Single photon detection of degenerate photon pairs at 1.55 µm from a periodically poled lithium niobate parametric downconverter

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(Received 3 July 2003)

Abstract. The performance of a communication system that uses 1.55 µm correlated photon pairs is analysed experimentally in terms of achievable coincidence rates, optimal pump rates, and the performance of custom-built photon-counting detectors at 1.55 µm. The testbed considered in this study uses standard telecom fibre, twin photons, and photon-counting detectors. Degenerate cw time–frequency entangled photon pairs are produced via quasi-phase-matched spontaneous parametric downconversion in bulk periodically poled lithium niobate. The photon pairs are efficiently collected into a single-mode fibre and are sent to a pair of custom-built InGaAs photon-counting avalanche photodiodes that are passively quenched, gated in Geiger mode, and thermoelectrically cooled to temperatures as low as −60°C. Reliable photon-counting operation with a quantum efficiency of 20% at a dark count probability of 0.04% per gate (20 ns) and negligible afterpulses is reported.

1. Introduction

Sources of twin photons and 1.55 µm sensitive photon counters are essential for the experimental demonstration of novel architectures for entanglement-based long-haul quantum communication [1]. Correlated and entangled pairs of photons can also be useful for implementing quantum key distribution (QKD) protocols [2, 3]. Many of these architectures require entangled photons that are generated in a continuous wave (cw) process [1, 2]. While the performance of indium gallium arsenide (InGaAs) single photon counting detectors has been analysed in faint-laser-pulse QKD systems [4] and pulsed photon-pair experiments [5], the gated operation of these detectors makes their use in cw architectures more challenging. In this paper, we analyse the performance of a basic quantum communication system that uses degenerate, cw, 1.55 µm photon pairs, standard telecommunication fibre, and two InGaAs photon counters with high intrinsic dark counts.

The polarization of light is not maintained in most installed optical fibre, so protocols using time–frequency, rather than polarization, entangled photons are generally used in fibre-based systems [2]. A basic setup for fibre-based quantum communication, shown in figure 1, includes a source of time–frequency entangled photons and a pair of single-photon counting detectors. Entangled-pair quantum
communication systems rely on the coincident detection of both photons from a pair. When the photon counters have high noise levels, the pair production rate must be carefully optimized to avoid errors from either uncorrelated pairs or the dark counts. In this paper, we evaluate this basic quantum communication testbed and we analyse issues related to the achievable pair distribution rate, signal to noise, and reliability of this system due to the less-than-optimal performance of currently available photon-counting technologies. We also report the development of a 1.55 μm correlated photon source and the performance characteristics of 1.55 μm photon counters suitable for use in fibre-based quantum communication experiments. Finally, we consider how a quantum communication system might perform if photon counting detectors at 1.55 μm were available with near-silicon quantum efficiency and dark counts.

This paper is structured as follows: in the following section, we describe the design and performance characteristics of our custom-built InGaAs photon counters. In section 3, we discuss the experimental setup and describe our cw source of 1.55 μm degenerate photon pairs. Section 4 analyses the performance of the basic quantum communication system shown in figure 1 in terms of the source and detector performance. This analysis is used in section 5 to consider the performance of a testbed using Geiger-mode InGaAs detectors (described in section 2) and a 1.55 μm photon-pair source (discussed in section 3). This model is experimentally verified and additional predictions are made for a system with realistic losses and better-performing detectors. We conclude with a discussion of results and by mentioning the implications of this study to quantum communication protocols.

2. Photon counters at 1.55 μm

The drawback to working at 1.55 μm is the difficulty of counting single photons at this wavelength. Silicon avalanche photodiodes (APDs) such as PerkinElmer’s model SPCM-AQR-14 offer turnkey, reliable, continuous Geiger-mode operation at peak rates of ~20 MHz, with dark counts of less than 100/s, and quantum efficiencies (QE) in excess of 70%. Two-dimensional photon-counting APD arrays with thousands of pixels are now fabricated in silicon [6] for use in a variety of communication, imaging, and laser radar applications [7]. However, the silicon bandgap strictly limits their detection range to wavelengths shorter than 1.1 μm.
Low-light-level operation at longer infrared wavelengths, including those in the telecom bands, requires either germanium, indium gallium arsenide/indium phosphide (InGaAs/InP) APDs or photomultiplier tubes (PMTs). Germanium APDs are extremely noisy, require cooling to cryogenic temperatures for decent performance and, at liquid nitrogen temperature, do not appear to work well for wavelengths beyond 1.45 µm [8]. A Hamamatsu near-infrared PMT (R5509-72) is functional as a photon counter up to 1.7 µm but only barely—at 1.6 µm it has a QE of ~ 0.4% at a temperature of −80°C.

For single-photon detection at telecom wavelengths, the best option is to use InGaAs/InP APDs. Several groups have reported the gated and passively quenched Geiger-mode performance of commercial, separate absorption and multiplication InGaAs/InP APDs [4, 9]. To be useful in photon counting, these detectors are typically cooled using liquid nitrogen and their temperature is adjusted via Peltier-heating of the fixture. This allows for the characterization of these devices over a wide range of temperatures and good numbers have been reported near 180 K [4, 9, 10].

The two main sources of noise are spontaneously excited dark counts and afterpulses. Dark counts constitute random noise which is indistinguishable from the signal counts and follow a Boltzmann-type exponential curve as a function of device temperature—they decrease exponentially with decreasing temperature. Afterpulses are generated by the trapping, and subsequent release, of charged carriers during avalanche events and they also contribute to the total dark count rate. Afterpulsing appears to vary inversely with temperature and linearly with gate duration. As the device temperature is increased, the thermally excited dark counts increase while the lifetime of trapped carriers, and thus the afterpulsing probability, decreases. The abundance of trapped-carrier-induced afterpulses and the high dark count rates preclude the continuous operation of the current InGaAs/InP APDs in Geiger mode. The APDs must instead be operated with short-duration gates. The gate repetition frequency, width, and magnitude all affect device performance and must be optimized when designing a custom photon counter.

The overall design of our detectors was a compromise between decent QE, low dark count probability, sufficient gate repetition frequency, and operation at temperatures that can be achieved and long-term stabilized entirely by Peltier elements. InGaAs APDs from the Epitaxx division of JDS Uniphase (EPM239BA) and PerkinElmer (C30644E-DTC) were evaluated for this purpose. The dark count reduction for ΔT ~ 50°C was not as large as desired in the PerkinElmer devices, which attested to the overwhelming existence of afterpulses. Additional tests were then performed on the JDS Uniphase devices, as they were superior to the PerkinElmer APDs. The following experimental setup description and performance results refer exclusively to the JDS Uniphase devices.

Encouraged by previous research, which indicated that the most desirable region of operation could be near −60°C [4, 9], we built a small, sealed, aluminum enclosure for our JDS Uniphase InGaAs APDs. The TE cooler, detector, and pre-amplifier circuit board were all housed inside this box. The fibre-pigtailed detectors were mounted in a small copper block, which sat on the cold side of a four-stage, moisture-protected, TE cooler. The hot side of the TE cooler was in contact with a trapezoidal heat sink. Two precision thermistors were used to monitor the temperatures of the copper block–APD fixture and the heat sink.
A TE cooler controller (Alpha-Omega) was used to adjust the temperature of the detector and hold it constant with ±0.1°C long-term stability. The entire cold box was placed on top of four additional TE coolers. If required, these coolers could actively heat sink the cold box. With this entirely solid-state setup, we were able to cool the APDs down to about −70°C without any need for liquid nitrogen [11].

The InGaAs APDs were plugged into a two-layer printed circuit board. The board was populated on one side with microwave capacitors and low-footprint resistors and had ground planes sandwiching 50Ω microstrip transmission lines for the gate input and wide-bandwidth APD output signal. All circuit components were located in near proximity to the APD to minimize ripples in the output signal resulting from high-speed operation of the device. An SMA output for the APD signal and a test point were available on the detector pre-amplifier board. The test point was used to monitor the gate and cathode voltage using a high-impedance oscilloscope, while the wide-bandwidth output measured the photon arrival time.

For passively quenched Geiger-mode operation, a positive DC bias was applied to the diode’s cathode or negative port. A 20 ns long, 4 V gating pulse was added to the variable DC voltage to bring the voltage across the diode (over bias) to the desired level. The gating pulse was applied through a bias-tee circuit directly to the detector’s cathode at selectable frequencies between 1 kHz and 1 MHz. The voltage drop resulting from the avalanche signal was coupled across a 50Ω resistor into an SMA coaxial cable and sent to an RF amplifier with adjustable gain. The resulting avalanche pulses had sub-nanosecond rise times and varying widths depending on when the photon arrived (early or late) within the gate [11].

Quantum efficiency measurements were performed using a cw tunable laser at 1.55μm (HP8168A) with < 0.6 pm linewidth. The light was first sent through a polarization-independent fibre isolator and then attenuated to ~ 0.1 photons per 20 ns (~ 0.85 pW) using a precision variable fibre optic attenuator (JDS Uniphase HA9) with a wide dynamic range and calibrated, wavelength-flattened, fibre optic tap couplers with 95–5% and 99–1% splitting ratios. Laser power was monitored using a precision lightwave multimeter (HP 8153A) with sensitivity to ~110 dBm. The APD output was fed into an event counter (Stanford Research SR620), which recorded the photoelectron hits.

At a fixed temperature, time-stamp measurements were used to obtain time-of-arrival histograms. These histograms were made both with and without input light in order to record the dark levels and to compute the QE. Since the detector is passively quenched, at most one count can be detected per gate, regardless of the incident photon flux. Therefore, care must be taken when computing the quantum efficiency. With an input light flux of ~ 0.1 photons/gate, the multiphoton probability is, assuming a Poisson process, no more than ~ 1.1%. The light-count histogram was computed for the JDS Uniphase APDs at a temperature of −50°C. The distribution of counts confirmed the existence of an evenly distributed detection probability throughout the gates, which were provided by an internally triggered DG535 pulse generator with 100 ps accurate digital delay. The dark-count histogram featured random hits during the gate duration, as expected from a Poisson process.

In typical evaluation experiments of these InGaAs APDs, the device temperature, gate repetition frequency, gate width, and DC bias were varied to map the detector performance and obtain a desirable set of operating parameters. The typical behaviour of the JDS Uniphase InGaAs APDs is summarized in figure 2.
The data confirmed several known facts about semiconductor device and Geiger-mode APD physics—dark counts increase exponentially with increasing device temperature (figure 2(c)) while the breakdown voltage increases linearly with temperature, at \( \sim 0.1 \, \text{V/}^\circ\text{C} \) (not shown). The QE was found to increase linearly
with over bias (figure 2(a)) while the dark counts rose at a faster rate (figure 2(b)). The total dark count rate is nearly constant over a wide gate repetition frequency range and shoots up when the contribution due to afterpulses begins to dominate, typically above 200 kHz at $-60^\circ$C for the devices tested (figure 2(d)). As expected, the total dark counts were found to increase linearly with gate duration (figure 2(e)). Finally, the typical shape of the detection efficiency as a function of wavelength is shown in figure 2(f).

A good combination of parameters suitable for our experiments consisted of temperatures between $-50^\circ$C and $-60^\circ$C with $\sim 3.7$ V over bias and less than 50 kHz gate repetition frequencies in order to completely eliminate the afterpulsing contribution to the dark count rate. Figure 3 plots the two most important Geiger-mode device parameters, QE and dark count probability, for

Figure 3. Quantum efficiency at 1.55 $\mu$m versus dark count probability for the two InGaAs APDs used in the photon-pair experimental testbed. The data shown are for detectors 1 and 2 both TE cooled to $-50^\circ$C and gated at 10 kHz with 20 ns long pulses.
the two InGaAs APDs used in the testbed (section 3). Each data point in figure 3 corresponds to a different over bias level. Quantum efficiencies in excess of 20% with dark count probabilities per 20 ns gate on the order of 0.075% at $-50^\circ\text{C}$ resulted in good signal-to-noise photon-counting performance. Operation at $-60^\circ\text{C}$ was also possible with $\sim 13\%$ to $19\%$ quantum efficiencies and $0.018\%$ to $0.041\%$ dark count probabilities per gate, respectively, for the better of the devices tested.

3. Experimental setup

Several photon-pair generation schemes that use the $\chi^{(2)}$ nonlinearity of optical crystals to generate pairs of photons have been reported in type-I and type-II single-pass and cavity-enhanced configurations [12]. The common feature of all these schemes is that they use spontaneous parametric downconversion (SPDC), a process similar to photon fission [13]. Many of these schemes have employed pulsed-laser SPDC in critically phase matched birefringent crystals, like beta-barium borate (BBO). Our source takes advantage of noncritical quasi-phase matching (QPM) [14] in a periodically poled lithium niobate (PPLN) crystal [15]. The advantage of this source is that it permits temperature-tunable noncritical-angle phase matching and allows access to the largest nonlinear coefficient of lithium niobate, $d_{33}$, which is not available for birefringent phase matching. Although first-order QPM reduces the effective nonlinear coefficient by approximately 40%, since $d_{33}$ is a factor of six greater than $d_{31}$, the effective nonlinearity is still $\sim$ four times larger than $d_{31}$, allowing for more efficient SPDC. Moreover, QPM allows for a wide acceptance angle and the output beams are co-polarized and collinearly propagating with little walk off, making the manipulation and eventual coupling of these beams into single-mode fibre easier.

A z-cut, 1 cm long, PPLN crystal (Deltronics Inc.) was used with a 19 $\mu$m grating period for first order, type-I quasi-phase-matched SPDC. The crystal, anti-reflection coated on both faces at 775 nm and 1.55 $\mu$m, was placed inside a commercial heater (Super Optronics) with $\pm 0.1^\circ\text{C}$ long-term stability. Figure 4 shows the schematic of the experimental setup for single-pass SPDC. At a crystal temperature of $\sim 58^\circ\text{C}$, quasi-phase-matched SPDC of 775 nm light resulted in degenerate signal and idler beams at 1.55 $\mu$m centre wavelengths over a 130 nm wide bandwidth.

A strong cw pump at 775 nm, from a Verdi 5-pumped Ti:Sapphire laser, was used to generate the co-polarized and collinearly propagating degenerate photon pairs. The 775 nm pump first passed through a Faraday isolator to prevent back-reflections and a half-wave plate and polarizing beam splitter that functioned as a variable attenuator. The polarization of the pump beam was TM-polarized relative to the plane of the optical table. The crystal’s z-axis was oriented horizontally or parallel to the table, and hence all input and output beams were horizontally polarized as required for type-I QPM. The residual 775 nm light was removed with two long-pass filters with $4 \times 10^{-10}$ net transmission at 775 nm and 70% transmission of 1.55 $\mu$m light.

Both the signal and idler 1.55 $\mu$m photons were collected into a single fibre. This fibre must be carefully aligned to the degenerate spatial mode so that only photons from correlated modes are sent to the detectors, a challenging task
In our setup, the focal length and position of the coupling lens are chosen such that the accepted spatial mode is loosely focused at the centre of the crystal, with a Rayleigh range many times longer than the physical length of the crystal. In order to efficiently couple the 1.55 μm downconverted photons into a standard telecom fibre, the spatial mode of 1.55 μm light is calculated starting from the fibre and working backwards into the bulk PPLN crystal. A lens with $f = 300$ mm is selected to focus the pump beam so that its diameter inside the crystal matches the diameter of the calculated 1.55 μm mode [16]. This arrangement is similar to the one reported by Kurtsiefer et al. [17]. Using measured detection efficiencies and insertion losses, the probability of coupling the idler photon into the fibre given a coupled signal photon was calculated to be greater than 60% for this setup.

The fibre-coupled photons were then split by a 50/50 wavelength-flattened coupler, and each output sent to the InGaAs APDs operating in Geiger mode. The electrical outputs from the detectors were sent into a time-to-amplitude converter (TAC) and single-channel analyser (SCA) that are used as a coincidence circuit. A counter is used to record the number of counts from each individual APD and the number of coincidences.

In order to optimize this setup for coincidence measurements, the difference in path length from the pulse generator to the detectors must be matched to the difference in fibre length following the 50/50 splitter, so that the detection of coincident photons occurs at the same point within the gate pulse for both detectors. While the difference in fibre path length is difficult to adjust, the electronic path lengths can be easily changed. The pulse generator allows an accurate digital delay to be introduced between the gating pulses that start Geiger-mode operation in each of the detectors, so the timing of these pulses can be set to compensate for the fibre path difference. Next, the SCA window must be centred
to accept output pulses from coincident detections. An additional length of coaxial cable can be added before the stop input to the TAC and the TAC/SCA controls can be adjusted to find the peak in coincidences while the downconversion is coupled into the detectors. The length of the SCA coincidence window cannot be smaller than the detector and electronics jitter, which is \( \sim 400 \text{ ps} \). A 1 ns coincidence window is selected so that most paired detections (> 90%) result in coincidences while minimizing coincidence counts from uncorrelated detection events.

In addition to optimizing the coincidence circuit for counting correlated pairs of photons, we also need to experimentally measure the background in the coincidence rate. Background coincidences can occur because of simultaneous dark counts, a dark count and a photon count or two photon counts from different pairs, so blocking the source of paired photons does not give an accurate background measurement. The best way to measure the background is to offset both the SCA window and the gating pulses by \( \sim 20 \text{ ns} \), an amount large enough to yield zero true coincidences between photon pairs. The offset in gate timing turns the detectors on at different times, preventing any paired events from being seen by both detectors. It does not, however, affect the single counting rates because the pairs are produced in a cw process. The SCA is also offset, so that coincidences occur between events that are 20 ns apart. This correlates events that occur at the same relative time with respect to the start of the gate at each of the two detectors. Since the noise is uncorrelated to begin with, offsetting both the gating pulses and the SCA allows the background to be measured experimentally.

4. Photon pair system performance analysis

The performance of a quantum communication system that uses twin photons can be evaluated with a simple testbed in terms of the achievable data rate and signal-to-noise ratio (SNR). The data rate is defined here to be the rate at which both photons of an entangled photon pair are detected, producing a coincidence count. The noise, or error rate, consists of any coincidences that are not the result of detecting both photons from an entangled pair.

Four detector parameters affect the performance of the system: detection efficiency, repetition rate, dark count probability, and timing jitter. The pair production rate, system losses, and background noise also influence the system’s performance. For this analysis, all noise will be considered to have Poisson statistics and will be attributed to either uncorrelated photon pairs or dark counts. We set the gate repetition frequency to 40 kHz to minimize the probability of afterpulses, which are omitted from the following analysis.

The InGaAs detector performance was described in section 2. We now consider the pair production rate and net system losses. The mean number of pairs generated per gate can be calculated using a procedure described in [18], where the coincidence rate and both single detector rates are used to infer the pair generation rate. This procedure can also be used to determine the total losses in the system. In order to apply this calculation to the low photon fluxes considered, we must perform background subtraction. The background for the single detector rate is simply the dark count rate. The coincidence background is the rate of coincidences that do not result from the detection of both photons from a pair, namely the error rate considered in this section. This rate can be measured by moving the gating
pulses and SCA window as described in section 3. The three rates can therefore be expressed as:

$$Counts_1 \approx \frac{S_{1,\text{signal}}}{1 - S_{1,\text{signal}}/2R_{\text{gating}}} - S_{1,\text{dark}} \approx p(cnt_1|\text{pair})N_{\text{pair/gate}}R_{\text{gating}}$$  

$$Counts_2 \approx \frac{S_{2,\text{signal}}}{1 - S_{2,\text{signal}}/2R_{\text{gating}}} - S_{2,\text{dark}} \approx p(cnt_2|\text{pair})N_{\text{pair/gate}}R_{\text{gating}}$$  

$$Counts_{\text{coinc}} \approx S_{\text{coinc, signal}} - S_{\text{coinc, backgrd}} \approx p(\text{split})p(cnt_1|\text{pairsplit})p(cnt_2|\text{pairsplit})N_{\text{pair/gate}}R_{\text{gating}},$$  

where, $Counts_{\text{channel}}$ are the background and dead time corrected counts on channel = \{1,2,coinc\}. $S_{\text{channel,signal}}$ represents the counts measured on channel = \{1,2,coinc\}, $S_{\text{chan,dark}}$ the dark counts measured on channel = \{1,2\}, $S_{\text{coinc,backgrd}}$ the background coincidences, $R_{\text{gating}}$ the gating repetition rate, and $N_{\text{pair/gate}}$ the mean number of pairs produced per gate. The scale factor, $1/(1 - S_{\text{channel,signal}}/2R_{\text{gating}})$, corrects for the fact each detector can only count one event per gate, although it is a small correction for the data in this paper. The probability of multiple dark counts within a gate is small enough to neglect a similar correction or coincidences.

The probability of the pair splitting, $p(\text{split})$, is 50%. It should be noted that the conditional probability of counting a photon given that the two photons are split into different channels is not exactly equal to the conditional probability of counting a photon given only that a pair is generated, as assumed in [18]. Before we condition the detection probability on the pair splitting, each channel has a 25% chance of receiving no photons, a 50% chance of receiving one photon and a 25% chance of receiving two photons. The photon counters can only resolve one event at a time, so the conditional probabilities are related by:

$$p(cnt_{\text{channel}}|\text{pair}) = p(cnt_{\text{channel}}|\text{pairsplit})\left[1 - \frac{p(cnt_{\text{channel}}|\text{pairsplit})}{4}\right].$$  

As the conditional probability of detection approaches zero (low detection efficiency or high system losses), the two probabilities become equal because the detector registers twice as many counts given two photons as it does given one photon. Equation (4) is actually two equations, so we can use equations (1)–(4) to solve for the five unknowns: the mean number of pairs generated per gate ($N_{\text{pair/gate}}$) and the four conditional probabilities.

The expected data and error rates can be expressed in terms of the parameters discussed above. Assuming the detector jitter is much smaller than the gate interval and assuming the fibre and electronic path lengths are matched so that coincident detections are centered in the SCA window, we can calculate:

$$R_{\text{Data}} = R_{\text{gating}}(1 - e^{-N_{\text{correvents/gate}}})\frac{N_{\text{pair/gate}}p(cnt_1|\text{split})p(cnt_2|\text{split})}{2N_{\text{correvents/gate}}}$$  

$$N_{\text{correvents/gate}} = N_{\text{pair/gate}}\left[p(cnt_1|\text{pair}) + p(cnt_2|\text{pair}) - \frac{p(cnt_1|\text{split})p(cnt_2|\text{split})}{2}\right] + N_{\text{dark, 1/gate}} + N_{\text{dark, 2/gate}}$$
and

$$R_{\text{Error}} = R_{\text{gating}}(1 - e^{-N_{\text{uncorrevents/gate}}}) \left[ \frac{N_{\text{pair/gate}}p(cnt_1|\text{pair}) + N_{\text{dark,1/gate}}}{N_{\text{uncorrevents/gate}}} \right]$$

$$\times \left( 1 - e^{(\Delta SCA/2\Delta\text{gate})(N_{\text{pair/gate}}p(cnt_2|\text{pair}) + N_{\text{dark,2/gate}})} \right)$$

$$+ \frac{N_{\text{pair/gate}}p(cnt_2|\text{pair}) + N_{\text{dark,2/gate}}}{N_{\text{uncorrevents/gate}}}$$

$$\times \left( 1 - e^{(\Delta SCA/2\Delta\text{gate})(N_{\text{pair/gate}}p(cnt_1|\text{pair}) + N_{\text{dark,1/gate}})} \right)$$

(7)

$$N_{\text{uncorrevents/gate}} = \frac{N_{\text{pair/gate}}[p(cnt_1|\text{pair}) + p(cnt_2|\text{pair})]}{N_{\text{dark,1/gate}} + N_{\text{dark,2/gate}}}$$

(8)

where $R_{\text{gating}}$ is the repetition rate of the detectors, $N_{\text{dark,chan/gate}}$ is the mean number of dark counts per gate on channel = chan = \{1,2\}, and $\Delta SCA/\Delta\text{gate}$ is the length of the coincidence window relative to the total gate interval.

The equations are derived by enumerating the sources of photon counts, which are referred to as events. We consider coincidences between paired photons as a single event so that only Poisson processes are considered. This allows one to find the total rate by adding together the rates of each separate process. The rates, including all events, are given by $N_{\text{correvents/gate}}$ when including true coincidences and $N_{\text{uncorrevents/gate}}$ when considering only background coincidences. The difference in rates comes from the fact that both photon counts are combined into a single event when they result in a true coincidence count.

The data and error rates can then be calculated by multiplying the gate repetition rate, $R_{\text{gating}}$, the probability of one or more events within a gate, $(1 - e^{-N})$, and the probability that a coincidence occurs given an event. This final probability can be calculated simply by dividing the rate at which coincidences occur by the total event rate, since we are splitting Poisson processes. The data, or true coincidence, rate is the product of the pair generation rate, $N_{\text{pair/gate}}$, the 50% probability of splitting a pair and the two conditional probabilities of detection, as first given in equation (3).

The errors, or background coincidences, have two independent sources. The counts resulting in background coincidences are uncorrelated, so either detector 1 or detector 2 fires first and this is considered the event. A coincidence occurs if the other detector also fires within the coincidence window. It was assumed that the coincidence window is centered on simultaneous events, so there is half the window remaining for the other detector to create a false coincidence. The dark counts and true photon counts are indistinguishable, so these two processes are combined for simplicity. The coincidence signal to noise can be calculated by taking the ratio $R_{\text{Data}}/R_{\text{Error}}$.

5. Results

In order to test the cw pair-distribution system two APD operating points were chosen, one with both detectors operating at $-50^\circ \text{C}$ and the second with detectors 1 and 2 operating at $-60^\circ \text{C}$ and $-55^\circ \text{C}$ respectively. The photon counters were
both gated with 4 V, 20 ns gates at a repetition rate of 40 kHz. The performance of the two detectors under these operating conditions was discussed in section 2 (also figure 3). The pump power was varied from 200 μW to 3 mW in order to generate pairs at rates ranging from 0.014 to 0.21 pairs per gate. Both the signal and background coincidences were measured for each pair generation rate. The length of time for each set of data was chosen so that approximately 500 coincidences were collected in each case. The background coincidences and coincidences at low pair generation rates therefore required longer collection times.

Figure 5(a) shows the measured SNR and figure 5(b) shows the data rate along with the theoretical results found from equations (5)–(8). It is clear from figure 5 that choosing the appropriate pair generation rate can optimize the SNR. The SNR decreases at high pair generation rates because the number of background coincidences from uncorrelated pairs increases approximately quadratically with the pair generation rate, while the signal coincidences increase linearly. At low pair generation rates, the SNR drops because background coincidences between dark counts dominate. This drop in the SNR at low rates is only visible when the detectors have high dark counts, which is the case for the InGaAs APDs used in this testbed.

The theoretical curves (dashed and solid lines) shown in figures 5(a) and (b) were calculated using values for the detector repetition rate, the gate and coincidence window widths, each detector’s dark count rate and the conditional detection probabilities. The dark counts of the InGaAs detectors were measured to
be $\sim 3.7 \times 10^4$/s and $4.6 \times 10^4$/s for detectors 1 and 2 both at $-50^\circ C$, $2.2 \times 10^4$/s for detector 1 at $-60^\circ C$ and $3.7 \times 10^4$/s for detector 2 at $-55^\circ C$. The conditional detection probabilities, including the fibre-coupling efficiency, splitting and detection losses, were 4.2% and 3.1% with both detectors operated at $-50^\circ C$ and 4.6% and 3.4% with the detectors operated at $-60^\circ C$ and $-55^\circ C$. These conditional detection probabilities were calculated using equations (1)–(4) from a single set of signal and background counts measured with $1.5 \text{ mW}$ pump power. The theoretical curves were calculated using this single set of data rather than being a fit to all of the collected data. Figure 5 clearly shows that this one single data point is enough to determine the entire curve. Equations (1)–(8) can therefore be used to choose an appropriate pair generation rate without the need to measure the signal to noise ratio at that point—which is very time-consuming for points with a high signal to noise ratio because the background level is so low.

In order to test the potential use of this setup as a testbed for a realistic quantum communication system, one may calculate the expected results if an additional loss was added associated with receiver optics such as beamsplitters, interferometers, and modulators. If we add an additional 4 dB of loss before each of the detectors, we predict an SNR of 40 and a data rate of 0.3 coincidences/s with both detectors operating at $-50^\circ C$. An SNR of more than 60 with a data rate of 0.2 coincidences/s can be obtained by operating the detectors at $-60^\circ C$ and $-55^\circ C$. Therefore, a setup using degenerate cw $1.55 \mu m$ photon pairs and two TE-cooled, Geiger-mode InGaAs APDs can be used as a practical testbed for quantum communication architectures.

It is evident from figures 5(a) and (b), however, that the achievable data rate is relatively low and would not allow commercialization of such a system. Advances in the detector photon-counting performance are clearly needed. We can use the model developed in section 4 to compute the performance of a system which employs $1.55 \mu m$ sensitive photon counters with silicon-like performance characteristics. Figure 6 plots the SNR and achievable data rate for a system that uses two such photon-counting detectors. These detectors are assumed to have 70% QE, 100/s dark counts, and 1 MHz operating speed. Furthermore, the system analysed in figure 6 is assumed to have our demonstrated 60% fibre-coupling efficiency, 4 dB of receiver losses and 20 km of SMF-28 fibre ($0.2 \text{ dB km}^{-1}$) in each arm. Excellent SNR and reasonable data rates can be achieved with these parameters. For example, an SNR of 100 is obtained at a pair distribution rate of $\sim 250$ coincidences/s.

6. Conclusions

In this paper we have analysed the performance of a testbed for the evaluation of quantum communication architectures that use cw pairs of degenerate photons from SPDC. Broadband twin photons at $1.55 \mu m$ centre wavelengths are generated in a bulk PPLN crystal, efficiently coupled into a single-mode fibre, and detected with a pair of $1.55 \mu m$ sensitive photon counting detectors. We report very good photon-counting performance at $1.55 \mu m$ with select InGaAs APDs that were entirely TE-cooled, gated, passively quenched, and custom-fitted to operate in Geiger mode. Quantum efficiencies in excess of 20% have been achieved with dark count probabilities of $\sim 0.075\%$ per 20 ns gate when cooled to $-50^\circ C$. The setup allows the operating conditions for the detectors to be easily varied for optimal
detection under different experimental conditions. Quantum efficiency, dark
count, and afterpulsing constraints can be accommodated by controlling the
operating temperature of the detectors, the bias voltage, gate width, and duty
cycle.

The experimental testbed considered in this paper is suitable for future studies
of quantum communication protocols that use degenerate cw 1.55 μm photon pairs
and photon-counting detectors. Formulas have been derived that allow the pump
power to be optimized based on the desired pair-distribution rate and SNR.
The quick optimization procedures allow the system to be a practical testbed for
quantum communication architectures despite the limited performance of InGaAs
APD-based photon counters. These results were applied to a realistic simulation
of a key distribution system which uses a cw source of time–frequency entangled
photon pairs from a degenerate PPLN downconverter, standard telecommunica-
tion fibre, lossy optical components and photon-counting detectors with various
performance characteristics.

We have computed the SNR and data rate that could be achieved using our
SPDC source of twin photons and a pair of 1.55 μm-sensitive photon counters with
the performance characteristics of silicon single-photon counting modules. Fibre
optic and receiver loss were included in the analysis. It was demonstrated that raw
key distribution rates in excess of 250 pairs/s are possible with SNR in excess of
100. This should allow the implementation of a pair-based cw QKD system with
good performance characteristics.

This study further highlights the need for better performing, truly photon-
counting detectors at 1.55 μm. Until more efficient single-photon detectors become
available or novel schemes for efficient photon counting at telecom wavelengths are

Figure 6. (a) SNR ratio and (b) data rate versus gated pump photon flux for 1.55 μm
sensitive photon counting detectors with silicon-like performance, after 20 km of
SMF 28 optical fibre and 6 dB optical loss in each arm.
reliably implemented [20], using available InGaAs APDs remains a researcher’s best option.

Acknowledgments
This work is sponsored by the Department of Defense under Air Force Contract F19628-00-C-0002. Opinions, interpretations, recommendations, and conclusions are those of the authors and are not necessarily endorsed by the United States Government. The authors thank F. Wong for valuable discussions and S. Constantine for help with securing laboratory equipment for several experiments.

References
[10] More recently, id Quantique S.A. has made available a photon counter which uses cooled and gated commercial, telecom-grade, InGaAs APDs.


