1550-nm time-of-flight ranging system employing laser with multiple repetition rates for reducing the range ambiguity

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Abstract: We demonstrated a time-of-flight (TOF) ranging system employing laser pulses at 1550 nm with multiple repetition rates to decrease the range ambiguity, which was usually found in high-repetition TOF systems. The time-correlated single-photon counting technique with an InGaAs/InP avalanche photodiode based single-photon detector, was applied to record different arrival time of the scattered return photons from the non-cooperative target at different repetition rates to determine the measured distance, providing an effective and convenient method to increase the absolute range capacity of the whole system. We attained hundreds of meters range with millimeter accuracy by using laser pulses of approximately 10-MHz repetition rates.

OCIS codes: (280.3400) Laser range finder; (280.3640) Lidar; (030.5260) Photon counting; (040.3780) Low light level; (040.1345) Avalanche photodiodes (APDs).

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1. Introduction

With the development of single-photon detection and data acquisition technology, time-of-flight (TOF) ranging systems using time-correlated single-photon counting (TCSPC) technique have been implanted in more and more applications of great importance, such as satellite altitude measurements [1], altimetry measurements for airborne platforms [2], topographic mapping [3, 4], and so on. Besides the efficient detection of the extremely weak scattered light returning from non-cooperative targets by the single-photon detector, the individual photon incidence events are recorded and correlated to the trigger signal precisely and repeatedly, making the system capable of determining the position of the targets kilometers away with high depth resolution [5]. Moreover, the depth resolution could be improved if appropriate signal-processing method is used [6].

A great deal of previous work has done to develop TCSPC based TOF ranging systems at the wavelengths below 1000 nm, mainly limited by the spectral response of the optical receiver detectors. The receivers, such as photomultipliers, Si avalanche photodiode based single-photon detectors or micro-channel plate detectors [7–10], performed well at visible wavelengths, improving the resolution of the ranging systems. However, it is difficult to attain long-distance measurement in daylight condition with such systems, due to the strong solar background noise and high atmospheric attenuation of the optical signal [11]. In this paper, we present a TOF ranging system working at 1550 nm. Compared to the system operated below 1000 nm, the ranging system shows higher single-to-noise ratio under daylight condition at 1550 nm. Moreover, it is at eye-safe wavelength as well. Unlike [5, 11], we chose the single-photon detector based on InGaAs/InP avalanche photodiode (APD) instead of superconducting nanowire single-photon detector, which is easier to be integrated in the system. In order to reduce dark counts and afterpulsing, the InGaAs/InP APD is usually operated in the gated Geiger mode. With the emergence of some ingenious methods, such as self-differencing and sine-wave gating techniques, the gating repetition rate of the detector has increased to be over 1 GHz, making the detector work in the quasi-continuous mode and more suitable for laser ranging [12–17]. The key to improve the performance of such single-photon detectors is to exact the avalanche signal from the spike noise produced by the APD's capacitive response effectively. In comparison to the technique using square-wave or short pulses, the sine-wave gating scheme exhibited obvious convenience in suppressing spike noise. As the spike noise exhibited a quite simple frequency spectrum, it is facile to suppress the capacitive response noise efficiently by using electric band-elimination filters (BEFs). However, the timing jitter in the traditional sine-wave gating technique is usually up to hundreds of picoseconds, decreasing the surface-to-surface resolution in the TOF ranging system. We came up with a new method by replacing BEFs with low-pass filters (LPFs), decreasing the timing jitter while maintaining the detection performance [17].

Even though the TCSPC based ranging system excels in long distance measurement, a major weakness in range ambiguity could not be ignored. The range ambiguity is quite essential for unknown targets or rapidly moving targets due to the uncertain flight cycles covered by the return laser pulses. When the laser pulse of unique repetition rate is used, the maximum distance that could be unambiguously determined d_{Rep} can be calculated by,

$$d_{Rep} = \frac{c}{2nf_{Rep}}, \tag{1}$$

where c is the speed of light in the vacuum, n is the refractive index of air and f_{Rep} is the repetition frequency of the periodic laser source. Here, n is set to be 1, regardless of the different refractive indexes in the testing condition. For instance, d_{Rep} is just 15 meters while f_{Rep} is set to be 10 MHz. The higher the repetition rate is, the shorter absolute range could be determined. To increase the range, f_{Rep} has to be further reduced. However, the acquisition time for valid data should be increased with the laser pulse of low repetition frequency, reducing the efficiency of the whole system. Thus far, many methods have been invented to solve this harsh issue, such as random pattern technique in [18, 19]. The exact flight time could be identified by correlation between the transmitted and received patterns, and the unambiguous range could be extended by increasing the length of the repeated pattern. However, it was difficult to set a suitable discriminating level to effectively distinguish the low-return targets in the presence of other high-intensity returns in this kind of ranging system. Differently, we set up the TOF ranging system employing laser source with multiple repetition rate to improve the unambiguous measuring range. In this scheme, the system could measure targets with varied return intensities accurately by using a sensitive detector. The distance s was determined by

$$s = n_1 d_{Rep1} + \frac{ct_1}{2n}, \tag{2}$$

$$s = n_n d_{Repn} + \frac{ct_n}{2n}, \tag{3}$$

where $n_1, n_2 \ldots\ldots n_n$ are the cycle numbers for laser pulses with different repetition rates in the round-way flight, $d_{Rep1}, d_{Rep2} \ldots\ldots d_{Rep3}$ are the maximum unambiguous distances for each and $t_1, t_2 \ldots\ldots t_n$ are the flight time recorded by the TCSPC. By this means, the eventual d_{Rep} of the ranging system was determined by

$$d_{Rep} = \frac{c}{2nF_{Rep}} = \frac{c}{2n}\left[\frac{1}{f_{Rep1}}、\frac{1}{f_{Rep2}}\cdots\frac{1}{f_{Repn}}\right], \tag{4}$$

where $1/F_{Rep}$ is the least common multiple of $1/f_{Rep1}, 1/f_{Rep2} \ldots\ldots 1/f_{Repn}$. We could increase the d_{Rep} simply by increasing the number of different repetition rates. In our experiment, the repetition rates of the laser pulse were 10 MHz and 9.7 MHz, respectively, increasing the d_{Rep} from ~15 meters to 1455 meters with ease.

In this paper, we established a TOF ranging system at 1550 nm wavelength based on InGaAs/InP APD, which was operated in 1-GHz gated Geiger free-running mode. The whole timing jitter of the system was ~240 ps FWHM. The approach employing pulsed lasers with

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multiple repetition rates was adopted to resolve the range ambiguity. Meanwhile, we characterized the accuracy of the system by changing the measured distances. The experiment was carried out in free space under daylight condition. As pulsed lasers of 10-MHz and 9.7-MHz repetition rates were used, we attained the absolute range of several hundred meters with millimeter accuracy

2. System description

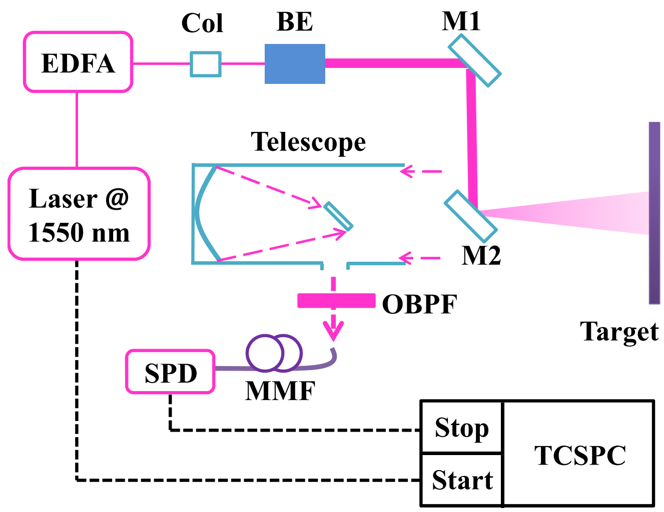

Fig. 1. Experimental setup of the TCSPC based TOF laser ranging system at 1550 nm. Col: collimator; BE: beam expander; M1, M2: high-reflection mirrors; OBPF: optical bandpass filter (center wavelength: 1549.60 nm, FWHM: 7.47 nm); MMF: multimode fiber; SPD: single-photon detector based on InGaAs/InP APD; TCSPC: time-correlated single-photon counting system (PicoHarp300, PicoQuant GmbH, Germany).

As shown in Fig. 1, a fiber-pigtailed pulsed laser diode at 1550 nm with ~35 ps pulse duration (PicoQuant GmbH,PDL 800-B) was used as the photon source. Before sending to the collimator and expanded by a beam expand, the laser pulses were amplified by an EDFA, with minimum magnification factor of 30 dB. The divergence angle of the output light beam was about 2.65×10^{-4}. By using two high-reflection mirrors, the optical transceiving system was operated in coaxial output mode, allowing the system to operate in a long distance without realignment and collecting the return scatted photons as many as possible. A 130-mm diameter Newtonian telescope was used to receive the retro-reflected photons. After the background noise from the daylight being blocked by an optical bandpass-filter (OBPF), the return photons were coupled into the fiber-pigtailed InGaAs/InP APD single-photon detector. Considering that the diameter of the sensitivity area of the APD was only 40 μm, the fiber core of the multimode fiber pigtail was set to be 62.5 μm. The optical loss from the telescope to the APD was approximately 3 dB, including the loss of OBPF and fiber coupling. The output of the single-photon detector 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 to be 4 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 a repetition cycle of the laser pulses.

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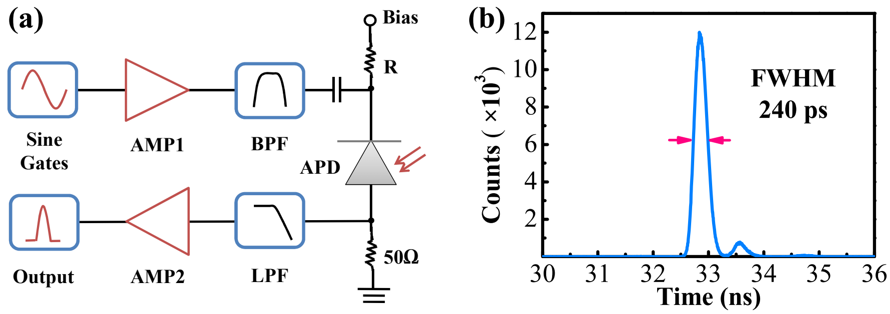

Fig. 2. (a) Schematic of the InGaAs/InP single-photon detector. AMP1, 2: amplifier; BPF: band-pass filter; LPF: low-pass filter. (b) Timing jitter of the single-photon detector in the free-running mode.

The single-photon detector used in the ranging system was operated in quasi-continuous Geiger mode, employing 1-GHz sinusoidal gating waves. Since the spectrum of the spike noises caused by the capacitance response of the APD was relatively simple, which just concentrated at 1 GHz and the harmonic frequencies, the avalanche signals could be extracted robustly by using a low-pass filter with a cut-off frequency at 700 MHz. The attenuation ratio of the LPF was higher than 40 dB at 1 GHz. By this means, the avalanche signals could maintain good signal integrity, leading to low timing jitter of the single-photon detector.

The peak-to-peak voltage of the amplified sinusoidal gating pulses applied on the APD was about 8 V, and the sinusoidal waves passed through a band-pass filter with the FWHM of 20 MHz at 1 GHz to minimize the amplified sideband noise and harmonic noise. We tested the features of the single-photon detector while being synchronized with the pulsed laser. The laser pulse with the repetition rate of 10 MHz was set to contain one photon per pulse. The delay between the laser pulse and the gating pulse was adjusted to attain the highest detection efficiency. When the bias dc voltage was 52.4 V, the detection efficiency was 10.4%, the dark count rate was 1.5×10^{-5}/gate, and the timing jitter was about 76 ps. The InGaAs/InP APD was Peltier cooled to 240 K. However, the target was non-cooperative, making the arrival time of the return photons an unknown parameter. In order to detect the return photons to obtain the distance information, the single-photon detector should be operated in the free-running mode, meaning that the laser pulse and the gating pulse had to be set unsynchronized. In that case, the detection efficiency was about 3.9%, and the timing jitter was only 240 ps, as shown in Fig. 2(b).

3. Experiment and results

In order to demonstrate laser ranging with multiple repetition frequencies to reduce the ranging ambiguity, we used the pulsed laser with the repetition rate of 10 MHz and 9.7 MHz. The single-pulse energy used in the system was about 0.1 nJ. The following equation was used to evaluate the performance of this system,

$$\overline{\mathrm{n}}_{in} = \frac{E_{out}}{h\nu}\frac{D^2}{8L^2}\mu T_{Opt} T_{Trans}, \tag{5}$$

where $\overline{\mathrm{n}_{in}}$ is the collected average return photons per pulse by the single-photon detector, E_{out} is the single-pulse energy of the laser, μ is the surface reflectivity of the target, D is the diameter of the telescope, T_{Opt} is the total optical loss of the receiving system (including the loss of the telescope, the focusing lens, the optical filter and fiber coupling), T_{Trans} is the transmission efficiency in the air at 1550 nm. The experimental measurements agreed well with the calculations. By analyzing the different arrival times of the return photons with the two different repetition rates, we could get the exact distance of the target. As mentioned above, the absolute range has been increased from ~15 m to 1455 m. The frequency has a

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high precision at mHz level (tested by Agilent 53131A). We carried out this experiment in a tall building under daylight condition, utilizing other surrounding buildings which had no significant specular reflection as targets. After spectral filtering of the return photons by the OBPF, the dark count rate was reduced to be about 25 kHz, enabling the ranging system work under daylight conditions. Limited by alternative targets around for test, the actual longest distance we measured was ~460 meters. Note that the ranging limit is much longer than 460 m.

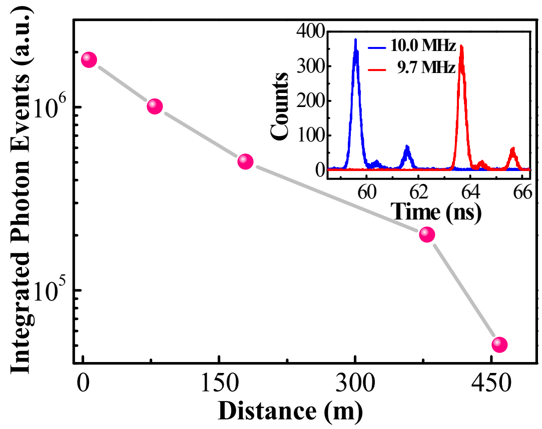

Fig. 3. Integrated number of photon events as a function of different measured distances. Inset: Histogram of the photons scattered from the target surface 460 m away.

Figure 3 showed the number of scattered return photons as a function of measured targets with different distances, while the acquisition time was set to be 1 s. With the increase of the distance, the total integrated counts gradually fell. When the target was 7.5 meters away, the number of the integrated photons was about 1.8×10^6. And when the measured distance rose to 460 m, the return photon number dropped to be 5×10^4. Meanwhile as shown in inset, the valid signal containing the distance message stood out against the background noise level. It could be thus found that longer distance could be measured with the ranging system of the same average laser power. The photon counting peak was centered at 59.580 ns with 10.0-MHz laser pulses, and at 63.644 ns with 9.7-MHz laser pulses. According to Eq. (3), the target was calculated to be at ~460 m away.

Except for the absolute range, the accuracy of the metered distance is another important parameter in the laser ranging system [20, 21]. To characterize the accuracy of this system experimentally, we took 30 sets of measurements, with the same distance and integral counts. The distance was determined in the method mentioned in Part 1, and the best result was calculated as the mean value of the 30 different measurements. As in Ref [20], the standard deviation of the distance for the 30 independent measurements can be regarded as a good estimate of the depth resolution of the system. Meanwhile, it can be seen from Fig. 3 that the scattered signal attenuated when the distance increased, in other words, the scattered signal was the representative of the measured distance. In order to analogize longer ranging distance, we increased the optical attenuation in the laser propagating channel while keeping the real distance constant.

Figure 4(a) exhibited the time resolution as a function of the integrated number of return photons determined by the distance of the tested targets. In the experiment, we kept the target 7.5 meters away and attenuated the output power of the EDFA to simulate the time resolutions at different distances. The acquisition time was kept 1 s. With larger accumulation numbers, the time resolution got better, implying that the resolution deteriorated with increase of the measured distance, in good agreement with those of Ref. 20. The time resolution could be easily converted to the distance resolution by the equation $d = ct/2$. As shown in Fig. 4(a),

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the experimental data fitted well with the simulated one. When the integrated number was 5×10^4, the actual time resolution was about 25 ps, while the simulated one was ~22 ps. Considering that the stamping resolution of the TCSPC used in the experiment was set to be 4 ps, the gap between the two time resolutions was quite small. When the distance was 7.5 m away, we could get the minimum distance resolution approximate 1.2 mm. In view of the timing jitter of the TCSPC, 1.2 mm almost reached the limits of the whole system.

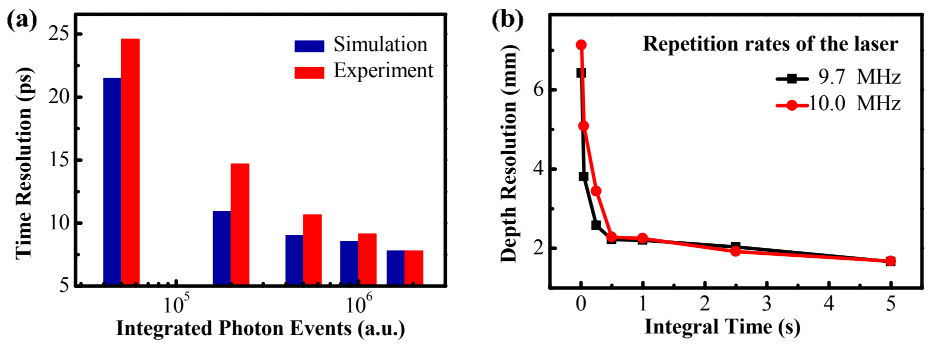

Fig. 4. (a) Time resolution versus the integrated number of return photons. The simulation data were plotted by increasing the optical attenuation in the laser propagating channel while keeping the target 7.5 meters away. (b) Depth resolution versus the integrated time when the distance was 380 m.

With the increase of distance, the scattered return signal attenuated, causing the signal-to-noise rate (SNR) decline, and furthermore resulting in the small differences between the experimental data and the simulated one demonstrated in Fig. 4(a). For better performance, we could increase the acquisition time to get more counts while the measured distance was expanded. We took the target 380 meters away for example. The integral counts collected by the single-photon detector were 2×10^5 per second. Since we used pulsed laser with two different repetition frequencies, the influence of this surveying method on the distance resolution should be taken into account. In Fig. 4(b), it could be found that the distance resolution was enhanced with the increase of the acquisition time. Moreover, the distance resolution was barely affected by the different repetition rates employed, the two curves almost keeping the same. When the integral acquisition time was 0.01 s, the distance resolution was about 7 mm. In contrast, when the time was increased to 5 s, the total counts were accumulated to be 1×10^6 and the resolution was about 1.7 mm.

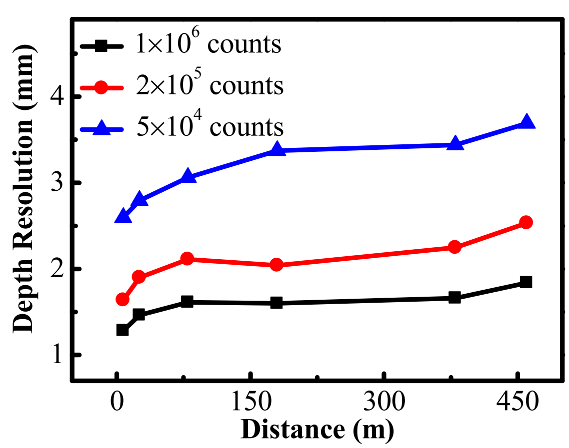

Fig. 5. Depth resolution as a function of distance with the same total photon-counts.

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On the other hand, to characterize the impact of the decreasing SNR with the expanding of the measured distance, we compared the depth resolutions while keeping the same total scattered photon-counts at different distances by changing the acquisition time. As demonstrated in Fig. 5, the total counts were set to be 1×10^6, 2×10^5, and 5×10^4 to test the performance. At the same distance, the distance resolution was improved with more counts. When the distance was 180 m, the resolution was ~1.6 mm with the count of 1×10^6, and 3.4 mm with the count of 5×10^4, matching with the results in Fig. 4(b). In the meantime, the depth resolution got worse when the distance increased, and the slope of the curve increased steadily with the decline of the total counts. Under this condition, the only varying factor was the SNR, so we could deduce that the decline of the distance resolution was caused by the growth of the SNR following the increase of the measured distance. Figure 5 shows that the resolution was approximately 2.6 mm at the distance of 7.5 m and increased to 3.7 mm at 460 m with the total photon-count of 5×10^4. The distance resolution would get worse with the increase of the measured distance, partly determining the maximum range capability of the whole system.

To investigate the role of SNR in determining the depth resolution in detail, we kept the distance and the power of the incident light constant. Meanwhile, a beam of continuous-wave light was coupled into the incident pulsed light to increase the noise level. The return desired signal remained unchanged, and the noise gradually augmented, leading to the decrease of SNR. Figure 6 reveals the depth resolution as a function of SNR, and the acquisition time was 1 s. The depth resolution was improved with the increase of SNR. When the SNR was beyond 80, the resolution improved quite slightly with the SNR. When the SNR was 400, the resolution was about 1.5 mm. When the SNR was as low as 2, the resolution was still ~4.5 mm. The inset of Fig. 6 showed SNR as a function of distance. SNR dropped to 30 as the distance was 460 m. The resolution should be ~2.1 mm when the SNR was 30 according to Fig. 6. However, in the experiment, the resolution was 3.7 mm when the distance was 460 m, a bit worse than the data presented in Fig. 6, due to the influence of the outdoor environment. Even so, we could conclude that the system could work at the range of hundreds of meters with the resolution better than 1 cm.

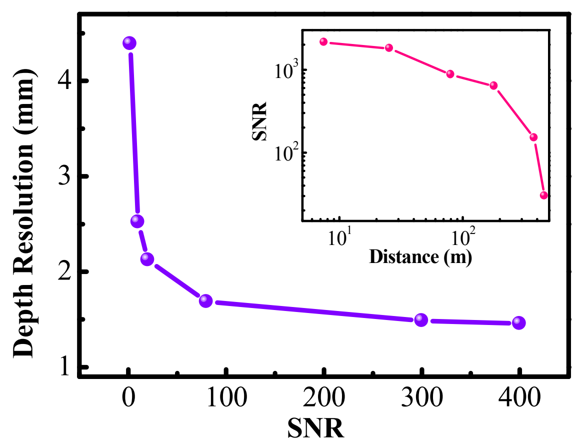

Fig. 6. Depth resolution as a function of SNR. Inset: SNR as a function of distance.

4. Conclusion

In this paper, we demonstrated a TCSPC technique based TOF ranging system employing pulsed lasers with multiple repetition rates at 1550 nm, offering a robust and convenient method to decrease the range ambiguity. While the repetition frequencies of 10 MHz and 9.7 MHz were used, the absolute range was increased from ~15 to 1455 m. A single-photon detector based on InGaAs/InP APD, working in the quasi-continuous mode, was applied to collect the scattered return photons to decide the distance. The detection efficiency was ~3.9%, and the timing jitter was ~240 ps. Finally, we attained several hundred meters range with millimeter accuracy while using lasers of approximately 10-MHz repetition rates.

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