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Photon-counting chirped amplitude modulation lidar system using superconducting nanowire single-photon detector at 1550-nm wavelength*

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We demonstrate a photon-counting chirped amplitude modulation (CAM) light detection and ranging (lidar) system incorporating a superconducting nanowire single-photon detector (SNSPD) and operated at a wavelength of 1550 nm. The distance accuracy of the lidar system was determined by the CAM bandwidth and signal-to-noise ratio (SNR) of an intermediate frequency (IF) signal. Owing to a short dead time (10 ns) and negligible dark count rate (70 Hz) of the SNSPD, the obtained IF signal attained an SNR of 42 dB and the direct distance accuracy was improved to 3 mm when the modulation bandwidth of the CAM signal was 240 MHz and the modulation period was 1 ms.

Keywords: photon counting, photodetectors, lidar

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1. Introduction

Light detection and ranging (lidar) systems have been widely used in various areas such as precise tracking, remote sensing, and terrain mapping.[1,2] However, in some photon-starved environments such as measurements with remote or non-co-operative targets, retroreflected light is very weak, so a single-photon detector (SPD) has to be employed in a lidar system. Thus, the time-correlated single-photon counting (TCSPC) technique has been introduced, making the detection system sensitive to ultra-low levels of light and offering excellent depth resolution. Nevertheless, TCSPC-based systems often suffer from range ambiguity. This ambiguity is inevitable for unknown or rapidly moving targets when uncertain flight cycles are covered by return laser pulses. In a TCSPC-based ranging system, the maximum distance that could be unambiguously determined d_{rep} can be calculated by $d_{\mathrm{rep}} = c/2nf_{\mathrm{rep}}$, where c is the speed of light in the vacuum, n is the refractive index, and f_{rep} is the repetition frequency of the periodic laser source. Thus, the lower the repetition is, the longer the absolute range can be. However, one cannot simply decrease the repetition rate of a pulsed laser to solve this problem because it increases the acquisition time of valid data, significantly decreasing the efficiency of the entire system. Thus, various methods, such as the random pattern technique[3,4] and laser pulses with multiple repetition rates,[5] have been introduced in TCSPC-based detection systems to extend the unambiguous range capacity. In 2006, the Army Research Laboratory reported a new method combining the single-photon detection and chirped amplitude modulation (CAM) techniques in a lidar system and called this method the photon-counting chirped amplitude modulation (PCCAM) lidar.[6] Unlike the traditional TCSPC-based lidar systems, the distance measured using a PCCAM lidar system was calculated according to the difference frequency, referred to as the intermediate frequency (IF) waveform, of the CAM signal and photon-counting pulses, whose arrival rates were also modulated by the CAM waveform with a round-trip time between the target and transceiver. The range ambiguity was avoided when using this method without compromising the system detection efficiency (SDE). For a PCCAM lidar system, the dead time of an SPD determines the upper limit of the modulation bandwidth and therefore sets the minimum achievable range accuracy.[6] Thus, an SPD with a short dead time is necessary for a PCCAM lidar system with high precision. In a PCCAM lidar system incorporating an SPD with a long dead time, some additional measures must be adopted to improve the system range accuracy; these measures include adopting the echo-signal intensity-optimization strategy with an iris diaphragm,[7] exploiting the phase of the IF signal,[8]

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and adopting the premixing method.[9] However, these measures may increase the complexity and cost of the system.

Much of the previous research on PCCAM lidar systems has been performed at a wavelength below 1000 nm, mainly limited by the spectral response of SPDs. With a relatively long SPD dead time, the distance accuracy was limited to more than 10 cm even when using the above mentioned improved systems.[7,8] Recently, Li *et al.*[10] reported a PCCAM lidar system at 1550 nm using an SPD based on an InGaAs/InP avalanche photodiode (APD). The APD was operated in a 1.5-GHz sine-wave-gated Geiger mode to decrease the dead time to 6.4 ns; the CAM bandwidth exceeded 200 MHz and the direct distance accuracy was 0.12 m using this system. More interestingly, this wavelength lies in the eye-safe region and offers much less solar background noise as well as low atmospheric attenuation, which is critical in the development of future PCCAM lidar systems.

In the last decade, superconducting nanowire single-photon detectors (SNSPDs) have attracted considerable attention because of their high DE, low dark count rate (DCR), lack of after-pulsing, low timing jitter, and short dead time. SNSPDs are considered to be a promising alternative to the conventional SPDs and have been successfully applied in near-infrared laser ranging and depth imaging.[11–17] In this paper, we demonstrated a 1550-nm PCCAM lidar system incorporating an SNSPD with a dead time of 10 ns. The modulation bandwidth of the CAM signal was increased to 240 MHz with a 42-dB signal-to-noise ratio (SNR) of the IF signal owing to a short dead time and a low DCR of the SNSPD. For the first time, the corresponding distance accuracy was improved to the order of millimeters (3 mm).

2. Experimental setup

The scheme of the PCCAM lidar system is illustrated in Fig. 1. A chirped electrical signal was produced by a signal generator with two identical output channels. One channel was applied to modulate a laser diode (LD) at 1550 nm and converted a continuous laser signal of constant intensity (500 μW) into a CAM laser signal; the other channel was applied to a frequency mixer. The modulated laser signal passed through a 3.6-km fiber delay to simulate a remote measuring environment. The CAM laser signal was then expanded and collimated with a single-mode fiber (SMF, 9-μm fiber core) pigtailed reflective collimator with an output beam size of 6 mm. The optical transmit–receive system was operated in a coaxial mode. In this experiment, as the target, we used a reflective mirror situated 20 m away from the receiver to reflect the CAM signal. After a round-trip time between the target and receiver, the echo signal was passed through a narrow-band filter to eliminate the background noise. The reflected photons were then converged using a lens (3-cm focal length) and coupled into a multimode fiber (MMF) with a core size of 50 μm. This MMF was then connected to an SMF to which an SNSPD was optically coupled. The total optical loss of the system was approximately 30 dB, including the 20-dB coupling loss from the MMF to SMF. The average photon-arrival rate of the echo signal was proportional to the laser power, although individual photon arrivals were randomly distributed; therefore, the photon-counting outputs of the SNSPD were modulated by the amplitude modulation of the laser power. Because the output voltage pulses of the SNSPD often had a sub-millivolt amplitude, a low-noise amplifier cascade was introduced before they were applied into the mixer to obtain a better SNR of the IF signal. After passing through a low-pass filter, the IF signal was directly measured using a spectrum analyzer.

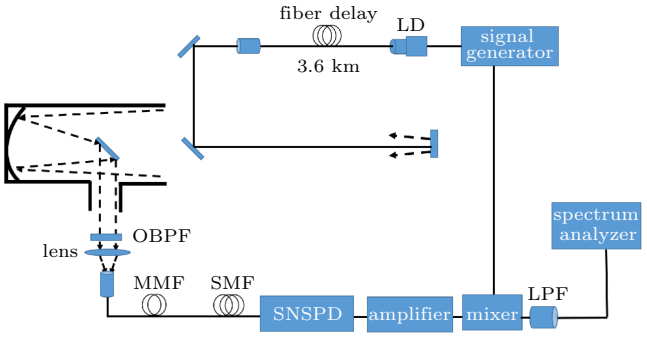


Fig. 1. (color online) Experimental setup of the laser-ranging system based on SNSPD.

Because the modulation bandwidth of the CAM signal was mainly determined by the dead time of the SPD, we prepared an SNSPD with a relatively short dead time for the experiments. The dead time of the SNSPD was limited by the kinetic inductance of the nanowires, which was proportional to the nanowires' length;[18] thus, we defined the SNSPD to have a small active area of 5 μm × 5 μm to obtain a short nanowire. The SNSPD was made of a 6-nm-thick NbN film sputtered on an Al_2O_3 substrate, ensuring a fast thermal relaxation process to avoid possible latching.[18] To simplify the fabrication process, no optical cavity was applied to the detector to enhance the DE. The SNSPD was coupled with the SMF and mounted inside a closed-cycle Gifford–McMahon cryocooler system, which was operated at 2.19 ± 0.02 K. The SDE was measured to be 5% at 1550 nm with a DCR below 100 Hz. For our SNSPD, the chip was backside-aligned with a commercial lensed SMF (9 μm fiber core). The graded index lenses were spliced to the tip of the SMF and the incident light spot was focused to the chip with a beam waist of about 7 μm. SDE = 5% was evaluated using the SMF mentioned above. However, in the lidar system, the MMF was used for echo signal coupling in free space, and was then directly connected to the SMF pigtail of the SNSPD which caused about

20-dB coupling loss. Some other solutions may be adopted in the future to provide better coupling such as lens or dual-lens beam compression.[19,20] The dead time of the SNSPD was evaluated using a method based on the statistical analysis of a long-term photon-response waveform.[21] Figure 2 shows the DE dependence on the time interval between two consecutive pulses. The DE increases when the interval of an adjacent optical pulse increases before saturating to the maximal DE. If we define the dead time as the time necessary for a 90% recovery of the DE, figure 2 shows a dead time of approximately 10 ns, which is five times better than that of SPDs (50-ns dead time) used in other PCCAM systems.[7,9]

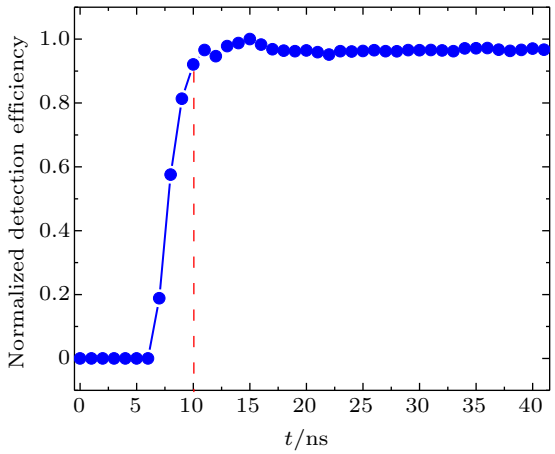


Fig. 2. (color online) Normalized detection efficiency of the SNSPD as a function of the time interval between two consecutive pulses.

3. Theory

The frequency of the amplitude modulation linearly changes with time, as represented by[6]

$$f(t) = f_0 + kt, \quad \left(-\frac{T}{2} \le t \le \frac{T}{2}\right), \tag{1}$$

where f_0 is the initial frequency and $k = B/T$ is the modulation rate of the CAM signal, with B being the modulation bandwidth and T being the modulation period. Thus, the corresponding CAM signal can be expressed as[6–9]

$$S(t) = \cos 2\pi \left[\int f(t)\,\mathrm{d}t\right] = \cos\left[2\pi\left(f_0 t + \frac{kt^2}{2}\right) + \varphi_0\right], \tag{2}$$

where φ_0 is the initial phase. The LD is modulated by the CAM signal and emits a laser signal, which can be written as

$$S_{\mathrm{E}}(t) = I_0 S(t), \tag{3}$$

where I_0 is the peak power of the LD. After a round-trip time τ over which the laser signal travels between the target and receiver, the echo signal can be represented as

$$S_{\mathrm{R}}(t) = M \times S_{\mathrm{E}}(t-\tau), \tag{4}$$

where M denotes the total loss coefficient of the system, including the optical transmission efficiency and the DE of the detector. Therefore, the mixing process can be written as

$$\begin{aligned} S_{\mathrm{IF}}(t) &= S(t) \times S_{\mathrm{R}}(t) \\ &= MI_0 S(t) \times S(t-\tau) \\ &= MI_0 \left\{\cos 2\pi \left[kt^2 + (2f_0 - \tau k)t - f_0\tau + \frac{k\tau^2}{2} + 2\varphi_0\right] \right. \\ &\quad \left. + \cos 2\pi \left(f_0\tau + kt\tau - \frac{k\tau^2}{2}\right)\right\}. \end{aligned} \tag{5}$$

The sum frequency term $S_{\mathrm{IF}}(t)$ will be filtered after the IF signal passes through the low-pass filter.[6–9] Then, applying fast Fourier transform to the IF signal yields

$$\begin{aligned} S_{\mathrm{IF}}(\omega) &= F\{S_{\mathrm{IF}}(t)\} \\ &= F\left\{\cos 2\pi \left(f_0\tau + kt\tau - \frac{k\tau^2}{2}\right)\right\} \\ &\propto \mathrm{sinc}(\omega)\delta(\omega - 2\pi k\tau) \\ &\propto \mathrm{sinc}(\omega - 2\pi k\tau). \end{aligned} \tag{6}$$

According to Eq. (6), the IF signal is a SINC function in the frequency spectrum with a peak located at $\omega_{\mathrm{IF}} = 2\pi f_{\mathrm{IF}} = 2\pi k\tau$, which is proportional to the round-trip time τ. Thus, the range of the target can be calculated by[6–9]

$$R = \frac{\tau c}{2n} = \frac{c f_{\mathrm{IF}}}{2nk} = \frac{cT f_{\mathrm{IF}}}{2nB}, \tag{7}$$

where n is the refractive index.

4. Experimental results

The frequency spectrum of the IF signal was directly recorded using a spectrum analyzer, as shown in Fig. 3, while the bandwidth was $B = 240$ MHz and the modulation period was $T = 1$ ms.

Because of discrete sampling detection, the IF signal spectrum was discrete, as shown in Fig. 3(b). The exact position of the IF signal peak can be estimated using the weighted centroid localization algorithm,[22] which can be expressed as

$$f_{\mathrm{IF|WCLA}} = \frac{\sum_{m=-l}^{m=l} P_m f_m}{\sum_{m=-l}^{m=l} p_m}, \tag{8}$$

where l is the total number of data points and f_m is the discrete frequency in the IF spectrum with a corresponding intensity of P_m.

The modulation band was set from 5 MHz to 240 MHz to evaluate the performance of our PCCAM lidar system. To demonstrate the influence of the dead time on the refresh rate of our system, different modulation periods T (0.1 ms, 0.5 ms, and 1 ms) were selected in the measurements. The SNR of the frequency spectrum of the IF signal was directly recorded using the spectrum analyzer, and the dependence of the SNR

on the modulation bandwidth is depicted in Fig. 4. The corresponding distance accuracy was also calculated and is plotted in Fig. 4 according to the typical accuracy formula for IF processing[23]

$$\sigma_{\mathrm{R}} = \frac{c}{2B\sqrt{2\mathrm{SNR}}}. \tag{9}$$

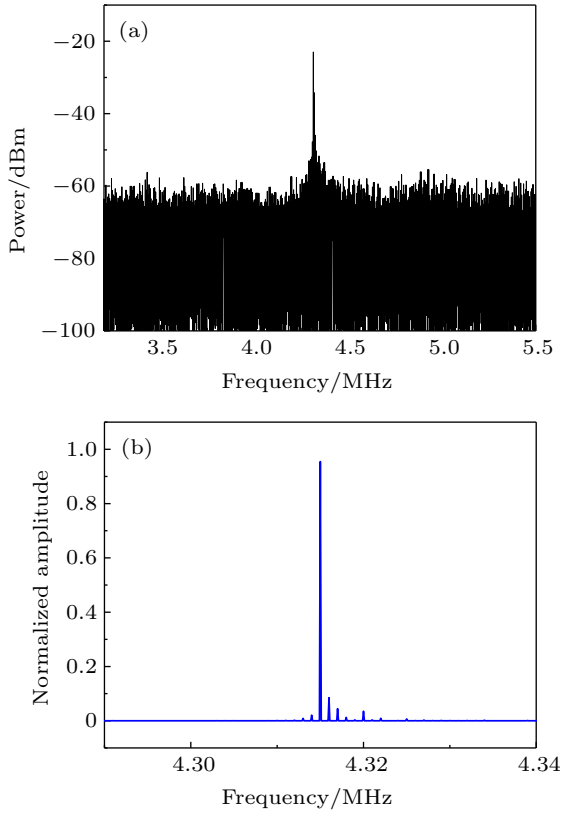


Fig. 3. (color online) Frequency spectrum of the IF signal recorded using the spectrum analyzer: (a) frequency spectrum of wide-range, (b) details of the frequency spectrum.

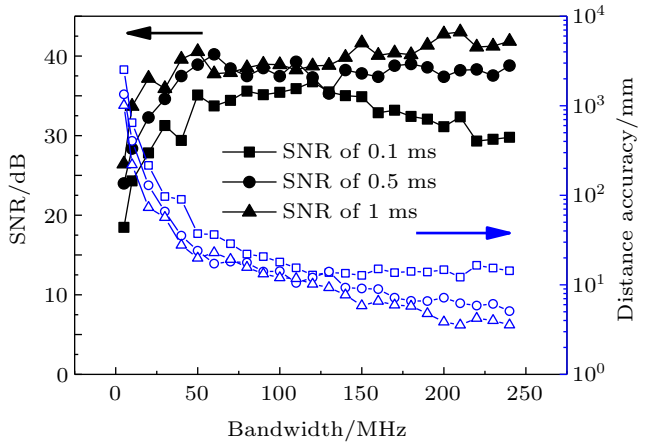


Fig. 4. (color online) SNR of the IF signal and the distance accuracy as a function of the modulation bandwidth with different modulation periods.

Regardless of the modulation periods, the SNR of the IF signal remained almost constant while the modulation bandwidth was above 50 MHz, indicating that the PCCAM lidar system performed well with a high modulation bandwidth. On the other hand, according to Eq. (9), the higher the bandwidth is, the higher the distance accuracy will be. The measured maximum system accuracies were 3 mm, 5 mm, and 11 mm for 1-ms, 0.5-ms, and 0.1-ms modulation periods, respectively. This result is one order of magnitude better than the previous results of other PCCAM systems, which had system accuracies of several centimeters.[7–10] On the other hand, the variance of the accuracy for different modulation periods implied that the system needed a certain amount of time to collect sufficient photons to recover accurate modulation information. For $T = 0.1$ ms, a slight decrease in the SNR was observed in Fig. 4 while the modulation bandwidth was above 150 MHz, which can also be understood from the limitation caused by the detector dead time. The modulation rate $k = B/T$ was very high so that the system required more time to collect sufficient photons to recover frequency information. The small modulation period resulted in a loss of modulation information and a decrease in the SNR of the IF signal.

Because the target range was limited by the length of the fiber in the lab, we applied an attenuator in the receiving system to investigate the detection performance of the remote target. While adjusting attenuation, reflected photon counts detected by the SNSPD varied from 50 kcps to 25 Mcps. We selected the modulation bandwidth as 200 MHz and the modulation period as 1 ms. The SNR of the IF signal was closely related to the effective signal counts of the SPD,[6] $\mathrm{SNR} \propto (C_{\mathrm{tot}} - C_{\mathrm{n}})/\sqrt{C_{\mathrm{tot}}}$, where C_{tot} and C_{n} are the total number of counts and the total number of noise counts, respectively. When the echo signal was weak, the modulation information loss was high owing to inadequate signal power, resulting in an IF signal with a low SNR and poor distance accuracy. The distance accuracy increased with the signal intensity and remained almost unchanged (6 mm) when the reflected photon intensity was higher than 10 Mcps, as shown in Fig. 5. The photon-counting CAM lidar system required a certain amount of time to collect sufficient photons to recover frequency information and it was useless to continuously increase the photon numbers for the accuracy improvement. Instead, excessive signal intensity may cause more modulation information loss and extra noise during the measurement.[23] Owing to the low DCR of the SNSPD system (approximately 70 Hz), the total noise count was measured to be 300 Hz, which was negligible when compared to the signal counts (from 50 kcps to 25 Mcps). Therefore, the influence of the noise intensity on SNR was negligible. Thus the SNR of the IF signal in our PCCAM lidar system reached 42 dB, which was approximately 10-dB higher than that of the system with an InGaAs/InP APD,[10] exhibiting a better distance accuracy of the millimeter order. Furthermore, even when reflected photon counts were as low as 50 kcps in our PCCAM lidar system, the SNR of the frequency spectrum of the IF signal was

approximately 5 dB with a barely satisfactory distance accuracy of 27 cm, showing a promising potential in long-distance measurement.

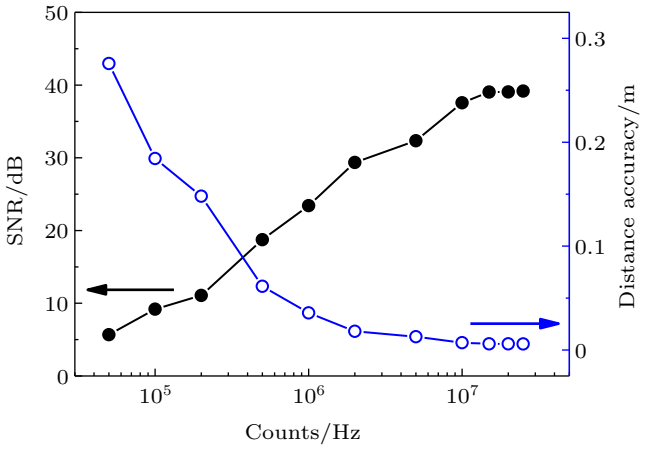


Fig. 5. (color online) SNR of the IF signal and the distance accuracy as a function of detected photon counts.

5. Conclusion

We demonstrated a PCCAM lidar system incorporating an SNSPD and operated at a wavelength of 1550 nm. Owing to the short dead time and low dark count of the SNSPD, the modulation bandwidth reached up to 240 MHz, the SNR of the frequency spectrum of the IF signal was approximately 42 dB, and the direct distance accuracy of the lidar system was first improved to 3 mm. The overall performance of the PCCAM lidar system using the SNSPD exhibited good prospects for applications in future satellite ranging or spaceborne ranging systems.

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