Can you take a photograph of a photon?

Single photon detection in the age of quantum information

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Introduction

Light of a given frequency exists in discrete units or quanta. A quantum of light is known as a photon, which can behave as a particle. The energy of a photon is given by

$$E = hf \tag{1}$$

where f is the frequency of light and h is Planck's constant [1]. This relation was hypothesised by Max Planck in 1901 [1], to explain the frequency signature of light observed from stars, the blackbody radiation curve. In 1905, Einstein, suggested that light exists as discrete wavepackets of electromagnetic radiation [2]. This led to the development of quantum theory. However, at this time, the evidence that photons existed was only indirect. Planck initially thought that his light quantisation theory was just a mathematical tool to explain the blackbody radiation curve [1]. There was no way to detect a single photon.

Most phenomena are detected by illuminating an object with a light source and detecting the light that reflects off. This is essentially a 'photograph' of an object. However, photons only interact very weakly with eachother, so it is difficult to use a photon to detect another. Clearly, we can detect multiple photons, because this is required for a photograph, but is it possible to detect a single photon?

Quantum information is a relatively new field, which has many exciting applications including quantum cryptography and quantum computing [3]. Through this field, it has become useful to detect single photons, generating renewed interest in single photon detectors [4]. This has led to the development of a number of new technologies. Can we now take a photograph of a photon?

Quantum information

Quantum information is the storage of information in quantum systems. This usually involves putting a particle into a superposition of two quantum states [3]. Each particle is known as a qubit, the equivalent of a bit in conventional computing.

Photons can be put into a superposition of horizontal and vertical polarisation states, which allows their use as qubits [3]. The field of quantum information that uses photons as qubits is known as optical quantum information. Using photons as qubits is useful because photons only react weakly with the surroundings and are therefore relatively free of decoherence [4]. Decoherence is a process by which coherence of quantum systems is lost through interaction with the surroundings. Therefore the wavefunction of a photon does not collapse easily, so the superposition can be retained more easily than in other methods. Photons are also easy to transport, which is useful for quantum communication [5]. The fastest way to transport information is with photons since they travel at the speed of light. They can also easily be transported long distances along optical fibers [6]. This makes photons an attractive candidate for qubits in quantum information.

There are a number of possible applications of optical quantum information. Quantum key distribution (QKD) is a method of producing a secure key with which messages can be encrypted. The key is sent using photons as qubits, and cannot be eavesdropped without the knowledge of the sender and receiver [5]. Linear optical quantum computing (LOQC) is a form of quantum computation, which uses photons as qubits [7]. Quantum computation facilitates simultaneous calculations, speeding up calculations such as factorisation. These technologies require high performance single photon detection, which can be quantified by measuring a number of parameters. The requirements for each parameter depend on the application.

Photon detection parameters

Photon detectors cannot detect every incident photon. The detection efficiency is the fraction of photons hitting the detector that produce a count. This must be high in most applications, since the photons hold quantum information. Therefore, if a photon has not been detected, the information has been lost. This is particularly vital for LOQC, where it has been shown that the product of the single photon source efficiency and the detector efficiency must greater than 2/3 [8]. This is a lower bound, but it is desirable for the detection efficiency to be higher than this, since the source efficiency will not be 100%. In QKD, this is less important, since any unsuccessful transmissions are discarded [5].

The detection efficiency of a detector varies with photon frequency, and the range of frequencies over which the detector is sensitive is known as the spectral range [4]. The range required is highly dependent on the application and in most applications it is more important to have a high detection efficiency at one specific frequency. For example, in QKD, photons must be transmitted along optical fibres, which have minimum loss at a wavelength of 1,550 nm [5]. Therefore, it is desirable to have a high detection efficiency at 1,550 nm. For LOQC, the wavelength is less important, but it is still useful to transmit signals along optical fibres [7].

Single photon detectors also often produce 'dark counts', counts that are produced when there is not an incident photon [4]. The detector picks up a signal when there is not one, leading to spurious results. The frequency of these dark counts is known as the dark count rate, and should be as low as possible.

In applications such as QKD, it is desirable for information to be transmitted as quickly as possible [5]. Multiple photons must be detected individually for this to happen. However, single photon detectors have a non-zero time between the incident photon reaching the detector, and the output signal being produced. This time is variable, and the extent to which it varies is known as the timing jitter. The full width at half maximum of the distribution in time is often taken as the timing jitter. In order to transmit information as quickly as possible, the timing jitter must be reduced.

There is often also a period after the detection of a photon in which another photon cannot be detected, or the detection of another photon is unreliable. This is known as the dead time of a detector [4]. Again, this must be reduced in order to increase the speed of transmission of information.

For applications such as LOQC, it is important that if two photons arrive at the single photon detector at the same time, both photons must be detected, to prevent information loss. This is known as the ability of a detector to resolve photon number [4].

Established technologies

Prior to the introduction of the field of quantum information, there were already a number of photon detection techniques in place.

The first photon detector developed was photographic film, invented in the 1800s [9]. The film is coated with a gelatin emulsion containing microscopic silver halide crystals. When a photon hits the film, it may initiate a chemical reaction, which causes metallic silver to be produced in the development process, blackening the film.

The next technology developed was the photomultiplier tube, invented in 1934, as shown in figure 1. When a photon enters the tube, it hits a photocathode (electrode), which may cause an electron to be produced due to the photoelectric effect. A number of dynodes (electrodes) at progressively more positive potential make up the electron multiplier. When an electron hits a dynode, more electrons are produced. Therefore the electron multiplier produces multiple electrons, which are then attracted to an anode, producing a detectable current.

As part of research into semiconductors in the 1950s, the photodiode was invented [11]. It is fundamentally a P-N junction, which generates a depletion region with an electric field [11]. When an electron hits the depletion region, it may produce an electron-hole pair. The electron and hole are accelerated in opposite directions by the electric field. A high reverse bias voltage is applied to the diode, causing an avalanche effect [11]. When an electron (or hole) is produced, it is accelerated by the strong electromagnetic field, giving it high energy. The electron can then excite bound electrons into the conduction band. This process continues, producing a detectable current.

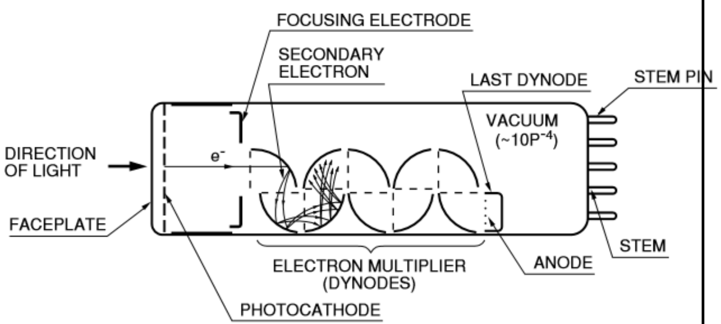

Figure 1: Diagram of a photomultiplier tube [10]. A photon hits the photocathode, producing an electron. The electron multiplier then produces many electrons.

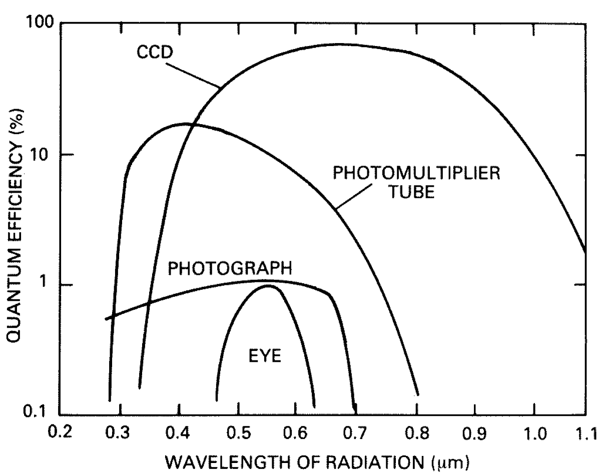

Figure 2: Detection efficiency against wavelength for established methods of photon detection [12].

These detectors have a number of different uses, but in order to be useful for quantum information applications, they must be capable of detecting single photons. Figure 2 shows how the detection efficiency of the established techniques vary with photon wavelength. It is clear that photographic film is not useful as a single photon detector, since the detection efficiency is less than 1% [4].

Photomultiplier tubes have a much higher detection efficiency. It is possible to achieve an efficiency of 40% at 500 nm [4], which is sufficient to be used for some forms of single photon detection, however it does not meet the minimum detection efficiency condition for LOQC. Also at the optimum wavelength for QKD, the maximum detection efficiency achievable is only 2% [4]. Therefore, photomultipliers are not sufficient for the new demands of quantum information.

Figure 2 clearly shows that photodiodes (which make up a CCD) have the highest detection efficiency and largest spectral range of the established methods. The detection efficiency can be improved by operating a photodiode above the breakdown voltage [4], the voltage at which the photodiode conducts in reverse bias. This means that the multiplication of electrons is diverging and a detectable current can be produced from a single photon. A photodiode operated in this way is known as an single photon avalanche photodiode (SPAD). It is possible to achieve a detection efficiency of 65% at 650 nm using a silicon SPAD [4], which is still insufficient for LOQC. However, at 1550 nm it is possible to achieve a detection efficiency of $\approx$ 20% by using semiconductor alloys [13], which is sufficient for QKD.

New technologies

As the field of quantum information developed, it became clear that the established techniques of photon detection were no longer sufficient due to the low detection efficiency discussed above. The only established technology which could possibly meet the demands of quantum information is the SPAD. However, SPADs are still very limited in their applications. Therefore, there has been a large growth in new technologies, with far improved single photon detection performance. These detectors have different strengths, depending on how the detector operates.

Frequency-up conversion:

It has been noted that 1,550 nm is the frequency of light with lowest loss in transmission through optical fibres. This is known as telecommunications frequency and is the optimal frequency for QKD. However, detection efficiency tends to be higher for smaller wavelengths or higher frequencies [13]. Therefore, if the frequency of a telecommunications wavelength photon is increased, it becomes easier to detect, and it is possible to achieve the maximum detector efficiency in QKD applications. Practically, this is achieved by combining the input photon signal with a pump signal [14]. This produces a signal with a frequency that is the sum of the input and pump frequencies. Tuning the frequency of the pump signal means that the final photons produced have a frequency that is the optimum frequency for the chosen single photon detector [14]. For example, telecommunications wavelength photons can be combined with a pump signal of wavelength 1064 nm to produce photons of wavelength 630 nm [15], which are then detected using a silicon SPAD.

This can be achieved with 90% efficiency, giving a 46% system detection efficiency [15] and a low dark count rate (20kHz). This is a large improvement on the 20% detection efficiency achievable with a semiconductor alloy SPAD alone. However, this technology is not useful in reaching the 2/3 efficiency required for LOQC. Also, the technique still relies on established technologies which cannot resolve photon number. Therefore, frequency-up conversion is more suited to applications such as QKD. However, the timing jitter is high (400 ps at 1,550 nm) and the dead time is high so the maximum rate of information transfer achievable is low [15]. A technology with a lower timing jitter and dead time would be desirable for QKD.

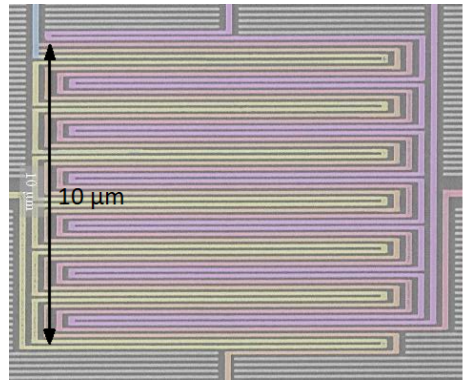

Figure 3: A typical superconducting nanowire single photon detector, made up of a wire of 100 nm width, which is maintained at a temperature below the critical temperature [16].

Superconducting nanowire single photon detectors:

A superconducting nanowire single photon detector (SNSPD) uses the properties of a superconducting material to detect photons. When a superconductor is cooled below its critical temperature, electrons form pairs known as cooper pairs, which act as bosons [17]. This allows all of the electrons to collapse into the ground state and become governed by a single wavefunction. Any 'kick' to increase the energy of the system, would perturb the whole system. Therefore, the electrons resist any 'kicks' which would cause resistance, leading to zero resistance [17]. An SNSPD is made up of a wire of 100 nm width, which is maintained at a temperature below the critical temperature (see figure 3) [18]. A current just below the critical current is passed through the nanowire. The critical current is the current below which the material has zero resistance. When a photon hits the nanowire, it breaks cooper pairs, causing an area with a non-zero resistance to form [18]. The current now flows through a region with some resistance, so a voltage pulse is produced, which can be detected.

The pulse produced is not correlated to the number of photons, so it is not possible to resolve photon number [18]. This means that the technology is not currently useful for LOQC. However, is possible to achieve a detection efficiency of 57% and a low dark count rate at a wavelength of 1,550 nm

[19]. The timing jitter (30 ps) and dead times are also very low, so this technology is capable of allowing high bit rates for QKD [19].

Currently, this technology is a superior alternative to frequency-up conversion for QKD and other similar applications.

Visible light photon counters:

Visible light photon counters (VLPCs) were developed from same principle as the avalanche photodiode. The key advantage of this technology arises from the fact that the avalanche is limited by the doping choice [20]. The area of the avalanche is much smaller than the detector area, meaning that multiple photons can be detected simultaneously and the detector is able to resolve photon number [20].

It is currently possible to resolve up to 5 photons using a VLPC[20]. The technique has a detection efficiency of 93% at a wavelength of 694 nm, with a low dark count rate (≈ 20 kHz) [21]. This makes VLPCs highly useful for LOQC and other quantum information applications. However, the timing jitter is high (270 ps at 694 nm), and the dead time is fairly high, meaning that the achievable rate of information transfer is fairly low [21]. Therefore, this technology is much better suited for LOQC than QKD.

Superconducting transition edge sensors:

A superconducting transition-edge sensor (TES) makes use of the temperature dependence of the resistance of superconductors. Near the transition temperature of a superconductor, a small change in temperature leads to a large change in the resistance, as the material transitions to zero resistance. A TES is made up of a thin sheet of superconducting material near the transition temperature [22]. If a photon hits the material, it is absorbed by the sheet, causing the temperature to increase. This causes the resistance of the superconductor to increase. The voltage across the sheet is kept at a constant value, so the current through the sheet drops, which is measured [22]. If one frequency of photon is used, the signal produced is proportional to the number of incident photons, so the detector is able to resolve photon number [4].

It is currently possible to resolve up to 8 photons with a TES [23]. The detection efficiency is also high at 95% at a wavelength of 1550 nm and the dark count rate is very low ($\approx 3kHz$) [24]. However, the timing jitter is high (100 ns) and the dead time is high [24]. Again, this technology is much better suited for LOQC than QKD.

Currently, TESs perform slightly better than VLPCs in quantum efficiency and ability to resolve photon number. However, with these technologies both advancing very quickly, either could become the superior detector for LOQC in the future.

Conclusion

Quantum information has triggered an explosion in single photon detection technologies. It has become possible to detect photons with near unity efficiency [24], so it can now be said that we can detect, or take a photograph of, a single photon.

In particular, the developments of LOQC and QKD have led to a very different set of requirements for single photon detectors. QKD requires low timing jitter and dead time, which has been provided by frequency-up conversion and SNSPDs [5]. SNSPDs provide far superior performance and appear to be the technology that will become used more often in the future. LOQC requires high detection efficiency and the ability to resolve quantum number, which has been provided by VLPCs and TESs [7]. Both technologies offer performance which is far superior to any established technology. Currently, TESs provide slightly better resolving ability and detection efficiency, but advances in the future could make either the technology of choice in this field.

These technologies have only recently developed, so are not yet widely used. In future years they will have a large impact in quantum information and other fields.

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A Plan feedback

Following the feedback from the plan, the article has been restructured, putting the quantum information section before the section on established detectors. The section describing the established detectors has been shortened as advised, to give more opportunity to discuss new technologies. An explanation of why the detectors are no longer sufficient has also been retained, as advised. However, the discussion on non-destructive detection has been removed, since this was somewhat tangential from the bulk of the material and did not flow well when included.

Can you take a photograph of a photon?

Single photon detection in the age of quantum information

Aim of the article:
The article will discuss the evolution of single photon detection, particularly with the advent of quantum information. The aim will be to assess whether we can now detect a single photon without destroying it.

Things that will not be discussed in the article:
The article will not discuss in detail how information is held in quantum systems or how this can be used in quantum computing and other applications. This will improve clarity and allow more focus on the photon detection itself.

Introduction:
This section will begin with a brief explanation of the concept of a photon as a particle of light and discussion of why and when the concept was first suggested. At the time, the existence of photons was only verified indirectly. This will be used to introduce the questions of whether we can detect a single photon and whether we can detect a photon without destroying it ('take a photograph' of it). The idea that this may be useful in quantum information will be suggested, but without any detailed explanation.

Traditional Photon Detection Techniques:
This section will outline how tradition methods of photon detection work and when they were introduced. The methods discussed will be photographic film, the photomultiplier and the photodiode (in order of invention). The limitations of these methods for detecting single photons will be discussed, introducing the concepts of spectral range, quantum efficiency and dark count rate, to quantify the performance of the detectors.

The new challenges of quantum information:
First, the field of quantum information will be introduced, with a mention of some applications. It will then be explained that photons are relatively free of decoherence, and can transmit signals quickly, making them useful for holding quantum information. The need to detect single photons for quantum information to be recovered will be discussed. This will lead on to an explanation of why the low performance and absorption of the photon in traditional techniques would lead to loss of information.

New technologies:
The first part of this section will discuss new forms of single photon detection which absorb the photon, including frequency-up conversion, single photon avalanche diodes and the superconducting nanowire. The fundamental principles of each technology will be explained. Then, the advantages of high detection efficiency and low dark count rate will be weighed up against the disadvantage that the photon is absorbed, potentially destroying information.

The second part will discuss non-destructive photon detection and the advantage that quantum information is preserved. It will also be discussed that this method currently has a much lower single photon detection performance than the other techniques. However, this is a relatively new technology, so the performance is likely to improve. Therefore, this appears to be the most likely technology to provide non-destructive, high performance photon detection in the future.

Conclusion:
The key questions of whether we can detect a single photon and whether we can detect a photon without destroying it will be restated. It will be concluded that while both can be separately achieved, we still cannot detect a photon with over 90% efficiency, without destroying it in the process. Therefore, storing quantum information using photons is not yet achievable. The final comments will summarise that we still cannot 'take a photograph' of a photon, but non-destructive photon detection could allow us to in the near future.

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