discussed by von Helmholtz, who came to the conclusion that, when counting identical objects, the counting unit is the object, not the number. In other words, when counting photons, the counting unit is one photon, not the number one. In metrology a unit of measurement is a particular quantity, defined and adopted by convention, with which other quantities of the same kind are compared in order to express their magnitudes relative to that quantity. On the contrary, a countable quantity is evaluated by counting its discrete and recognizable elements, e.g. photons, and differs from quantities that are treated as infinitely divisible in that its unit is indivisible. The question is whether it needs or not to be defined by reference to a standard or a physical experiment

Photon standards

In radiometry absolute standards are usually either sources or detectors. They both require using cumbersome metrological chains to reach the photon-counting level where QOT necessarily operates. QOT standards instead guarantee the better reliability and dynamic range for measurements in the quantum area of few-photon operation, i.e. the better accuracy when characterizing practical devices for quantum information processing and quantum communication.

As to detectors, the most important issue is the absolute measurement of the quantum efficiency of photon-counting detectors from the visible (VIS) to the IR region. This task is difficult to achieve due to a high level if intensity fluctuations in a weak light in general and, particularly, in the IR region where semiconductor detectors are typically extremely noisy. The major routes toward achieving this goal will be discussed thoroughly in this paper. Results on the absolute calibration of photo-detector quantum efficiency, using correlated photon sources generated via parametric down-conversion, have already been published. An inter-laboratory comparison demonstrated the inherent absoluteness of the photon correlation technique by showing its independence of the particular experimental setup used for down.conversion generation. The ultimate result of these investigations is the development of a robust measurement protocol that allows the uncertainties of individual measurements to be determined experimentally and verified operationally.

A new scheme proposed recently consists of producing polarization-entangled states. The measurement technique is based on a 90° rotation of the polarization of one photon member of a correlated pair produced by parametric down-conversion, conditioned on the detection of the other correlated photon after polarization selection. An interesting property of this technique is that measurement of the photons detected on the second detector allows a measurement of quantum efficiency of the first one, without needing, in principle, coincidence counts (at variance with the traditional bi-photon scheme).

As to standard sources, the major goal is the development of single-photon sources of known photon number over a wide spectral range. The truly efficient single-photon sources are presently still not available. The recent attempts using either single quantum dots, or single impurities, or single atoms as emitters bring hope and constitute a step forward in this direction. These devices provide ‘on-demand’ single photons in response to an optical or electrical pulse. A reasonable approximation of the physical single-photon source can be provided by the heralded SPDC with a multiplexed detection scheme and storage loop that has been proposed recently and the proof of principle has been demonstrated. In the short term the results from Parametric Down Conversion in a multiplexed configuration are expected to reach probabilities of single-photon generation of 70% per laser pump pulse (with a probability of multiple-photon emission suppression to better than 3%), given a theoretical expectation of 90% for an ideal quantum channel.

Conclusions

The major thrust of Photon Metrology is to make possible a scientifically supported performance analysis of different devices and procedures in real world applications of QOT. This paper shows that it provides a solid and accurate metrological basis governing the application and use of quantum resources, namely non-classical states of light and quantum entanglement, for characterizing detectors, sources and novel optical and photonics materials. Photon Metrology provides also intrinsically consistent, absolute, and self-testing methodology in terms of parameter evaluation, standards and procedures, and the necessary experimental background to move these methods out of the laboratory and into the hands of industry.

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