Drozdova, T. V., Pavlenko, Yu. F., & Tverytnykova, E. Ye. (2024). Quantum technologies in optical measurements. *Actual Issues of Modern Science. European Scientific e-Journal, 29*, 25-35. Ostrava: Tuculart Edition, European Institute for Innovation Development.

DOI: 10.47451/inn2024-04-01

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Quantum technologies in optical measurements

Abstract: The importance of light measurements from the point of view of ensuring accuracy and saving energy is considered. The study object is the quantum approach in the reproduction of optical units of measurement. The study subject is modern methodology in theoretical metrology, based on the concept of the New SI (2019). The purpose of the study is to analyze the current state of light measurements from the view point of ensuring accuracy and their energy efficiency. The analysis of quantum technologies of reproduction of optical units – candela, lumen is performed. The standards of Ukraine of candela and lumen, which were developed at the National Scientific Center "Institute of Metrology", Kharkiv, are analyzed. Practical aspects of realization of quantum effects on the example of modern light-emitting diodes which principle of action is based on quantum points are defined. Examples of the practical implementation of quantum photonics in the perspective of the next decade are identified. The opinion is expressed that the development of quantum technologies and practical achievements in the counting of individual photons bring us closer to the creation of devices of a new generation and to new achievements in precision and practical photometry.

Keywords: photoelectric effect, candela, lumen, photodetector, trap detector, standard of Ukraine, LED.

Introduction

The importance of light measurements is determined by the role played by vision in human life: about 80% of information about the world is one of the senses – sight.

The history of standards for light measurements begins in the 19th century, when the candle flame was used as a unit of light power. Over time, the technique of reproducing light quantities improved. The light intensity of all "flaming" standards largely depended on the purity of the fuel, the accuracy of maintaining the combustion regime, atmospheric pressure, air humidity, the percentage of carbon dioxide in it and a number of other factors. Taking into account all these conditions made it very difficult to assess the accuracy of the reproduction of the received light values.

In 1948, at the General Conference on Weights and Measures, a new name for the unit of light power was adopted – the candela. After a long discussion, in 1979, at the 16th General Conference on Weights and Measures, the following definition of the candela was adopted and is still valid: "The candela is equal to the power of light in a given direction of a source that emits monochromatic radiation with a frequency of $540 \cdot 1012\ Hz$, the energy power of which light in this direction is 1/683 W/sr".

The new definition of the candela opened the way to the development of new methods of its reproduction using not only a reference emitter (blackbody), but also a reference receiver. Today, two types of reference receivers are used: a cryogenic radiometer and a photoreceiver. The best metrological characteristics are provided by a cryogenic radiometer, but the use of new types of photodetectors in photodetectors – trap detectors with one hundred percent quantum efficiency – made them competitive in the creation of reference equipment.

The study object is the quantum approach in the reproduction of optical units of measurement.

The study subject is modern methodology in theoretical metrology, based on the concept of the New SI (2019).

The purpose of the study is to analyze the current state of light measurements from the point of view of ensuring accuracy and their energy efficiency.

Based on the purpose of the study, the following tasks were solved:

- analysis of the current state of optical quantum technologies, the principle of operation of which is based on the photo effect for the reproduction of optical blocks;
- research on the use of a precision radiometer based on a receiver to measure the power of light radiation from the point of view of accuracy;
- study of the metrological characteristics of the cryogenic radiometer during the practical implementation of the Ukrainian state standard of the unit of luminous intensity (candela);
- analysis of the accuracy of reproduction of a light flux unit (lumen) using the goniometric method and the ionizing sphere method;
- determination of ways of applied implementation of quantum effects in precision photometry, taking into account practical achievements in control and calculation of individual photons.

To achieve the set goal and solve research tasks, methods of such sciences as quantum physics, radiometry, photometry were used.

The research used the works and scientific sources of leading world scientists such as Barry N. Taylor, Christopher Chunnilall, Joanne C. Zwinkels, Shibu Saha, Ivano Ruo-Berchera, Giorgio Brida, Marco Genovese, Xiaobo Xue, Xiang Peng and Ukrainian scientists L. Nazarenko, P. Neyezhmakov, T. Timofeev, L. Grishchenko, M. Guriev, O. Kupko, V. Tereshchenko.

An analysis by the International Energy Agency showed that lighting costs 19% of the total energy budget. Therefore, it is important to create lighting technologies that provide not only high-quality lighting, but also energy conservation. Recently, the intensive development of light technology is noticeable not only in lighting, but also in medicine, biology, microelectronics, agriculture. Revolutionary advances in microelectronics have given impetus to new light sources – LEDs, which can be called light sources of the 21^{st} century. Solar panels, photometric converters of solar energy are used not only in space, but also in everyday life. In this regard, in many countries' special programs for energy conservation and ecology in the field of lighting are formed and implemented, which cannot be implemented without metrological support, which would meet the challenges of the time (*Pavlenko et al., 2017*).

The results of the study

1. Quantum technologies and reproduction of optical units

The main quantum effect on which optical quantum technologies are based is the photoelectric effect.

The following three laws of external photoeffect are experimentally established:

(1) the maximum initial velocity of photoelectrons is determined by the frequency of light and does not depend on its intensity;

(2) for each substance there is a "red border" of the photoeffect, to wit the lowest frequency of light v_0, at which the photoeffect is still possible;

(3) the number of photoelectrons emitted from the cathode per unit time (saturation photocurrent) is directly proportional to the light intensity.

In addition, the practical inertia of the photo effect is established: it occurs instantly when illuminating the surface of the body, provided that the frequency of light $v = v_0$, i.e., the effect exists.

First and second laws of the photoelectric effect contradict the electromagnetic theory, the propagation of light in space must occur in the form of separate portions of energy – photons. This interpretation of the nature of light allowed a new explanation of the laws of the external photoeffect, in particular, that the kinetic energy of the photoeffect depends on the frequency of light v and the output $A0$, and not on light intensity (the first law).

In addition, it turns out that the external photo effect is possible only at $hv > A_0$. From this formula, the lowest frequency of light at which a photoeffect is possible (red border) is calculated (the second law).

It is also substantiated that the number of photoelectrons that fly out of the metal every second is proportional to the intensity of light (third law).

On the basis of this effect the reference means of measuring equipment, and also the whole class of measuring photoelectric converters (sensors) are created. These include photoresistors, photodiodes, phototransistors, photothyristors. On the basis of these elements, a number of devices have been created, in particular, meters of optical quantities – photometer receivers.

The basic unit of SI in optical measurements (radiometry and photometry) is the candela, and the main method of its reproduction is the use of the photoelectric effect, which is realized with the help of a receiver – a photometer.

The photometer receiver uses photodiodes that convert light radiation into photocurrent. The circuit of the photodetector (photometer) is shown in Appendix (*Figure 1*), its essential components are a precision diaphragm, a filter adjusted for $v(X)$ function, and a photodetector.

Consider the principle of measuring the intensity of light using a photodetector (*Saha et al., 2020*; *Zwinkels et al., 2010*; *Nazarenko, 2000*).

We pay attention to the correcting filter, the frequency response of which corresponds to the characteristics of the human eye (*Zwinkels et al., 2010*), shown at Appendix (*Figure 2*).

2. Light flow standards based on the receiver

Using a new definition of the candela (*Taylor & Thompson, 2008*; *Xiaobo et al., 2014*), in the UK it was possible to create a standard based on the receiver, which provided an error of reproduction of the candela at 0.1%. A precision radiometer (optical radiation power meter) with electrical replacement was used as a receiver. Of the existing radiometers of this type, cryogenic radiometers have the highest accuracy. The cryogenic radiometer is a unique device that provides accurate measurements of radiation power in a wide spectral range, which covers the ultraviolet, visible and infrared regions of the spectrum (*Fox, 1991*).

The cryogenic radiometer is now considered to be the most accurate means of reproducing radiometric scales, it heads the traceability chain and forms the absolute radiometric basis. Cryogenic radiometers, which are used to sell the candela, make it possible to reduce the expanded uncertainty to (0.2-0.4)%. But, despite the positive qualities, the cryogenic radiometer is an expensive and quite complex device to manufacture and operate. Therefore, in recent years, alternative methods and means of reproduction of candelas have been developed, and the highest precision devices – cryogenic radiometers – are mainly used as unique devices that provide several areas of optical and physical measurements.

An important metrological characteristic of the photodetector is quantum efficiency – the ratio of the number of photons, the absorption of which caused the formation of quasiparticles (electrons), to the total number of absorbed photons. The term "photodiode conversion factor" is also used. It is a measure of light sensitivity and the main characteristic of photon detectors. In the receiver, the scheme of which is shown in Appendix (*Figure 1*), it is quite limited, because part of the light is not absorbed, reflected and penetrates the output of the photometer.

Initially, these devices had to be calibrated separately for photodiodes, but later this approach acquired new properties due to the advent of "trap detectors" (trap detectors), which increase the efficiency of photodiodes, creating light traps by repeatedly reflecting light. These photometers have a predicted high quantum efficiency (PQED) of about 99.95% and do not require calibration. Trap detectors allow you to measure the intensity of light with an uncertainty of several units by 10^{-6}. For serial photodetectors on trap detectors, the typical measurement uncertainty is from $0{,}5 \cdot 10^{-3}$ to $1 \cdot 10^{-3}$.

On the basis of this technology, standards of chandeliers, lumens, just like precision laser power meters were created (*Pavlenko et al., 2017*). Please note that the meters of photometric units (candelas, lumens) have a corrective filter "visibility", and the power meter – no.

The use of trap detectors as absolute receivers has become common practice. The primary standards of Canada, New Zealand, Germany, and Turkey are based on this principle. Given this, the use of expensive and complex during operation cryogenic radiometers becomes economically impractical. In recent years, there has been the development of a new configuration of the trap detector, consisting of two large photodiodes forming a wedge (*Figure 3*).

This configuration can be used as at cryogenic temperatures (while the uncertainty of power measurements may be less $1 \cdot 10^{-6}$), and at room temperature (*Figure 4*) with an uncertainty of about 10^{-4}.

The use of such devices opens up the possibilities of a new version of candela reproduction based on a white LED as a light source and a receiver based on a trap detector.

The development of photodiode receivers and their latest developments allow us to say that there has been a qualitative leap in the accuracy of calculating the conversion factor of photodiodes, which allows them to be used as receivers with predicted quantum efficiency (Predictable Quantum Efficient Detector).

3. The primary standard of Ukraine's unit of light intensity is candelas

In 1996, the primary standard of Ukraine was built on the basis of an absolute cryogenic radiometer, which successfully performed its functions until 2015 (*Pavlenko et al., 2017*). In 2015, it was decided to create a standard based on a trap detector (*Fox, 1991*; *Nazarenko et al., 2012*).

As part of the work on improving the standard in the NSC «Institute of Metrology» was developed, created and studied photometer (*Figure 5*), based on a trap detector.

The primary standard of Ukraine, in addition to the unit of light intensity (candela), also reproduces the units of illumination (luxury) and illumination (candela per second).

The standard has the following metrological characteristics:

- light reproduction range $1 - 500\ cd$;
- light reproduction range $0.1 - 1000\ lux$;
- lighting playback range $10^{-3} - 500\ cd \cdot s$.

The relative errors (random S and non-excluded systematic error Θ) and the extended uncertainty (U) of the reproduction of units of light intensity, illuminance and illumination do not exceed:

- the power of light – candela
  $S = 0{,}15 \cdot 10^{-2}; \theta = 0{,}15 \cdot 10^{-2}; U = 0{,}3 \cdot 10^{-2}\ (k = 2);$
- lighting – luxury
  $S = 0{,}15 \cdot 10^{-2}; \theta = 0{,}15 \cdot 10^{-2}; U = 0{,}3 \cdot 10^{-2}\ (k = 2);$
- lighting – candelas for a second
  $S = 0{,}25 \cdot 10^{-2}; \theta = 0{,}35 \cdot 10^{-2}; U = 0{,}6 \cdot 10^{-2}\ (k = 2).$

These values correspond to the world level.

4. Reproduction of a unit of luminous flux – lumen

Luminous flux, the unit of which is the lumen, has become the most important photometric quantity. In recent years, the international community of photometric photometrists has repeatedly raised the question of revising the basic unit of optics, namely the lumen instead of the candela. Therefore, one of the basic standards in the field of photometry, together with the standard of candela, is the standard of lumen. All developed countries of the world have such standards and are working to improve them.

There are two main methods of measuring total luminous flux, to wit lumen reproduction, on which the reference measurements are based:

(1) goniometric method;
(2) the method of integrating sphere.

It is the method of the integrating sphere, as more promising, that was chosen to create the primary standard of the lumen of Ukraine. The standard consists of a number of installations (*Figure 6*):

- installations for reproduction and transmission of a unit of light flux to radiation sources of small sizes;
- installations for reproduction and transmission of a unit of light flux to large radiation sources;
- systems of automatic control, registration and processing of information on the basis of computer technology;
- power supply systems for radiation sources.

The created standard has the following metrological characteristics (*Fox, 1991*; *Nazarenko et al., 2012*):

- range of luminous flux values $1 - 1500\ lm$;
- random error (SLE) – from $0.1 \cdot 10^{-2}$;
- unrecovered systematic error – from $0{,}25 \cdot 10^{-2}$;
- extended uncertainty – from $0.3 \cdot 10^{-2}$.

These characteristics are at the level of the corresponding characteristics of the national standards of economically developed countries.

Precisely due to the lack of reliable methods and means of manipulating individual photons, the redefinition of photometric units in quantum terms has not yet taken place.

Recent advances in the control and calculus of individual photons, just like in the creation of single-photon sources, look promising (*Xiaobo et al., 2014*). It is to be expected in the near future to create radiation sources with a precisely set number of photons per second, which will allow to obtain unprecedented precision of measurements. The ability to reliably manipulate individual photons will contribute to the development of new types of devices, which, in turn, require further development of metrology, the creation of new ones based on quantum phenomena, calibration methods and appropriate standards. For these reasons, sooner or later we should expect a redefinition of the candela in terms of photon units.

Currently, the international project “Quantum Candela” (*Neyezhmakov et al., 2013*), funded by the European Commission and aimed to review the basic unit of SI candela in terms of determining it by the number of photons, rather than optical power, thus linking to the Planck constant. It is also noted that this “will bridge the gap between macroscopic (optical power) and quantum quantities (photon), achieve greater consistency between the definitions of basic units and will promote the development of both quantum technology and classical radiometry” (*Xiaobo et al., 2014*).

5. Applied implementation

Today there are problems and even a crisis of modern semiconductor electronics. It has been found that integration in computing devices doubles every two years. However, at this time further integration is already difficult, heat dissipation increases significantly, parasitic quantum effects begin to appear, technologies become more expensive. Switching speeds and memory are also limited. All this leads to increased energy consumption, unprofitability and crisis. It is believed that semiconductor electronics has exhausted its capabilities.

According to the forecast, the basis of the new electronics, which replaces the semiconductor, are quantum principles and effects.

Modern quantum technologies and practical achievements in the control and calculation of individual photons promise new achievements in precision and practical photometry, the creation of new generation devices.

Separately it is necessary to talk about creation on the basis of quantum technologies of highly effective sources of illumination – light-emitting diodes which have made a kind of revolution in lighting engineering. Modern directions of development include the use of quantum dots, which allow to obtain white light (*Neyezhmakov et al., 2017*).

The first white LEDs were expensive and inefficient. However, the light output of LEDs has increased exponentially. Recent research and development have been disseminated by Japanese manufacturers such as Panasonic and Nichia, just like Korean and Chinese manufacturers such as Samsung, Kingsun and others.

Experimental white LEDs were demonstrated in 2014 to produce $303\ lm/W$; some can last up to 100,000 hours. However, commercial LEDs have an efficiency of up to $223\ lm/W$. The previous record of 135 lm/W was set by Nichia in 2010. Now the light output of modern LEDs reaches $190\ lm/W$ (*Samsung Achieves…, 2023*). The theoretical limit of the technology is estimated at more than $300\ lm/W$ (*Cree…, n.d.*). Compared to incandescent lamps, this is a huge increase in electrical efficiency, and although LEDs are more expensive to purchase, the total cost is much cheaper than incandescent lamps (*The quantum candela, 2011*; *In new quantum-dot…, 2010*; *LED bulb…, 2016*).

EURAMET sees among the most promising practical implementations of Qu-Photonic for the next decade single-photon LIDAR (technology for forest structure and carbon monitoring at large spatial scales because it acquires 3D measurements of vegetation faster and more efficiently than conventional lidar instruments), Quantum illumination (a model for target detection that employs quantum entanglement between a signal electromagnetic mode and an idler electromagnetic mode, just like joint measurement of these modes), Sub-shot-noise imaging, amplitude-squeezed spectroscopy, NV-centre sensing, squeezing and entanglement for gravity wave detectors etc. (*Figure 7*) (*Chunnilall, 2022*; *Tang et al., 2016*; *Brida et al., 2010*).

6. On the prospect of quantum redefinition of light units

In the frequency range $0 - 108\ Hz$, the mathematical apparatus of electric circuits with concentrated parameters works. Above these frequencies, the apparatus of Maxwell's equations begins to operate, which is used up to frequencies of about $1015\ Hz$ and even higher. Next, there is a rather wide transition region where the classical approach must be supplemented by a quantum one, and it is in this region that the visible frequency range is located.

Quantities, the value of which is due to the number of photons, are quantities of optical radiation, which are expressed in terms of the number of photons or the photon flux. Due to the ambiguous (corpuscular-wave) nature of electromagnetic radiation, photometric and/or energy quantities can also be expressed in terms of the number of photons. The relationship between the energy value at a given wavelength ($\mathrm{X}_{e,\lambda}(\lambda)$) and the corresponding value, the value of which is determined by the number of photons ($\mathrm{X}_{p,\lambda}(\lambda)$), is expressed as

$$\mathrm{X}_{e,\lambda}(\lambda) = \frac{hC}{\lambda} \cdot n_a(\lambda)\mathrm{X}_{p,\lambda}(\lambda),$$

where:

h is Planck's constant,

C is the speed of light in a vacuum,

$n_a(\lambda)$ is the index of refraction in air at a wave of a given length (λ).

The practical implementation of the above units can be performed using a receiver (detector) or a source, just like using the conversion of radiometric values into values whose value is determined by the number of photons given in equation. However, it is also possible to use sources that generate individual photons at a known speed, and count the number of photons ("one-photon tunneling" method). This approach is called "conditional on the number of photons".

In other words, it is necessary to be able to create radiation sources with a precisely known number of photons per second, just like receivers whose sensitivity and resolution can be at the level of one photon.

Since each photon can be thought of as a frequency-dependent quantum of energy, it is conceptually easy to relate the number of photons to the amount of energy or power.

For example, the light flux Φ can be represented by the number of photons n:

$$\Phi = \frac{n \cdot h \cdot f}{t},$$

where:

h is Planck's constant,

f is the frequency of light radiation ($540 \cdot 1012\ Hz$).

In turn, if we know Φ, we can calculate the photon flux:

$$\frac{n}{t} = \frac{\Phi}{h \cdot f}.$$

The energetic power of the radiation corresponds to the photon power (intensity)

$$(683 \cdot 540 \cdot 10^{12} \cdot 6.62603896 \cdot 10^{34})^{-1}$$

photons per second per steradian.

At this time, there are already experimental single-photon sources, just like detectors capable of counting individual photons (photomultipliers, single-photon avalanche diodes, superconducting nanowire detectors, etc.).

Today, it is still too early to talk about a reliable practical implementation of the "one-photon tunneling" method and photometric units determined by the number of photons. but single-photon sources and photon number detectors as experimental models already exist.

As in the "one-electron tunneling" method, there are, first of all, technological problems in practical implementation. However, research in this direction is actively continued, especially since one of the tasks of modern metrology is the creation of the "quantum candela" (and other photometric units).

Conclusion

The new definition of candela paved the way for the development of new methods of its reproduction using not only the reference emitter (black body), but also the reference receiver. Today, two types of reference receivers are used: cryogenic radiometer and photodetector. The best metrological characteristics are provided by a cryogenic radiometer, but the use of new types of photodetectors in photodetectors – trap detectors with 100% quantum efficiency – has made them competitive in the creation of reference equipment. One of the areas of research in fundamental radio and photometry is the search for ways to redefine photometric quantities through the number of photons, binding to the Planck constant. It is expected that this will achieve greater consistency between the basic SI units and promote the further development of optical measurements in general.

Research on quantum measurement technologies has contributed to the development of a number of applied optical quantum technologies and related devices: solar electricity sources – using the photo effect, thermal imagers and night vision devices – using the conversion of infrared radiation into visible light, photodiode lighting sources – using the quantum conversion of electricity into light.

Modern quantum technologies and practical achievements in the control and counting of individual photons promise new achievements in precise and practical photometry, the creation of new generation devices, the redefinition of photometric quantities through the number of photons, i.e., binding to Planck's constant. It is expected that this will allow for greater consistency between the basic SI units and contribute to the further development of optical measurements in general. Recent advances in the control and counting of single photons, just like in the creation of single-photon sources, look promising.

* * *

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Appendix

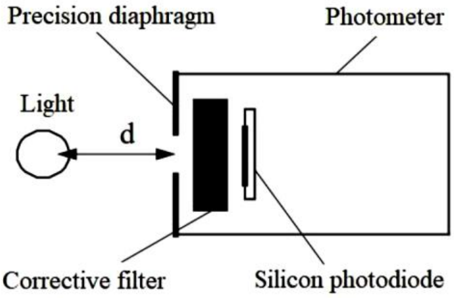


Figure 1. Optical scheme of the photodetector

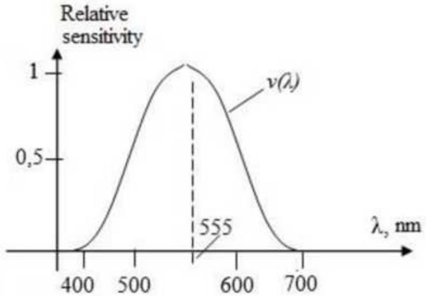


Figure 2. Characteristics of the spectral sensitivity of the human eye (curve of “visibility”)

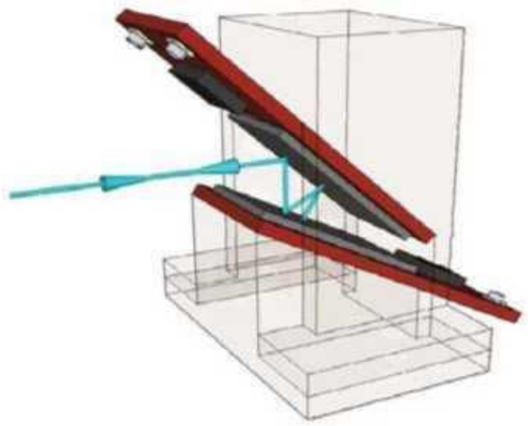


Figure 3. Optical circuit of a two-diode trap detector with 7-fold reflection

Figure 4. Industrial device with predicted quantum efficiency

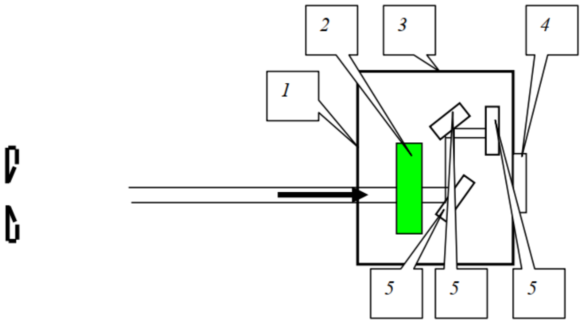
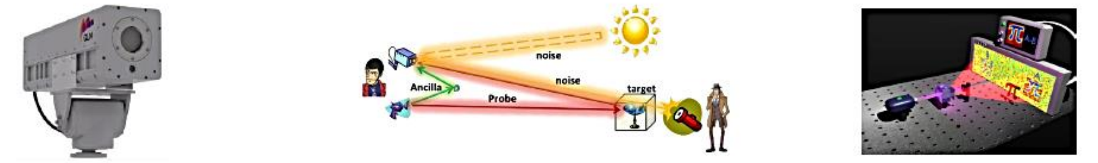


Figure 5. Scheme of a photometer based on a trap detector:
1 – diaphragm; 2 – filter V (λ); 3 – housing; 4 – a mirror; 5 – photodiodes S1337

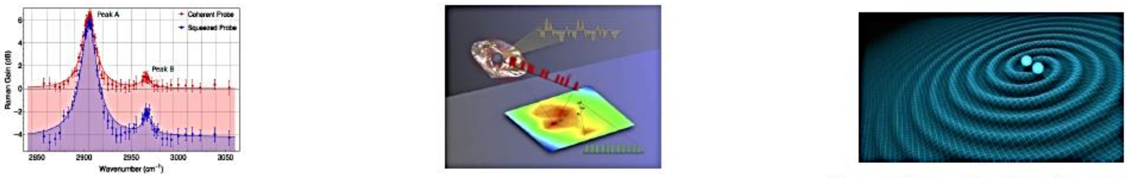
Figure 6. Appearance of the standard unit of luminous flux



Single-photon LIDAR

Quantum illumination

Sub-shot-noise imaging



Amplitude-squeezed spectroscopy

NV- centre sensing

Squeezing and entanglement for gravity wave detectors

Figure 7. Some photonics applications (*Chunnilall, 2022*)