Dynamic time-correlated single-photon counting laser ranging*

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We demonstrate a photon counting laser ranging experiment with a four-channel single-photon detector (SPD). The multi-channel SPD improve the counting rate more than 4×10^7 cps, which makes possible for the distance measurement performed even in daylight. However, the time-correlated single-photon counting (TCSPC) technique cannot distill the signal easily while the fast moving targets are submersed in the strong background. We propose a dynamic TCSPC method for fast moving targets measurement by varying coincidence window in real time. In the experiment, we prove that targets with velocity of 5 km/s can be detected according to the method, while the echo rate is 20% with the background counts of more than 1.2×10^7 cps.

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The time-correlated single-photon counting (TCSPC) technique can improve the single-photon detection to the quantum-limit sensitivity, which has been widely applied in the laser ranging and imaging[1-6]. In principle, no matter how weak the echo light is, the signal can be distilled by increasing the counting time of TCSPC, while the noise counts are random and their fluctuation is lower than the counting peaks of the signals. However, it became difficult to detect fast moving targets within short TCSPC time[7-9], especially in high background illumination. There are two methods to improve detection rate by increasing the laser power. One is based on the TCSPC technique, which decreases the counting time by using high repetition-rate laser pulses, such as random pattern technique[10-13] and multi-repetition technique[14]. The other method is based on the photon-number-resolving detection, which suppresses the noise through increasing the threshold of the photon number and realized single-shot detection[15, 16]. But, all these methods need to obtain enough signal photon counts in short time, which are not useful for long-distance detection, as the laser power is limited.

In order to detect high background, long-distance and fast moving targets, we propose a method of dynamic TCSPC laser ranging. In this method, compared with the traditional TCSPC, a variable coincidence window is set to extend the counting time, and a 4-channel single-photon detector (SPD) is used to increase the efficient counting rate more than 4×10^7 counts per second (cps) for daylight detection.

The experimental system of the dynamic TCSPC laser ranging is shown in Fig.1. A short pulsed laser at 532 nm with the width of 0.7 ns was used. The laser energy was about 0.6 μJ per pulse with the repetition rate of 33 kHz. A fast PIN photodiode was behind the reflecting mirror to detect the laser pulses as the synchronization. The laser beam was expanded to 5.0 mm in diameter with the divergence angle of 0.1 mrad. At the receiver, a plano-convex lens with the focal length of 50 mm and the diameter of 25.4 mm was used to collect the echo light. Two bandpass filters (BPFs) were used to suppress the background. The first one had a transmittance of 90% with the 3-dB bandwidth of 2.0 nm, and the second one had a transmittance of 85% with the 3-dB bandwidth of 10 nm. After BPFs, the light was coupled into a multi-mode fiber with core diameter of 105 μm. This light was equally divided into four beams by a 1/4 fiber coupler, and sent to 4 fiber-pigtailed SPD.

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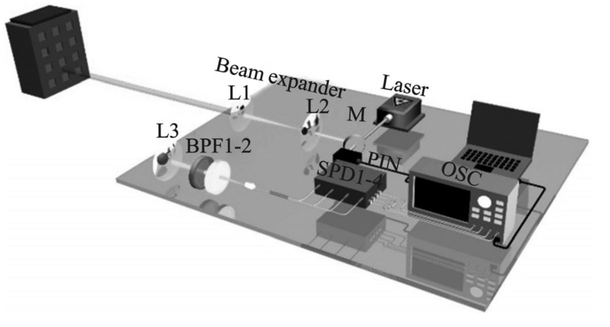

M: reflecting mirror; PIN: PIN photodiode; L1, L2: beam expander; L3: plano-convex lens; BPF1-2: two bandpass filters; SPD1-4: 4-channel single-photon detector; OSC: oscilloscope

Fig.1 Schematic diagram of experimental setup

In the 4-channel SPD, four Si avalanche photodiodes (APDs) are operated in Geiger mode with active quenching. The detection efficiency of each APD is about 50% at 532 nm, with the dark counts less than 2 000 cps. The dead time of each SPD is about 50 ns with the saturated counts more than 1.5×10^7 cps. And the efficient counting rate of the 4-channel SPD is more than 4×10^7 cps. The total timing jitter of the system is about 900 ps, including the jitters of 4 APDs and the laser pulse width. It is equivalent to the measurement accuracy of 13.5 cm.

The output of the 4-channel SPD was sent to a 4-channel digital oscilloscope (OSC, Agilent Technologies DSO9054H). The oscilloscope was triggered by the pulse synchronization from the fast PIN photodiode. The segmented memory acquisition mode of the oscilloscope was used to register all the photon counts within each segment. The sampling rate is 2.5 GS/s corresponding to the sampling period of 400 ps. The acquisition window is 5 μs, and the maximum number of segment is 1 024 for each acquisition. Then these data was sent to a computer for dynamic TCSPC analysis.

In this paper, we propose a dynamic TCSPC method for fast moving targets under high background. The constant coincidence window in the TCSPC technique is replaced by a variable coincidence window. Assuming that the repetition rate of laser pulse is f, the maximum velocity of the targets is v, the original time is T_0, and the original coincidence window is $T_0\pm\Delta t_0$, the dynamic coincidence window at the nth pulse is

$$t_n = T_0 \pm \Delta t_0 \pm 2(n-1)\frac{v}{c}\cdot\frac{1}{f},\quad n\in[1,p] \quad ,\qquad (1)$$

where Δt_0 is the static coincidence window, c is the velocity of light, and p is the number of the laser pulse within one coincidence period. If there is a coincidence count at the mth pulse, the dynamic coincidence window at the nth pulse is changed to

$$t_n = T_m \pm \Delta t_0 \pm 2(n-m)\frac{v}{c}\cdot\frac{1}{f}, n\in[m,p] \ ,$$

$$m\in[1,p] , \qquad (2)$$

where T_m is the arriving time of the coincidence photon at the mth pulse.

We set a threshold for the dynamic TCSPC to distill the signal photon counts from the high background quickly, as shown in Fig.2. Due to the limited experimental conditions, it is difficult for us to find a target with the velocity of a few kilometers per second. So we simulate a fast moving target with the velocity of 5 km/s based on the experimental data of the photon-counting ranging of the static target 1 850 m away by our ranging system. We set the number of laser pulse p<33 within one coincidence period, to ensure that the measurement rate of the laser ranging is less than 1 ms. The optimal threshold L_1 can be calculated by

$$L_1 = 1.5\cdot p\cdot EMR + p\cdot N\cdot(p-1)\frac{2v}{fc} + p\cdot N\cdot 10^{-9} \ , \qquad (3)$$

where EMR is the effective echo rate, and N is the noise counts. Assuming that the repetition rate of the laser pulse is 33 kHz, and the acquisition window is 5 μs, the optimal threshold L_1 with different noise counts and EMR are shown in Fig.3.

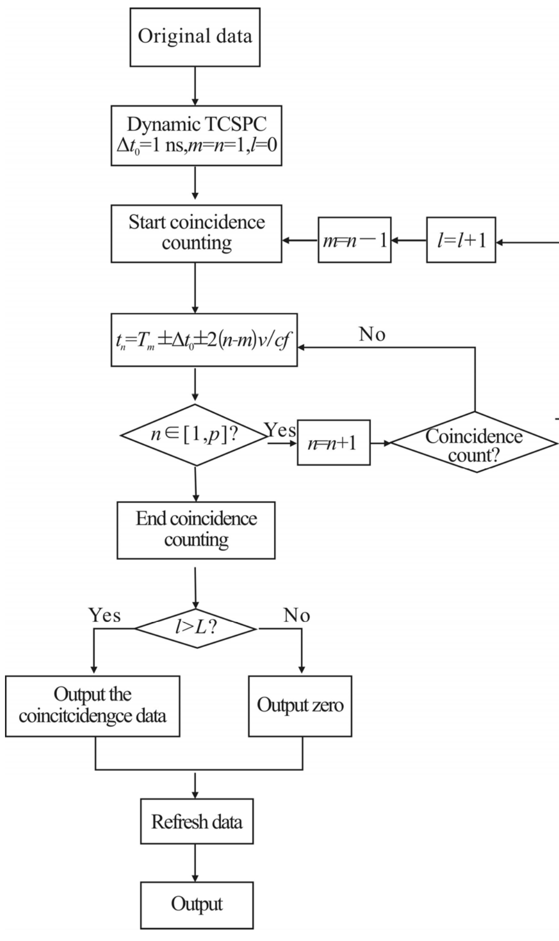

Fig.2 The flow chart of the program

Through the dynamic TCSPC, more than 80% signal photon counts can be preserved, and most of the noise counts are suppressed, as the signal-to-noise ratio (SNR) is larger than 20 dB.

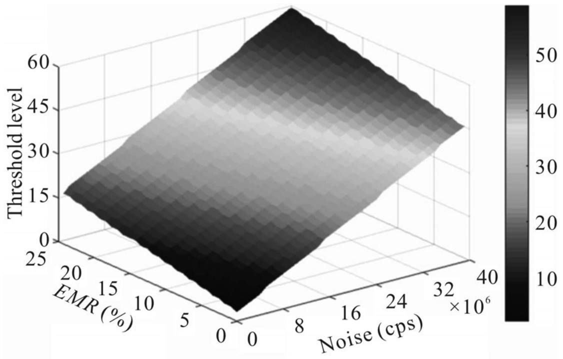

Fig.3 Threshold with different noise counts and *EMR* at the repetition rate of the laser pulse of 33 kHz

In the long-term dynamic TCSPC, the threshold L_2 can be set according to

$$L_2=\begin{cases} q, (EMR\cdot p>1) \\ EMR\cdot p\cdot q, (EMR\cdot p\le 1) \end{cases}. \tag{4}$$

The dynamic TCSPC method is limited by the noise counts and the *EMR*. In order to keep more than 70% of the signal photon counts, the system required a minimum *EMR* at each corresponding noise counts. As shown in Fig.4, the minimum *EMR* is increased with increase of the noise counts. In our laser ranging system, the *EMR* of about 6% is enough, while the noise counts is about 1×10^6 cps. And *EMR* is increased to 20% while the noise counts are above 1.2×10^7 cps. The minimum *EMR* should be increased to 40%, as the noise counts is up to about 4×10^7 cps on a clear day.

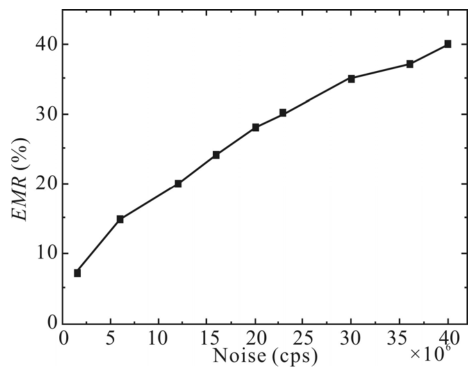

Fig.4 The minimum *EMR* with the increase of the noise counts

We design a flight path of a fast moving target, and simulate the photon counting result at the speed of 5 km/s based on the original data of photon counting laser ranging. The average photon number of the echo light is about 0.6 photons per pulse of a static target 1 850 m away. The noise counts are about 8×10^6 cps, which is much larger than the signal photon counts. In this condition, we set t_0=1 ns and p=20 for the dynamic TCSPC. Fig.5 demonstrates the laser ranging results of TCSPC and dynamic TCSPC, respectively.

Fig.5(a) shows the original data, where the total signal photon counts is 195 with the *EMR* of 19.04%, the noise counts are about 42 050, and the *SNR* is about 13.65 dB. Through the TCSPC technique, the *EMR* is degenerated to 2.73%, and it is hard to distinguish the track of target, as shown in Fig.5(b). So it is difficult to discriminate the track of the target in high background with the velocity exceeding 5 km/s by using a static coincidence window of the TCSPC technique.

Fig.5(c) shows the track of target through dynamic TCSPC method. We set the threshold L_1 as 10. Most signal photon counts are reserved, as the *EMR* is 15.04%, while the noise counts fall from 42 050 to 2 552, and the *SNR* is improved from 13.65 dB to 24.79 dB. And then, we make a long-term dynamic TCSPC by setting q=8. The noise counts are decreased to 413, and the *SNR* reaches to 32.3 dB, while the threshold L_2 is 8. As a result, a clear trajectory is obtained as shown in Fig.5(d). It proves that the dynamic TCSPC method is suitable for the detection of fast moving targets.

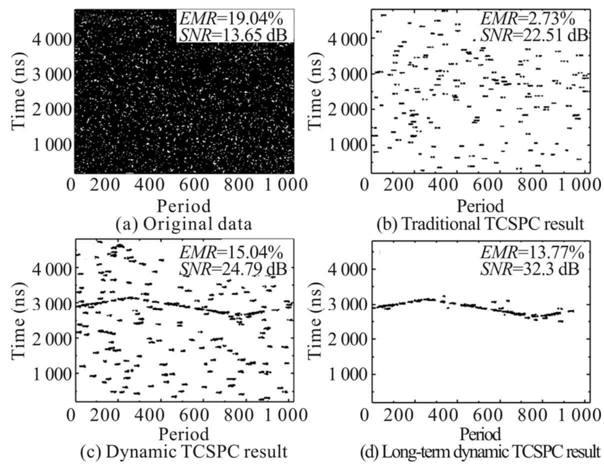

Fig.5 The detection results of fast moving target with different analysis methods

In conclusion, we demonstrate a laser ranging system with a 4-channel SPD, which allows for the measurement under high background light illumination with noise counts up to 4×10^7 cps. Traditional TCSPC technique uses a static coincidence window. When the velocity of target is fast, the short coincidence window can hardly distill the signal from high background, which leads to difficulties to discriminate the track of the fast moving target. In this paper, we propose a dynamic TCSPC method with a variable coincidence window for the detection of fast moving targets. The trajectory can be distinguished clearly with 72.3% of the signal photon counts being reserved, while the echo photons are 0.3 photons per pulse, the velocity of the moving target is up to 5 km/s, and the noise counts are as high as 8×10^6 cps. It is an efficient method for detecting and tracking of the fast moving targets with very few echo photons under high background.

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