

1.5- μm single photon counting using polarization-independent up-conversion detector

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Abstract: We report a 1.5- μm band polarization independent single photon detector based on frequency up-conversion in periodically poled lithium niobate (PPLN) waveguides. To overcome the polarization dependence of the PPLN waveguides, we employed a polarization diversity configuration composed of two up-conversion detectors connected with a polarization beam splitter. We experimentally confirmed polarization independent single photon counting using our detector. We undertook a proof-of-principle differential phase shift quantum key distribution experiment using the detector, and confirmed that the sifted key rate and error rate remained stable when the polarization state was changed during single photon transmission.

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1. Introduction

Single photon counting in the 1.5- μm band is an important technology for realizing fiber-based quantum communication systems such as quantum key distribution (QKD) [1]. In the 1.5- μm band, InGaAs avalanche photodiodes (APD) have been conventionally used for single photon detection [2]. However, a single photon detector based on InGaAs APD generally has a lower quantum efficiency than one based on a Si APD, which is used for short wavelength bands. Moreover, an InGaAs APD usually requires gated mode operation with a gate frequency of <10 MHz, because of the large afterpulse probability.

To overcome these drawbacks of conventional 1.5- μm band single photon detectors, single photon detectors based on frequency up-conversion in periodically poled lithium niobate (PPLN) have been proposed and developed intensively in recent years [3, 4, 5, 6, 7]. Hereafter, we refer to these types of detectors as up-conversion detectors (UCD). In a UCD, a 1.5- μm single photon is combined with a strong pump light and injected into PPLN, in which the 1.5- μm photon is frequency-converted to a short-wavelength photon through a process of sum frequency generation (SFG). The converted photon is then passed through filters to suppress pump and second harmonic generation (SHG) photons, and then detected by a Si APD. UCDs using bulk PPLNs and those using PPLN waveguides have already been reported. A quantum efficiency as high as 46% has been reported when using a UCD with a PPLN waveguide [6]. Moreover, quantum key distribution (QKD) experiments using UCDs have already been conducted [8, 9, 10, 11]. Since a UCD can be operated in a continuous mode, a significant increase was achieved in the key generation rate in those experiments. Also, very fast optical time domain reflectometry (OTDR) has been realized using a UCD [12].

Despite the successful results mentioned above, the UCD has a drawback that prevents it from being used in practical systems: polarization dependence. Since the efficiency of a nonlinear process in bulk/waveguide PPLN is polarization dependent, the polarization of an incoming single photon should be adjusted. Recently, a method for realizing a polarization-independent UCD was reported by Albota et al [13]. They employed a reflective configuration to compensate for the polarization dependence of PPLN, in which the input horizontal (vertical) polarization is up-converted in the forward (backward) direction. They successfully demonstrated polarization independent frequency up-conversion, but they have not yet achieved single photon counting using their novel scheme.

In this paper, we report a polarization independent UCD (PI-UCD) based on a different approach. We employed a polarization diversity configuration similar to that used in telecom-band wavelength conversion [14]. In this configuration, we used two UCDs, one for each polarization component. We demonstrated polarization independent single photon counting with

our detector. We also undertook a proof-of-principle differential phase shift QKD (DPS-QKD) [15, 16] experiment using the PI-UCD, with which we successfully showed that our detector is useful for practical QKD systems.

2. Configuration

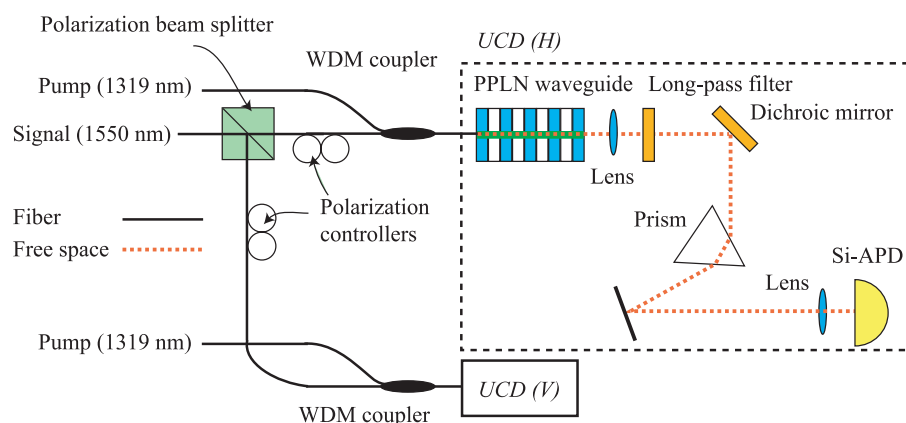


Fig. 1. Configuration of PI-UCD.

Figure 1 shows the configuration of the PI-UCD with polarization diversity. A $1.5\text{-}\mu\text{m}$ signal photon is input into a fiber-coupled polarization beam splitter (PBS), where the polarization of the incoming photon is projected to a horizontal (H) or vertical (V) polarization. Each projected state is combined with a $1.3\text{-}\mu\text{m}$ pump light using a wavelength division multiplexing (WDM) coupler and then input into a UCD, which is composed of a PPLN waveguide, optical filters, and a Si-APD (MPD 50ct). The frequency converted photon generated in the PPLN waveguide is passed through a long-pass filter to suppress the second harmonic generation (SHG) light of the pump, and reflected by a dichroic mirror, which separates components with long wavelengths such as the pump and residual signal photons. Then, the photon is received by a Si-APD after passing through a prism that further suppresses the pump and SHG lights.

The quantum efficiency of the Si-APD is specified to be 20% near 700 nm. This reduced the peak detection efficiency of the UCD, including coupling, propagation, and collection losses to $\sim 8\%$ for 120 mW of pump power. At around the peak quantum efficiency point, noise photons caused by spurious nonlinear processes such as spontaneous Raman scattering or parametric down conversion in PPLNs were observed. The number of these noise photons increased quadratically with increases in pump power, so the signal to noise ratio degraded when the quantum efficiency was at its peak value. Therefore, we set the quantum efficiency of the UCD for each polarization at around 2.7% in the following experiments, by which we were able to obtain a relatively good signal to noise ratio in the QKD experiment. The average dark count rate (sum of the dark count rates two of UCDs for H and V polarizations) was 14000 cps.

3. Experiments

3.1. Photon counting experiment

First, we confirmed that the count rate of the PI-UCD was stable when the polarization state of an incoming photon was changed. To change the polarization state of the $1.5\text{-}\mu\text{m}$ photons that were input into the PI-UCD, we used the setup shown Fig. 2. A continuous light with a wavelength of 1550 nm is input into a polarization controller fiber module that is followed by

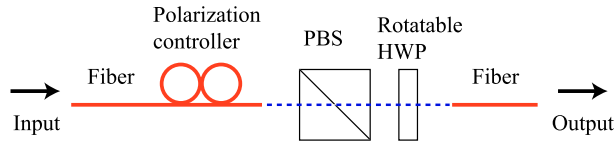


Fig. 2. Configuration for changing the input polarization to the PI-UCD.

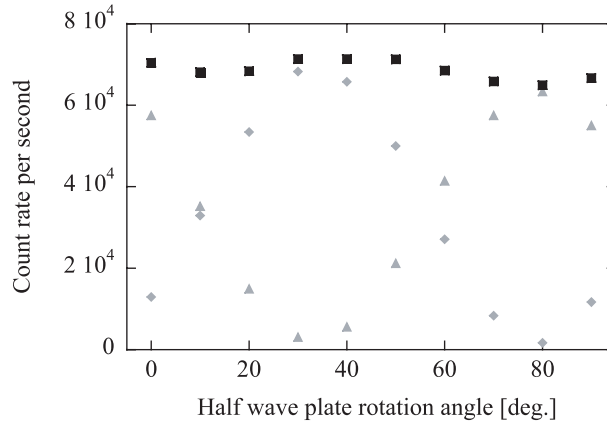


Fig. 3. Count rate as function of HWP rotation angle. Squares, diamonds and triangles denote total count rate, the count rate of a UCD for H polarization, and that for V polarization, respectively.

a free-space PBS that transmits an H polarization component. The polarization of the 1550-nm light is adjusted to maximize the transmitted power from the PBS. The light is then passed through a rotatable half wave plate (HWP) whose birefringence axis is aligned to the horizontal plane when the rotation angle is zero. Thus, by rotating the HWP angle from 0 to 90 degrees, we can rotate the angle of the linearly-polarized 1550-nm light by 180 degrees. Using this configuration, we input an attenuated coherent light with an average photon number of 3×10^6 per second into the polarization independent UCD, with the HWP angle changed from 0 to 90 degrees. The count rate as a function of HWP angle is shown in Fig. 3. Here, the diamonds, triangles and squares denote the count rate of a UCD for H polarization, a UCD for V polarization, and the combined count rate, respectively. The count rate at each point was measured five times and the average value is shown in the figure. The error bars were smaller than the symbols, and thus not shown. Although the count rate of a UCD for each polarization changes sinusoidally with the rotation angle, the combined rate clearly remains stable. The fluctuation in the total count rate was less than ± 0.2 dB. This slight fluctuation was caused by the small quantum efficiency mismatch of the two UCDs, which was caused by the temperature drift of the PPLN waveguides. The average quantum efficiency was 2.3%, which is 0.7 dB lower than the quantum efficiency of each UCD. This small decrease is attributed to the loss of the PBS in the PI-UCD. Thus, polarization independent single photon counting is successfully demonstrated.

3.2. Proof-of-principle DPS-QKD experiment

We then undertook a proof-of-principle DPS-QKD experiment using the PI-UCD. In the following, we briefly explain the DPS-QKD protocol based on the setup shown in Fig. 4. Alice modulates a coherent light from a laser into sequential pulses with a 70-ps width and a 1-GHz

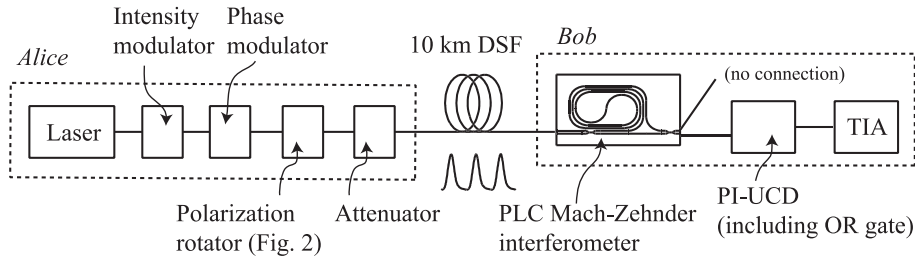


Fig. 4. Configuration of DPS-QKD experiment.

repetition frequency using an intensity modulator. The phase of each pulse is randomly modulated by $\{0, \pi\}$ with a phase modulator. The pulse train output from the phase modulator is input into the 'polarization rotator' shown in Fig. 2, and then attenuated so that the average photon number per pulse becomes 0.2. The attenuated pulse train is sent to Bob through a 10-km dispersion shifted fiber (DSF). At Bob's site, the incoming pulse train is input into a 1-bit delayed Mach-Zehnder interferometer fabricated using planar lightwave circuit (PLC) technology [17]. The insertion loss of the interferometer was 2.5 dB. When we launched a pulse train with no phase modulation, the ratio of the two output powers was ~ 20 dB, which was probably limited by the crosstalk of the interferometer. We then applied a phase modulation with an alternating pattern ($0\pi 0\pi 0\pi \dots$), by which we switched the port where the majority of light was output. Here too, the ratio of the two output powers was ~ 20 dB. This means that the interferometer works similarly at both output ports, and the error caused by the imperfect interferometry in the QKD experiment is suppressed to $\sim 1\%$. When the phase difference between two adjacent pulses is zero (π), the photon is output from port 0 (1) of the PLC interferometer, and detected by a single photon detector. Since the average photon number per pulse is less than 1, Bob observes photons only occasionally. Therefore, with the DPS-QKD protocol, Bob records the time instances at which he observed clicks, and which detector clicked at those instances. Then, Bob discloses the time instance information to Alice through classical communication, while withholding the which-detector information. Using the original modulation data and time instance information obtained from Bob, Alice now knows which detector clicked at the time instances that Bob observed. Therefore, by allocating a click at the detector for port 0 (1) as bit 0 (1), Alice and Bob share an identical bit string that can be used as a secret key.

In this experiment, we constructed only one PI-UCD. Therefore, the PI-UCD was connected to port 0 of the interferometer output, while the other output was terminated. The electrical signals from the UCDs for the H and V polarizations were input into an OR logic gate. The output signal from the logic gate was input into a time interval analyzer (TIA), with which we recorded all the time instances at which the PI-UCD detected photons. To reduce errors caused by dark counts, we applied a 100-ps time window to the obtained data. The use of the time window reduced the effective detection efficiency by 61%. We measured the error rate by comparing Alice's modulation data with Bob's recorded data. We also calculated the sifted key rate by dividing the number of recorded data by the time span. The quantum efficiency and dark count rate of the PI-UCD were the same as those of the photon counting experiment.

We rotated the HWP from 0 to 90 degrees in 10-degree steps and measured the sifted key rate and error rate. We undertook five QKD measurement runs for each HWP rotation angle and calculated the average and the error bar. The results are shown in Fig. 5, where the squares and crosses represent the sifted key rate and error rate, respectively. Thus, the fluctuation in the sifted key rate was suppressed to within $< \pm 0.4$ dB. The slight increase in fluctuation compared with the photon counting experiment may be caused by the small polarization dependent loss

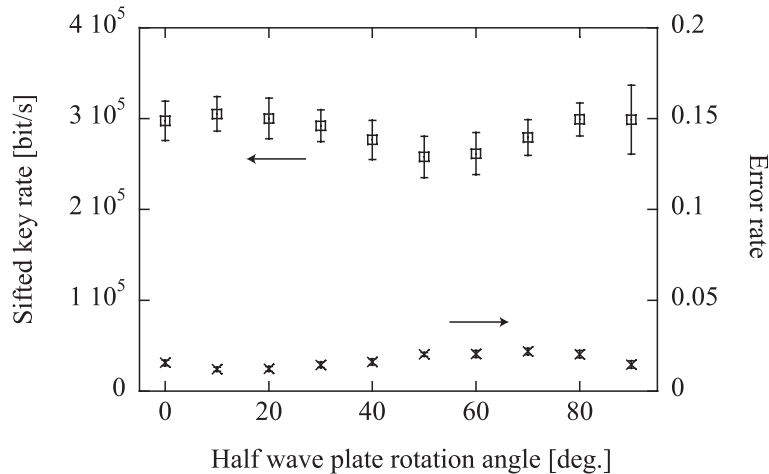


Fig. 5. Sifted key rate (squares) and bit error rate (x symbols) of the DPS-QKD experiment as a function of the HWP rotation angle.

of the PLC interferometer. More importantly, the average error rate was 1.7% with a fluctuation of less than 0.2%, which suggests that secure keys were obtained stably even if the polarization state of the photons changed during transmission through the fiber.

4. Conclusion

We described a PI-UCD based on a polarization diversity configuration. We undertook a single photon counting experiment, and showed that the count rate was very stable when the polarization of the input photons was changed. We also demonstrated a proof-of-principle DPS-QKD experiment using our PI-UCD. We showed that the sifted key and error rates were successfully stabilized, which implies that our PI-UCD is useful for constructing practical QKD systems.

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