A balanced gated-mode photon detector for qubit discrimination in 1550 nm

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Abstract

A photon detector combining the two avalanche photon diodes (APD) has been demonstrated for qubit discrimination in 1550 nm. Spikes accompanied with the signals in gated-mode were canceled by balanced output from the two APDs. The spike cancellation enabled one to reduce the threshold in the discriminators, and thus the gate pulse voltage. The dark count probability and afterpulse probability were reduced to $7 \times 10^{-7}$ and $10^{-4}$, respectively, without affecting the detection efficiency (11%) at 178 K.

One of the key devices for the optical implementation of quantum information technology is a photon detector to determine the quantum states, or to discriminate qubits. In discriminating qubits, we often split the photons according to the state ($|0\rangle$ or $|1\rangle$) and detect them. For example, qubits encoded on polarization states can be discriminated by a polarization beam splitter followed by two photon detectors. Phase information will be also obtained by detecting photons at the two output ports of a Mach-Zehnder interferometer. We can find application of the qubit discrimination in quantum key distribution (QKD) experiments[1, 2, 3, 4]. The use of two identical photon detectors is necessary for such demonstrations. Though a single photon detector can act as two detectors by the use of time division multiplexing technique[5], this will increase the loss in the detectors. Once we admit the requirement of two detectors, we should make the most use of them. We show, in the following, the improved detector performance by taking the differential signals of the two photon detectors.

The photon detectors should show high detection efficiency, low dark counts, and short response time. The ratio of the detection efficiency $\eta$ to the dark count probability $P_d$ determines the error rate, and so the range of QKD transmission[3, 4, 5, 6]. The ratio $P_d/\eta$ should be less than $10^{-3}$ for 100 km fiber transmission in 1550 nm even with an ideal single photon source. Clock
frequency is limited mainly by the afterpulse, false photon detection caused by residual electrons created by the previous detection. The QKD experiments\cite{1, 2, 3, 4} in 1550 nm have employed the photon detectors using InGaAs/InP avalanche photodiodes (APDs) in Gaiger mode\cite{8}, where the reverse bias higher than the break down voltage is applied. The high bias increases the avalanche gain to enable single photon detection. However, this also results in large dark count probability and afterpulse, which cause errors in the qubit discrimination. The dark count probability and the afterpulse can be reduced by using gated-mode\cite{5, 6, 7, 8}, where gate pulses combined with DC bias are applied to the APD. The reverse bias exceeds the break down voltage only in the short pulse duration. Though this method works well, the short pulses produce strong spikes on the transient signals. High threshold in the discriminator is therefore necessary to avoid errors, at the cost of detection efficiency. High gate pulse voltage is also required to obtain large signal amplitude by increasing avalanche gain. Impedance matching helps to reduce the spikes to some extent\cite{9}. Bethune and Risk\cite{3} have introduced a coaxial cable reflection line to cancel the spikes. We propose a much simpler method: canceling the spikes by taking the balanced output of the two APDs required for the qubit discrimination.

Figure 1: Schematic of the photon detector. HJ and DISC stand for a hybrid junction, and discriminators. The values of the resistors were 51 Ω.

Figure 1 depicts the schematic of the photon detector. Two APDs (Epitaxx EPM239BA) and load resistors were cooled to 140 K-213 K by an electric refrigerator. Short gate pulses of 2.5 V p-p and 750 ps duration were applied to the APDs after being combined with DC bias by Bias-Tees. The output signals from the APDs were subtracted by a 180° hybrid junction of 2-2000 MHz bandwidth (M/ACOM H-9.) The differential signal was amplified and discriminated by two discriminators (ParkinElmer 9307.) Since the spikes were the common
mode input for the 180° hybrid junction, they would not appear at the output. The APD 1 provided negative signal pulses at the output, while the APD 2 provided positive pulses. We can determine which APD detects a photon from the sign of the output signals. Figure 2 shows the output signal of the amplifier without photon input. Almost identical I-V characteristics of the APDs enabled us to obtain a good suppression of the spikes.

![Figure 2: Cancellation of the transient spike. Thin solid: APD 1, Dots: APD 2, Thick solid: the differential output of the APD 1 and the APD 2.](image)

We first characterized the APDs separately. The attenuated light from a 1550 nm DFB laser was used as a photon source. The laser emitted the light pulse of 100 ps duration at the frequency of 100 kHz. The detection efficiency was estimated by fitting to the theory assuming Poisson distribution of the incident photons\[10\]. We accumulated pulse counts up to $10^8$ clocks to obtain accurate dark count probability to the order of $10^{-7}$. We focused on the DC bias region where the detection efficiency larger than 10 %. As shown in Fig. 3, we observed the lowest dark count probability of $7 \times 10^{-7}$ per pulse with detection efficiency of 11 % at 178 K. The ratio $P_d/\eta$ was as small as $6 \times 10^{-6}$, which corresponds to 220 km QKD transmission with an ideal photon source. To our knowledge, this is the highest value of $P_d/\eta$. The detection efficiency and the dark count probability are increasing functions of the bias. The maximum value of the detection efficiency is obtained when the DC bias is set to the breakdown voltage. We obtained larger values of the maximum detection efficiency at higher temperatures: the detection efficiency of 20 % at 213 K with the dark count probability of $3 \times 10^{-5}$ per pulse.

Afterpulse probability was measured by applying two successive gate pulses to the APDs. As seen in Fig. 4, afterpulse is prominent at low temperatures. We found that afterpulse probability remained about $10^{-4}$ for the 1 $\mu$s pulse.
interval at the temperatures higher than 178 K. This corresponds to $10^{-5}$ error probability (per pulse) for 10\% detection efficiency. Though Fig. 4 shows the results on APD 1, we obtained almost the same afterpulse characteristics on APD 2. Based on the observation on the dark count probability and the afterpulse probability, we conclude that the optimal operation temperature for the present APDs is around 178 K.

Afterpulse also depends on the bias; the more afterpulse effect was observed for the higher bias. This can be interpreted that higher bias produces more electrons to contribute to the afterpulse during the avalanche process. The present photon detector has shown a good afterpulse characteristic, because a small bias voltage was enough to respond to a single photon. This is an effect of the spike cancellation, by which we could reduce the threshold voltage in the discriminators. We also found that afterpulse can be reduced by increasing the DC bias with a constant total (DC + gate pulse) bias. The high DC bias may sweep out the trapped electrons during the pulse interval.

We observed photon detection by two APDs. The light was divided by a 3 dB fiber coupler, and fed to the input ports of the APDs. In the photon picture, the photon wave function will be collapsed by the photon detection at either of the two APDs. This can be regarded as a "which path" experiment or the latter part of a Mach-Zehnder interferometer. Figure 5 shows the photon detection for 2 ms. Photon flux was set to 0.2 photons per pulse. APDs were cooled to 178 K and the DC bias voltages were set to yield the detection efficiency of 11\%. We found that the detection probability of the two APDs were almost the same for a weak light input. However, detection on the APD 1 became dominant.
as increasing photon flux. In the present experiment, APD 1 showed slightly larger detection efficiency than APD 2; so that APD 1 detected predominantly the event that more than one photon entered the 3 dB coupler. This observation implies that we should carefully adjust the detection efficiency of the two APDs when more than one photon will be expected to be detected. This is not the case in the qubit discrimination, however.

In conclusion, we have shown an improved photon detector for qubit discrimination by taking the balanced output of two APDs. Canceling the spikes enables to reduce the threshold at the discriminators, and thus decrease the bias voltage. This reduces the dark count probability and the afterpulse without sacrificing the detection efficiency. The present photon detector would help to construct practical quantum information systems, such as QKD in the light-wave communication wavelength.

References

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Figure 5: Photon detection in a ‘which path’ experiment.

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