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Detection performance improvement of photon counting chirped amplitude modulation lidar with response probability correction*

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Geiger mode avalanche photodiode detector (Gm-APD) possesses the ultra-high sensitivity. Photon counting chirped amplitude modulation (PCCAM) light detection and ranging (lidar) uses the counting results of the returned signal detected by Gm-APD to mix with the reference signal, which makes PCCAM lidar capable of realizing the ultra-high sensitivity, and this is very important for detecting the remote and weak signal . However, Gm-APD is a nonlinear device, different from traditional linear detectors. Due to the nonlinear response of Gm-APD, the counting results of the returned signal detected by Gm-APD are different from those of both the original modulation signal and the reference signal. This will affect the mixing effect and thus degrade the detection performance of PCCAM lidar. In this paper, we propose a response probability correction method. First, the response probability correction model is established on the basis of Gm-APD Poisson probability response model. Then, the response probability correction model is used to adjust the original modulation signal that is used to drive laser, in order to make the counting results of the returned signal detected by Gm-APD better mix with the local reference signal in the same form. Through this method, the detection performance of PCCAM lidar is enhanced efficiently.

Keywords: photon counting, chirping, lidar

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1. Introduction

In the past several decades, light detection and ranging (lidar) has been widely used in various fields, and it possesses the advantages of good directionality, high spatial resolution, and detection accuracy.[1–3] Now, many application backgrounds of remote and weak signal detection put forward higher requirements for the detection sensitivity. In this case, the scattered photons are very rare (called photon starved scenes), normally a few photons or less than a single photon. Therefore, conventional approaches are quite invalid due to the limitation of the detector sensitivity.[4,5] Geiger mode avalanche photodiode detector (Gm-APD) is a new kind of detector working in critical state with a bias voltage slightly higher than the breakdown voltage, and thus Gm-APD has an ultra-high sensitivity, even responding to a single photon.[6–9] Shortly after the Gm-APD detector appeared, MIT Lincoln Laboratory conducted the first experiment with a single detector, which showed the feasibility of using a Gm-APD for 3D imaging.[10,11] East China Normal University demonstrated various methods of laser ranging using Gm-APD single-photon detectors, including laser ranging with 1-GHz sine-wave gated InGaAs/InP APD single-photon detector,[12] single-photon ranging system with multiple repetition rates for reducing the range ambiguity,[13] coincidence photon-counting laser ranging for moving targets with high signal-to-noise ratio,[14] etc. Subsequently, many groups conducted a substantial amount of research work on the performance of Gm-APD lidar, which showed that Gm-APD detection technology is an effective way to detect the weak signal.[15,16] Besides, the heterodyne detection is also an effective way to detect the weak signal, and it could improve receiver sensitivity compared with direct detection due to the mixing process of echo signal and reference signal.[17,18] Therefore, a bold and innovative idea was proposed: whether a combination of the Gm-APD single photon detection and the heterodyne detection is feasible. The answer is yes, and this is completely feasible. In 2006, the Army Research Laboratory used Gm-APD in the chirped amplitude modulation (CAM) lidar for the first time, and proposed photon counting chirped amplitude modulation (PCCAM) lidar.[19] In 2015, East China Normal University demonstrated photon-counting chirped amplitude modulation lidar with 1.5-GHz gated InGaAs/InP Gm-APD.[20]

This novel PCCAM lidar could yield high sensitivity approaching the signal shot noise limit, and thus became a hot research topic. In this respect, we have made significant re-

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search efforts. In 2011, the sliding window and the threshold were used to reduce the error photon counting pulses that were caused by noise and mostly distributed in the intensity troughs of the chirped AM waveform, and this method efficiently improved the signal noise ratio (SNR) of PCCAM lidar.[21] In 2013, a new premixing method for PCCAM lidar was proposed, and it adopted the reference signal to directly modulate the sampling gate width of the Gm-APD to complete the mixing process before Gm-APD. This new premixing method could improve the SNR due to avoiding the noise introduction from a separated mixer commonly used in the traditional PCCAM lidar.[22] In the same year, an echo signal intensity optimization strategy with an iris diaphragm was employed in PCCAM lidar, and the experimental results demonstrated that it could effectively improve the SNR of PCCAM lidar under different signal and noise intensities.[23] Through a lot of research efforts, we also found that due to the nonlinear Poisson response of Gm-APD, the photon counting results of the returned CAM signal are a joint function of the CAM signal and Poisson probability response. The photon counting results have different functional forms with the original modulation signal and the reference signal, which would affect the mixing effect and thus degrade the detection performance of PCCAM lidar. Therefore, in this paper, we present an improved method of PCCAM lidar based on the response probability correction. Through the response probability correction, we are able to ensure that the photon counting results of the returned CAM signal and the local reference signal are in the same form, which will lead to a better mixing effect and improve the detection performance of PCCAM lidar.

2. Theoretical analysis

PCCAM lidar originates from the traditional chirped amplitude modulation lidar. They both use chirped amplitude modulation (CAM) signal, whose normalized form can be expressed as

$$S(t)=\left[\cos\left(f_0t+\frac{1}{2}kt^2+\phi_0\right)+1\right]\Big/2, \tag{1}$$

where f_0 is the initial frequency, ϕ_0 is the initial phase, and $k=B/T$ is the modulation rate of the CAM signal, in which B is the modulation bandwidth and T is the modulation period. The CAM signal is divided into two paths. One is used as the local reference signal $S_{\rm L}(t)=S(t)$ to wait for the mixing process in the lidar receiver, and the other is used to modulate the transmitted laser signal $S_{\rm T}(t)=I_0S(t)$, where I_0 is the peak power of the transmitted laser. In the round trip transmission and target reflection, M is the total loss (including the system and atmosphere loss) and the round trip time is τ. So the echo signal is $S_{\rm R}(t-\tau)=M\cdot S_{\rm T}(t-\tau)$. Then through the mixing process and fast Fourier transform (FFT), the intermediate frequency (IF) is obtained as $S_{IF}(\omega)=F\{S_{\rm L}(t)\cdot S_{\rm R}(t-\tau)\}\propto \sin c(\omega-k\tau)$. Finally, according to the IF peak position, the round trip time τ is obtained and thus the target distance is $R=\tau c/2$.

However, Gm-APD is different from the traditional linear response detector, it is a nonlinear device. The probability response model of Gm-APD meets the Poisson probability distribution and can be expressed as[24]

$$P(t)=1-\exp[-N_{\rm s}(t)], \tag{2}$$

where $N_{\rm s}(t)$ is the signal intensity of photon number form (namely, the mean numbers of signal photons per nanosecond at the time point of t). Through the round trip time, the echo signal can be written as $N_{\rm s}(t-\tau)=S_{\rm R}(t-\tau)\eta/h\nu=MI_0S(t-\tau)\eta/(h\nu)$. $N_{\rm s}(t-\tau)$ is in the same function form as both the CAM signal $S(t-\tau)$ and the local reference signal $S(t)$. But through the nonlinear response of Gm-APD, formula (2) changes into

$$\begin{aligned}P(t-\tau)&=1-\exp[-MI_0S(t-\tau)\eta/(h\nu)]\\&=1-\exp\left[-N_{\rm s}S(t-\tau)\right],\end{aligned} \tag{3}$$

where $N_{\rm s}=MI_0\eta/h\nu$ denotes the intensity of the echo signal, and $P(t-\tau)$ is the probability distribution of the photon counting result of the returned CAM signal. From the detection of Gm-APD, the intensity modulation of the echo signal produces a corresponding modulation in the probability distribution of the photon counting results.[21] However, $P(t-\tau)$ is in a different function form from the local reference signal $S(t)$, which will affect the mixing effect and degrade the performance of PCCAM lidar.

In Fig. 1, the black solid curve denotes the original CAM signal, and the other three curves represent the normalized response probability curves of Gm-APD detecting the CAM signal with different echo signal intensities: $N_{\rm s}=1,3,5$. It can be seen that the difference between the Gm-APD response probability results and the CAM signal becomes larger with the increase of the echo signal intensity. This difference is caused by the nonlinear response of Gm-APD. As a matter of fact, the Gm-APD response probability result $P(t-\tau)$ is the joint function of the CAM signal and Poisson probability response. In order to obtain a better mixing effect, we perform a response probability correction in order to make the Gm-APD response probability result $P(t-\tau)$ and the CAM signal be in the same functional form. Substituting the normalized Gm-APD response probability result $P'(t-\tau)=S(t-\tau)$ instead of $P(t-\tau)$ into formula (3), we can reversely deduce the normalized modulation function form that the laser signal should have, which is as follows:

$$S'(t)=-A\ln\left[1-S(t)\right], \tag{4}$$

where A is the normalized parameter. This formula will be used to correct the modulation function of the transmitted laser signal. This method can ensure that the Gm-APD response probability result and the CAM signal are in the same function form, which results in the better mixing effect, and thus the performance of PCCAM lidar will be improved.

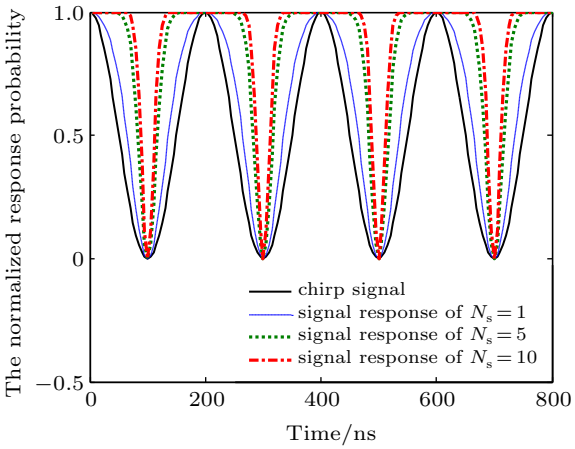


Fig. 1. (color online) Normalized response probability versus time of photon counting results for different echo signal intensities $N_s = 1, 3, 5$.

3. Improved system and experimental results

The operational principle of the improved PCCAM lidar using response probability correction is shown in Fig. 2. Firstly, the original CAM signal $S(t)$ is generated by a signal generator (Tektronix AFG3252). The period of the CAM signal is $T = 1$ ms, and the modulation bandwidth is $B = 5$ MHz from 1 MHz to 6 MHz. Then the CAM signal is divided into two channels. One is used as the reference signal to wait for the mixing process. The other is used as the driving signal. Traditional PCCAM lidar directly uses $S(t)$ to modulate the laser signals. The proposed response probability correction adds the modulation correction module which transforms the CAM signal $S(t)$ into $S'(t)$ according to formula (4), then $S'(t)$ instead of $S(t)$ is used to modulate the transmitted laser signal. Thus, the returned signal modulated by $S'(t)$ is detected by Gm-APD and has the same form as the local reference signal. This will ensure better mixing effect and improve the detection performance of PCCAM lidar. A 532 nm fiber laser is used, whose power is continuously tunable and capable of varying from 0 to 10 mw with the external electric signal. The modulated laser signal is transmitted to illuminate the target through a fiber collimator. After a round-trip time, part of the laser signal is reflected and returns to the lidar receiver. A narrow-band filter is used to filter the background noise, and its filter bandwidth is 10 nm and center transmittance is 65% at 532 nm. Then through a lens, the echo signal is detected by Gm-APD. The Gm-APD is COMPONENTS COUNT-50C (the photon detection efficiency at 532 nm is above 60%; the dead time is 50 ns). Then the photon counting result of Gm-APD is mixed with the other channel of the CAM signals in the mixer. After the mixing process, the low pass filter (LPF) extracts an intermediate frequency (IF) signal. Finally, through FFT, the computing result shows the IF signal peak from the IF spectrum.

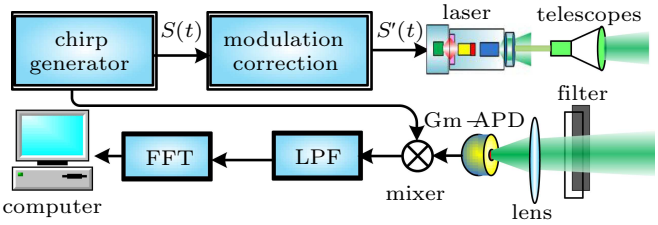


Fig. 2. (color online) Schematic diagram of the improved PCCAM lidar system with response probability correction. LPF stands for low-pass filter; FFT denotes fast Fourier transform.

Under the same conditions, we compare two methods: one is the improved PCCAM lidar system that is proposed in this paper with response probability correction method; the other is the traditional PCCAM lidar system without response probability correction method. From Fig. 3, it can be seen that the IF signal of the traditional PCCAM lidar system gradually decreases with the increase of the signal intensity N_s as shown in Figs. 3(b), 3(d), and 3(f), while the proposed correction method of this paper can obtain a better IF signal peak as shown in Figs. 3(a), 3(c), and 3(e). The improvement of the IF signal is due to the fact that the response result of the returned signal detected by Gm-APD is in the same form as the local reference signal, and thus has a higher mixing efficiency. Besides, the proposed correction method has lower root-mean-square (RMS) noise than the tradition method. This is because in the traditional method, the response result of the returned signal is distorted by Gm-APD response, and is a superposition signal of many frequency trigonometric functions. This distorted signal energy will be distributed in the noise spectrum. The response probability correction method in this paper is able to reduce the loss of this distorted signal energy, improve the signal utilization rate, and reduce noise. In this way, the signal-to-noise ratio can be improved as shown in Fig. 4.

The SNR is the ratio of the IF signal to the RMS noise in dB. Many performance parameters of the PCCAM lidar system will be improved with the increase of SNR, such as the range accuracy $\delta R = c/(2B\sqrt{2\mathrm{SNR}})$.[25] The proposed correction method in this paper is capable of obtaining a better IF signal and lower RMS noise, which will improve the SNR and the performance of PCCAM lidar system efficiently. In Fig. 4, the experimental results demonstrate that the proposed correction method can improve the SNR of PCCAM lidar system under different average signal intensities.

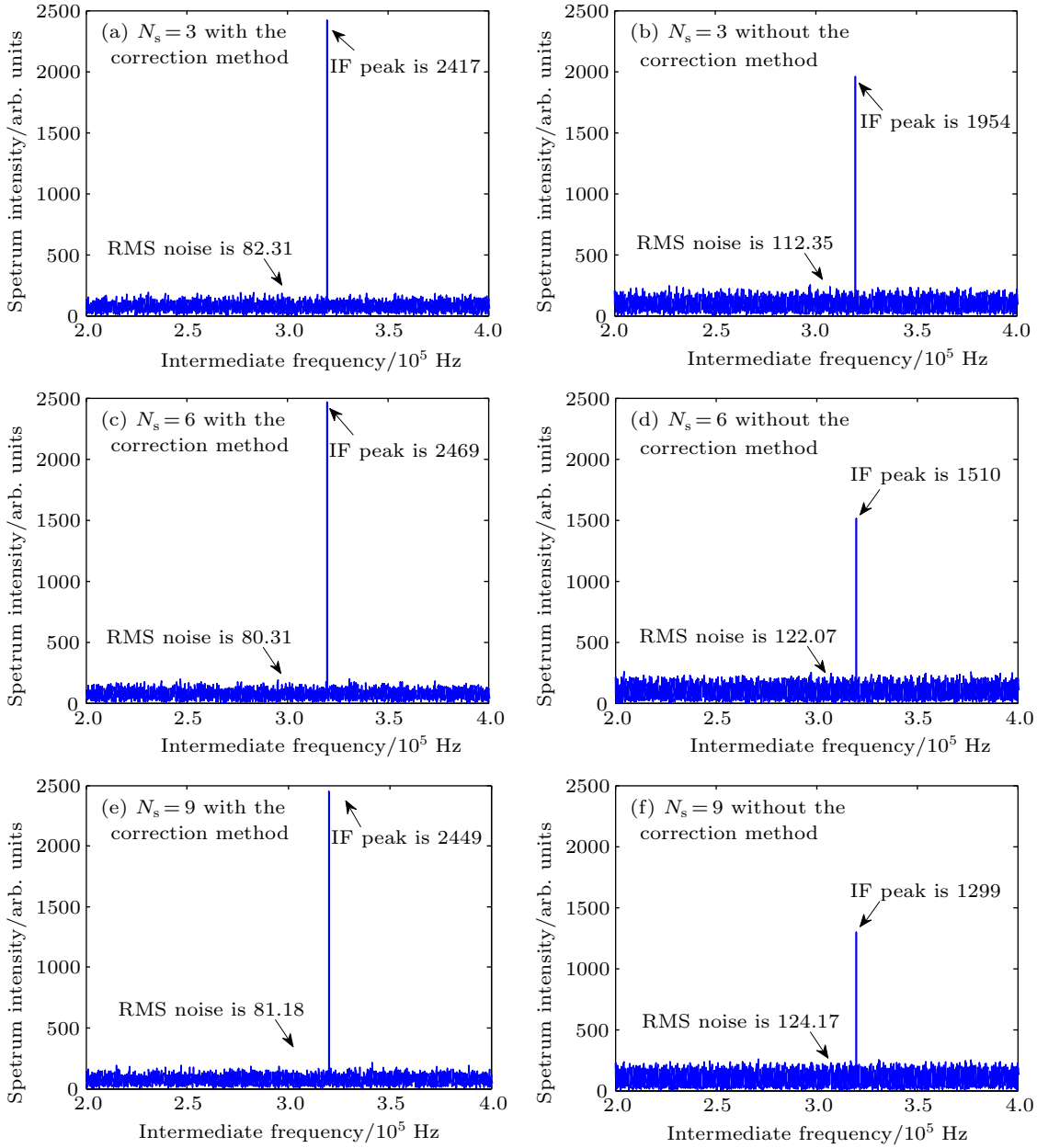


Fig. 3. (color online) Comparison between intermediate frequency (IF) signals with and without the correction method for different echo signal intensities: (a), (b) $N_s = 3$; (c), (d) $N_s = 6$; (e), (f) $N_s = 9$.

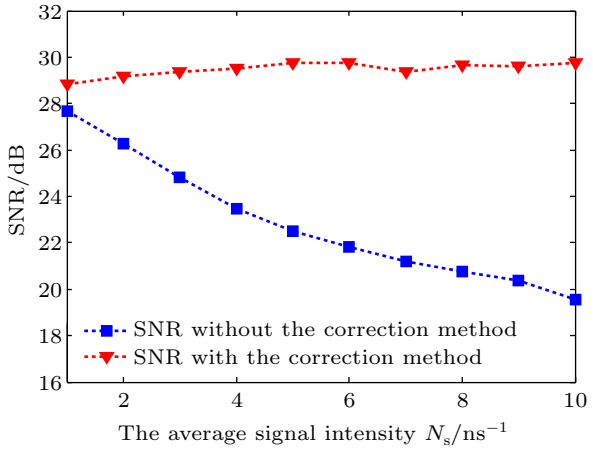


Fig. 4. (color online) Comparison between signal noise ratio (SNR) with and without the correction method.

4. Conclusion

We present an improved PCCAM lidar system based on the response probability correction method. First, the response probability correction model is deduced through the theoretical analysis. Then the response probability correction model is used to adjust the laser signal. This method makes the photon counting results of the echo CAM signal and the local reference signal be in the same form, thus ensuring the better mixing effect. Finally the experimental results show that the proposed correction method in this paper is capable of obtaining better IF signal and lower RMS noise, and thus efficiently improving the SNR of PCCAM lidar system.

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