High-Speed Single-Photon Detection Using 2-GHz Sinusoidally Gated InGaAs/InP Avalanche Photodiode

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Abstract. We report a telecom-band single-photon detector for high-speed quantum key distribution systems. The single-photon detector is based on a sinusoidally gated InGaAs/InP avalanche photodiode. The gate repetition frequency of the single-photon detector reached 2 GHz. A quantum efficiency of 10.5 % at 1550 nm was obtained with a dark count probability per gate of 6.1×10^{-7} and an afterpulsing probability of 3.4 %.

Keywords: Single-photon detector, sinusoidal gate operation, telecomm-band.

1 Introduction

Single-photon detector (SPD) is the most important component to realize quantum key distribution (QKD) [1]. A gated InGaAs/InP avalanche photodiode (APD) is a practical solution for the SPD [2,3,4]. However, conventional one cannot operate at high gate repetition frequency, since afterpulses occur with a high probability. Therefore, there are many efforts to suppress the afterpulse by means of the avalanche signal detection with a low avalanche gain [5,6]. We have supposed the sinusoidally gate operation of InGaAs/InP APD (SG-APD) [5] that achieved much higher gate repetition frequency than that of conventional gate operations. the detector has been already applied to the QKD experiment and achieved key generation rates in orders of megahertz [7]. In SG-APD, it is realized to suppress a transient pulse noise due to the capacitive response of the APD to an applied gate voltage pulse. As a result, the avalanche multiplication gain can be reduced to $10^5\sim10^6$ (two orders of magnitude lower than that in the conventional gate operation), which contributes to suppression of afterpulsing. Ultimately, the avalanche multiplication gain enough to discriminate an avalanche signal can be reduced to the value defined only by the thermal noise. In the gating regime, discrimination of an extremely weak avalanche signal at the thermal noise limit of detector circuit has not been realized yet, since it is required to output no extra noise despite the fact that the huge gate voltage pulse is applied to the APD, described above. In this report, we demonstrated

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that using the sinusoidal gating scheme at the thermal noise limit of a detection circuit, the SG-APD can be operated at the 2 GHz gate repetition frequency with a low afterpulsing probability.

2 Sinusoidally Gated InGaAs/InP Avalanche Photodiode

A diagram of our SPD is shown in Fig. 1. The tested InGaAs/InP APD is AGD-25-SE-1-T8 (Princeton Lightwave). The APD is cooled to -50 °C by a Peltier cooler driven by PID (proportional-integral-derivative) controller. In order to supply an AC voltage superposed on the DC reverse bias voltage V_{DC} to the APD, we used a gated passive quenching circuit (GPQC) [3]. The sinusoidal voltage at a frequency of ω_g was produced by the signal generator (SG) and used as the gate voltage after amplification by the high-power amplifier (HP-AMP). Here the amplified sinusoidal voltage passed through the band-pass-filter (BPF) (center frequency: $f = \omega_g$) to reject amplified sideband noise, harmonics, and non-harmonics, which contributes to reduce the noise level of the GPQC output. The GPQC output signal passed through three band elimination filters (BEFs) whose center (elimination) frequencies f were set to ω_g. Then the signal was amplified by an inverting broadband amplifier (B-AMP) whose gain and bandwidth were 40 dB and 3 GHz, respectively. The total elimination ratio of the BEFs was 100 dB at ω_g. The BEFs distorted the avalanche pulse, since the BEFs eliminated the ω_g component and gave a large phase shift around ω_g. This distortion causes a wider time jitter in the avalanche signal discrimination. Therefore, to fix the pulse form, the avalanche signal was passed through a low-pass-filter (LPF) with a cutoff frequency of $\sim 1.5\omega_g$ before entering the discriminator. The transferred

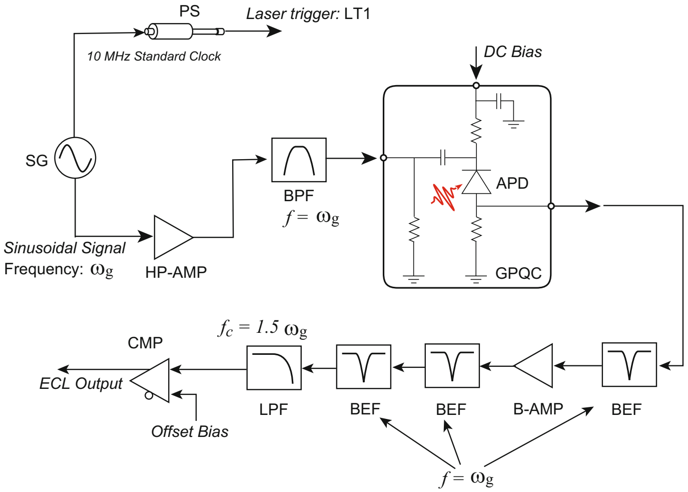

Fig. 1. Diagram of Sinusoidally gated avalanche photodiode

gate signal at ω_g was sufficiently rejected by the BEFs and the LPF, and the avalanche signal was distilled well. The rms voltage noise V_n of the LPF output was approximately 5 mV when the 23 dBm sinusoidal voltage at ω_g =1 GHz was used as a gate. Taking the gain and noise figure of the B-AMP into account, the V_n is close to the thermal noise limit $V_{th} = \sqrt{4kTRB}$ of a detector circuit, where k, T, R, and B are the Boltzmann constant, the absolute temperature of the output resister in the circuit, the resister's value, and bandwidth, respectively. A threshold voltage for the avalanche signal discrimination was set to -25 ∼ -30 mV, which indicates that avalanche signals containing only 10^4 electrons (before amplification) can be discriminated. The avalanche signal was discriminated by the ultra-high-speed comparator (CMP) circuit that accepts subnanosecond pulses. We finally obtained the logic output in the emitter-coupled-logic (ECL) level.

3 Detector Performance

We evaluated the SPD performance for 50 ps weak laser pulses at 1550 nm. The SPD performances were evaluated changing the V_{DC}. Figure 2 shows the dark count probability per gate P_d and the afterpulsing probability P_a as functions of quantum efficiency η at a gate repetition frequency of 2 GHz. P_d is in orders of 10^{-7} when η is less than 13 %, more specifically the SG-APD was achieved a detection efficiency of 10.5 % at 1550 nm with a dark count probability of 6.1×10^{-7} and an afterpulsing probability of 3.4 %. The dark count probability and afterpulsing probability is considerably lower than the other reported APD-based SPDs, while our APD-based SPD achieved the highest repetition frequency.

Figure 3(a) shows the time histogram of detection events when a gate repetition frequency ω_g was 2 GHz. The peak at 135.9 ns corresponds to the illuminated

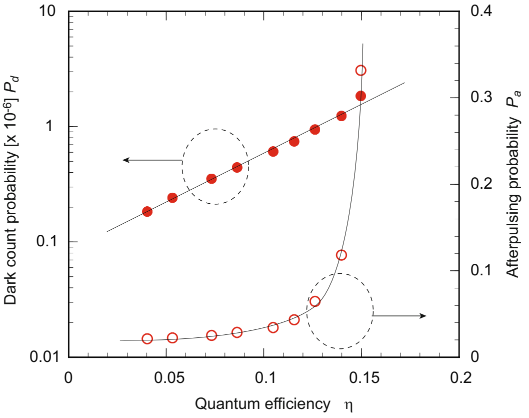

Fig. 2. Detector performance

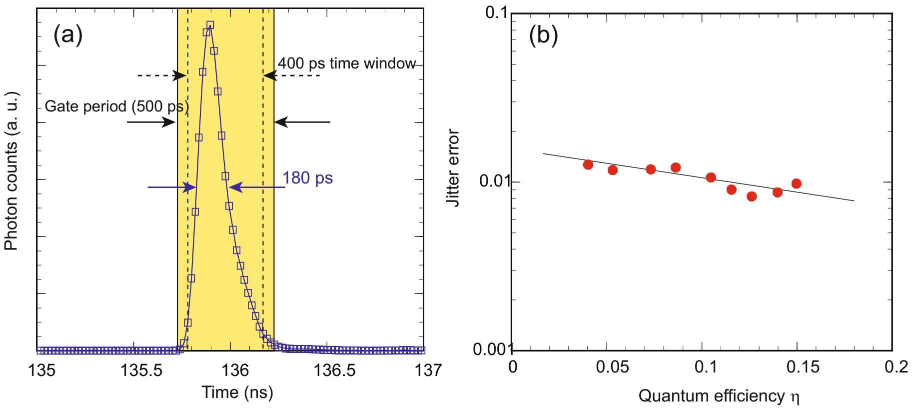

Fig. 3. Jitter characteristics. (a)Time histogram of detection events. (b) Probability for the jitter error as a function of the quantum efficiency η.

gate. The time jitter distribution has a FWHM of 180 ps, which is shorter than the gate period (500 ps). However, the peak is not completely separated from adjacent peak. This fact means that a fraction of the detection events is registered in an incorrect gate, which obviously causes bit errors. To reduce the error counts due to the time jitter, we employed a 400 ps time window to obtain the detector clicks. The probability P_e of error caused by the time jitter is plotted as a function of the quantum efficiency in Fig. 3(b). Increasing η, corresponding to increasing the reverse bias voltage applied to APD, P_e slightly reduces, since the response speed of APD made higher as the reverse bias voltage is increased. Although P_e can be reduced by employing a shorter time window, the net detection efficiency also reduces in this case, which indicates that ω_g higher than 2 GHz does not guarantee to obtain a higher detection rate.

4 Conclusion

In conclusion, we have developed a single-photon detector at 1550-nm using a sinusoidally gated InGaAs/InP APD. A gate repetition frequency of 2 GHz was achieved with high quantum efficiency, low dark count probability, and low afterpulsing probability. The single-photon detector can be easily applied to practical high-speed QKD systems.

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References

1. Gisin, N., Ribordy, G., Tittel, W., Zbinden, H.: Rev. Mod. Phys. 74, 145 (2002)
2. Yoshizawa, A., Tsuchida, H.: Jpn. J. Appl. Phys. Pt.1, 40, 200 (2001)
3. Namekata, N., Makino, Y., Inoue, S.: Opt. Lett. 27, 954 (2002)
4. Ribordy, G., Gisin, N., Guinnard, O., Stucki, D., Wegmuller, M., Zbinden, H.: J. Mod. Opt. 51, 1381 (2004)
5. Namekata, N., Sasamori, S., Inoue, S.: Opt. Express. 14, 10043 (2006)
6. Yuan, Z.L., Kardynal, B.E., Sharpe, A.W., Shields, A.J.: Appl. Phys. Lett. 91, 041114 (2007)
7. Namekata, N., Fujii, G., Honjo, T., Takesue, H., Inoue, S.: Appl. Phys. Lett. 91, 011112 (2007)