Laser ranging at 1550 nm with 1-GHz sine-wave gated InGaAs/InP APD single-photon detector

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Abstract: We demonstrated a laser ranging system with single photon detection at 1550 nm. The single-photon detector was a 1-GHz sine-wave gated InGaAs/InP avalanche photodiode. In daylight, 8-cm depth resolution was achieved directly by using a time-of-flight approach based on time-correlated single photon counting measurement. This system presented a potential for low energy level and eye-safe laser ranging system in long-range measurement.

OCIS codes: (280.3400) Laser range finder; (280.3640) Lidar; (030.5260) Photon counting; (040.3780) Low light level.

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1. Introduction

The time-of-flight of laser pulse is widely used to measure the distance directly [1–10]. The resolution of time-of-flight laser ranging (depth resolution) is determined by the timing jitter of the optical receivers, typically in the order of hundreds of picoseconds, resulting in the depth resolution of centimeters. Meanwhile, coherent laser ranging has also been used for short-range measurement of several hundreds of meters with higher depth resolution in the order of millimeter. Recently, the resolution of laser ranging has been much improved by using a laser comb [10], which shows a high depth resolution in the order of nanometer even for long-range measurement. However, the time-of-flight laser ranging technique is still necessary in ultra-long-distance measurement, where the retro-reflected light is so weak that single-photon detector (SPD) should be employed. In these time-of-flight systems, the measurement technique is based on time-correlated single-photon counting (TCSPC) with picosecond timing resolution. The TCSPC technique has been implanted in laser ranging for many years in applications such as earth-satellite distance measurements and, more recently, altimetry measurements for airborne platforms [1,6].

Most of the laser ranging systems based on TCSPC technique use light sources of visible wavelengths, as the optical receivers used in the system, such as photomultipliers (PMTs) and Si avalanche photodiodes (APDs) for single-photon detection, response to the photons with wavelengths shorter than 1000 nm. Owing to the high performance of these SPDs, single-photon ranging [2–4,6–9] and 3-D imaging [11–14] using TCSPC technique have been realized with high resolution. Although the Er-doped lasers at 1550 nm are superior to their opponent laser sources of visible wavelengths in laser ranging applications due to their eye-safe wavelengths, the imperfect SPDs at 1550 nm region limited the improvement on eye-safe single-photon ranging. Ref. [7] reported a lasing ranging at 1550 nm with sub-centimeter depth resolution by using a nano-patterned superconducting SPD. However, the cryogenic operation of the superconducting SPD at about 4 K limited the practical application in laser ranging. Another kind of SPD for the near infrared wavelengths is based on an InGaAs/InP APD, which has been widely used in fiber-based quantum key distribution at 1550 nm [15–

18]. Due to the large dark count and afterpulsing effect, the InGaAs/InP APDs are usually operated at gated Geiger mode that a reverse bias is applied on the InGaAs/InP APD combining a DC voltage with a short electric gating pulse. And the SPD requires a synchronous clock trigger in order to detect the photon pulses. Therefore, the InGaAs/InP APDs in gated Geiger mode are not suitable for lasing ranging as the detecting gate could not be synchronized with the reflecting photons from the target with unknown distance. Recently, ultra-high speed gated InGaAs/InP APD single-photon detection has been demonstrated based on several novel techniques [19–29]. The gating rate was promoted up to 2.23 GHz. The InGaAs/InP APD was operated in quasi-continuous mode when the gating rate was ≥ 1 GHz. Meanwhile, high performance continuous operated InGaAs/InP APD single-photon detection was also realized based on active or passive quenching [30–32]. Thanks to these novel techniques, the InGaAs/InP SPDs become competitive in the laser ranging at 1550 nm.

In this paper, we demonstrate an eye-safe laser ranging with TCSPC based on InGaAs/InP APD SPD at 1550 nm, which was operated in 1-GHz sine-wave gated mode with a timing jitter of 80 ps. The ultrahigh speed gating frequency of the SPD enabled photon detection without the synchronous trigger. In daylight, 8-cm depth resolution was achieved, as the timing jitter was 460 ps when the laser pulse source and the SPD were free running without synchronization. The implantation of the high speed InGaAs/InP APD SPD in the laser ranging may promote the low-energy level and eye-safe laser ranging system for long-range measurement.

2. Single-photon laser ranging scheme at 1550 nm

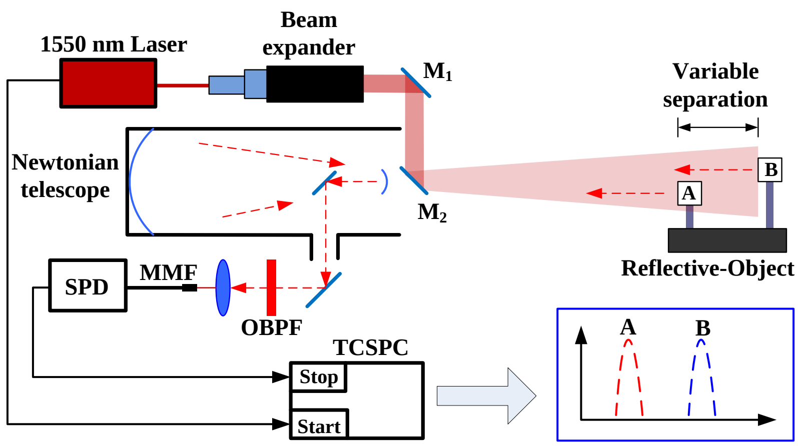

Fig. 1. Experimental setup of the laser ranging system based on single-photon detection at 1550 nm. SPD: single-photon detector based on InGaAs/InP APD; OBPF: optical bandpass filter (center wavelength: 1550.10 nm, FWHM: 6.47 nm); M1, M2: high-reflection mirrors; MMF: multimode fiber; TCSPC: time-correlated single-photon counting system (PicoHarp300, PicoQuant GmbH, Germany).

As shown in Fig. 1, the light source was an Er-doped fiber laser actively mode-locked by an optical switcher. The repetition rate of the pulsed laser source was 12.5 MHz and the full-width of half maximum (FWHM) pulse duration was 20 ps. With the average output power of 3.3 mW, the single-pulse energy was about 0.26 nJ. The laser output beam spot was expended by a beam expander. The divergence angle was about 2.65×10^{-4}. By using two reflective mirrors, the optical transceiving system was operated in coaxial output mode. The diameter of the output beam was 13 mm, while it became 21 mm on the target 32-m far away. A 140 mm diameter Newtonian telescope was used to receive the retro-reflected photons. The stray noise from the daylight was blocked by an optical bandpass interference filter (OBPF) before the retro-reflected photons were coupled into the fiber-pigtailed InGaAs/InP APD SPD. The InGaAs/InP APD had a multimode fiber pigtail with the fiber core of 62.5 μm. The diameter

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of the sensitivity area of the InGaAs/InP APD was only 40 μm, limiting using larger diameter fiber for higher collection efficiency. The optical loss from the telescope to the APD was 16 dB, including fiber coupling loss from the output of telescope and the loss of OBPF. The output of the SPD was connected to the "Stop" of TCSPC, while the synchronous trigger signal of the laser source was connected to the "Start" of the TCSPC. The timing resolution of the TCSPC system was set shorter than 10 ps for time correlation analyzing. The period between the "Start" and "Stop" was the round-way flight time of the photons from the laser source to the target directly. In the measurement, we used two non-cooperation reflective-objects (A and B). They were two cubes covered with white paper, and the laser beam could cover both reflective-objects which were 32 m away from ranging system as shown in Fig. 1.

Generally, InGaAs/InP APDs operated in gated Geiger mode are not available to detecting photons continuously [19–27] as they require a trigger clock as a reference to catch the photons in the detecting gate. However, in laser ranging, the arrival time of the retro-reflected photons is an unknown parameter that needs to be measured to obtain the distance information. In order to detect the photons at unknown arrival time, the gating pulse should be scanned during the cycle duration, meaning that the laser pulse source and the gating pulse are both in free running mode. Usually, the duty cycle ratio of the detecting gate (T_{dc}) is very low, e.g. $T_{dc} < 0.001$ as the gate pulse is 1 ns at the gating rate of 1 MHz. The acquisition time will be 1000 times longer than that using SPD in continuous operation mode. This is intolerable for practical applications. This problem could be solved by increasing T_{dc} through increasing the gating pulse width or repetition rate. However, increasing the gate width will degrade the detector due to the afterpulsing effect. Thus, we chose to increase the gating pulse repetition rate.

3. Experiment setup and results

In the single-photon ranging experiment, the InGaAs/InP APD was operated in sine-wave gated mode. A 1-GHz sinusoidal wave came from an RF signal generator with the amplitude of 3.2 V. The frequency spectrum of the capacitive response of the APD became simple as we used sine-wave gate. Most of them were at 1 GHz combined with a little harmonic signal of 1 GHz, while the frequency of the avalanche pulse was almost lower than 1 GHz. So the capacitive response was canceled easily by using a low pass filter (LPF) as shown in Fig. 2(a). The attenuation of this LPF was 3 dB at 700 MHz and >40 dB at 1 GHz. Then the avalanche pulses were detected by the TCSPC after being amplified by an RF amplifier. The InGaAs/InP APD was Peltier cooled to −33 °C. The detection efficiency was 10% at 1550 nm with the bias voltage of 50.7 V. Its dark count rate was 10 kHz, and afterpulse probability was 3% with a 10-ns deadtime. The effective gate width was measured as about 340 ps by scanning the delay of the laser, as well as the duty cycle of the 1-GHz gated SPD was 34%.

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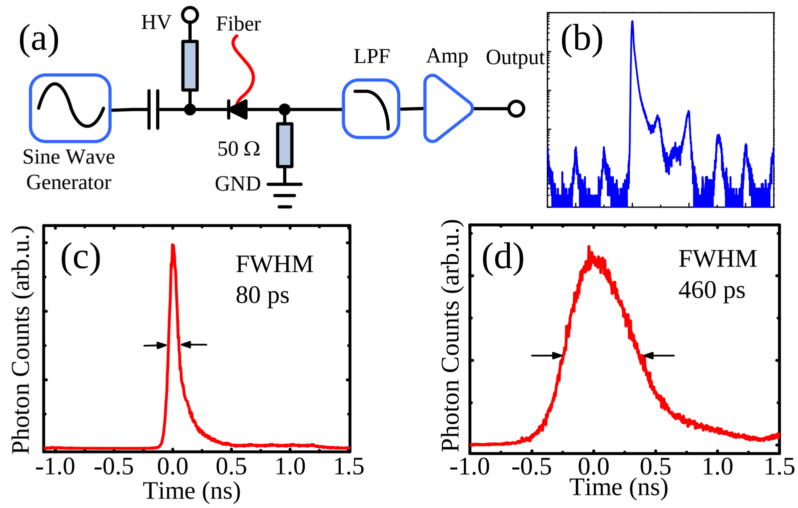

Fig. 2. (color online) (a) Schematic of the InGaAs/InP APD SPD. LPF: low-pass filter; HV: bias voltage; Amp: RF amplifier (gain: 13 dB, bandwidth: 3 GHz). (b) Avalanche trace of the APD output. Timing jitter of the single-photon with (c) and without (d) synchronization to the laser pulse.

In the single-photon ranging, the depth resolution was not only determined by the timing jitter of the detector, but also the light pulse width. The FWHM of the TCSPC output (T) was determined by the timing jitter of the detector (t_1), the timing jitter of the TCSPC (t_2 *~10 ps*), and the pulse width of the laser source (t_3 *~20 ps*), as the function of $T = \sqrt{t_1^{\,2} + t_2^{\,2} + t_3^{\,2}}$. The timing jitter of the detector was dependent on the trigger clock. We measured that T was only 80 ps when the gate was synchronized with the laser source as shown in Fig. 2(c). However, we could not offer a synchronized trigger clock for the detector in the single-photon ranging. The 1-GHz sine wave applied on the InGaAs/InP APD was not synchronized with the laser source. The relative phase was randomly shifting between the laser pulse and the detection gate. Figure 2(d) shows the TCSPC output of the SPD without synchronization to the laser source, showing a total timing jitter of about 460 ps. In this "free-running" mode, the detection efficiency was 4% with dark count rate of 10 kHz, and the afterpulse probability was 3% with a 10-ns deadtime.

We performed three measurements as shown in Fig. 3. The black straight lines are the actual time correlation trace, and the red-dashed lines and blue-dotted lines are the linear fittings of the time correlation for reflective-object A and B. The heights of the traces are slightly different due to variations in optical alignment among the three measurements, where the decreasing of the peak from object A is induced by the fluctuation of the fiber coupling. The acquisition time was 2 seconds. The objects positions were obtained by the center of counting peaks. The distance of target could be calculated directly by $L = vt/2$, where v is the light speed in the air, t is the flight time of the photons. When the two cubes were separated by 30 cm, the two peaks in the time-correlation measurement were clearly separated. And the centers of the two peaks were separated by 2.0 ns, which was the correct time of flight between the two targets. When the cubes were separated by 8 cm, although the two peaks were partly overlapped, we could still distinguish them easily. Decreasing the distance between the two cubes to 6 cm, the two peaks were overlapped and we could no longer discriminate them directly. Therefore, the depth resolution was about 8 cm corresponding to 500 ps time-of-flight of the photons, which was close to the timing jitter of the SPD of 460 ps. The daylight environment did not have effect on the single-photon ranging, as a narrow optical bandpass filter was used to extract the signal photons. The timing jitter of the InGaAs/InP APD SPDs can be further decreased by using a higher repetition rate gate [21,22,24,28,31] or a continuous operation mode [30–32], by which the depth resolution can

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be further improved. In this experiment, the output power of laser source has very low, which was 3.3 mW average power and 0.26 nJ per pulse energy. With this laser source, the largest measure distance could be about 300 m. We calculated a theoretical curve to show the required optical energy per pulse vs. longest measure distance in Fig. 4. The largest measure distance could be extended to 18.6 km, if the output energy of laser source could be amplified to 1 μJ per pulse.

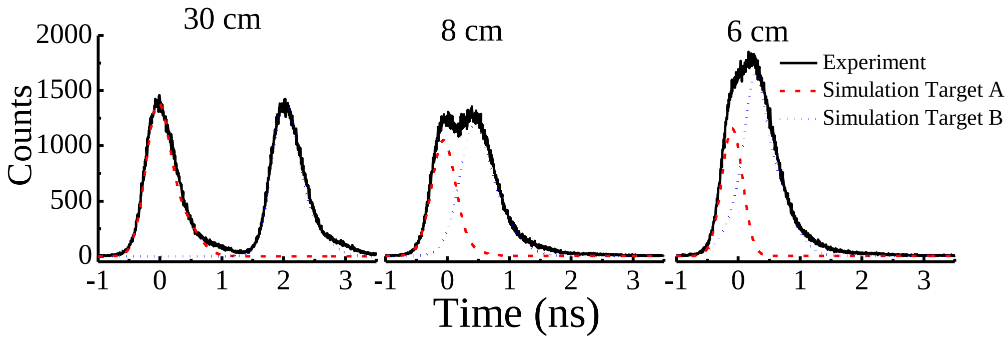

Fig. 3. Time correlation results from the targets of different surface separations.

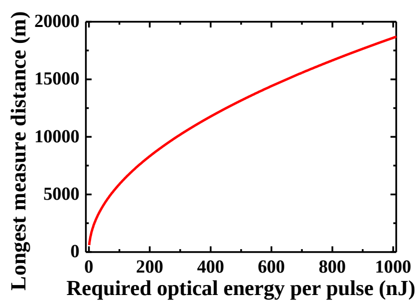

Fig. 4. The theoretical curve of output optical energy vs. largest measure distance.

4. Conclusion

In conclusion, we demonstrated a single-photon ranging system at 1550 nm with a 1-GHz sine-wave gated InGaAs/InP APD SPD. By using a time-of-flight TCSPC approach, we achieved 8 cm depth resolution at 32 m distance in daylight environment. It provides a simple way to build an ultra-high sensitive 1550 nm laser ranging system at eye-safe spectral regime. Benefitting from low power consumption of the devices used in this system, it is promising to be a mobile single-photon range finder for long-distance application.

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