High speed pseudorandom modulation fiber laser ranging system

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A laser ranging system using all fiber high speed pseudorandom (PN) coded laser at 1550 nm and photon counting is proposed to realize high spatial resolution. Different lengths of PN code are employed in the optical fiber delay ranging test, the results show the improvement in both ranging accuracy and signal-to-noise ratio (SNR) as PN code trains increase. A ranging accuracy of 3 cm is acquired when transmitting pulses propagate to a target of 1.77 km away and received by an InGaAs/InP avalanche photodiode (APD). Simulation is also carried out under space borne condition based on current system. The system is demonstrated to have a potential for remote ranging and imaging.

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Laser altimeter has been widely used in geosciences and space borne probing systems, such as GLAS[1], Chang'E[2], LALT[3], and MLA[4]. The traditional altimeters were mostly based on mono-pulse time-of-flight (TOF) direct detection approach. The receivers measured the range by the round-trip time from the spacecraft to the target. In these ranging lidar, diode pumped solid-state lasers (DPSSLs) were used as lidar transmitter at the wavelength of 532 or 1064 nm with high peak power, narrow pulse width, and low repetition frequency[5]. As the demand for altimeter working in three-dimensional imaging and high-accuracy long distance ranging probing[6], it is necessary to improve the pulse measurement rate so as to realize high spatial resolution. However, the repetition frequency of solid-state laser is restricted by lifetime and huge waste heat. So, the alternative laser such as fiber laser has been used as laser source for its appealing properties in LIDAR systems[7]. The other ranging system, pseudorandom (PN) code modulation detection, which has been wildly used in atmospheric profile systems[8,9] arouse the interest for the application of remote sensing. Compared to mono-pulse lidar transmitters, the demand for peak power is reduced when continuous wave laser is modulated by PN code. In recent years, many simulations and experimental investigations on PN code lidar were conducted in ranging or imaging systems[10−14], such as adapting new[10] and modified PN code[12] or solving range ambiguity in imaging system[14].

In this letter, we conduct a series of experiments using PN code modulation fiber laser at eye-safe 1550 nm and photon counting module. We vary the length of PN code and measure the performance of the system, the result show that ranging accuracy and signal-to-noise ratio (SNR) improve significantly as the sequence length increases. The other experiment using 63.8 W peak power laser illumination show a ranging accuracy of centimeter when ranging the building of about 1.77 km out of the lab window. Since our previous publication[15], several modifications have been made to the system. We use 10-kHz repetition frequency to emission PN code instead of 1 kHz to realize a high ranging frequency. Ranging resolution is enhanced to 15 cm in free space as the bit rates increase from 622 Mb/s to 1 Gb/s. The adaption of a new InGaAs/InP avalanche photodiode (APD) with multimode fiber core and larger sensitivity area can effectively improve receiving efficiency and allow realizing long distance ranging. We also have conducted simulation under space borne environment. The result shows it is a potential method for the application of remote sensing and imaging.

In a ranging system, the receiver SNR in a measurement is given by[16]

$$\mathrm{SNR}=\frac{S}{\sqrt{S+N}}, \tag{1}$$

where S represents the number of received signal photons and N is the number of noise photons mainly consists of dark counts of the detector and background noise. When using single photon detector, receiver usually accumulate many cycles of the received signal[11] in order to discriminate the signal from noise and improve SNR. After multi-times' accumulation, the noise becomes small for its randomness, so the SNR can be approximately expressed as

$$\mathrm{SNR}\approx\sqrt{nS}=\sqrt{\frac{nE_{\mathrm{sig}}}{hv}}, \tag{2}$$

where E_{sig} is the received signal energy, n is the number of times of accumulation. According to radar equation, the peak power of the received signal is shown as

$$P_{\mathrm{sig}}=P_{\tau}\eta_{\mathrm{atm}}\eta_{\mathrm{sys}}\frac{\pi D^2}{(4R)^2}\rho P_{\mathrm{de}}, \tag{3}$$

where P_τ is transmit peak power, η_{atm} is atmospheric loss factor, η_{sys} is system loss factor, D is telescope aperture, R is ranging distance, ρ is target reflectivity, and P_{de} is detector efficiency. So, SNR can be written as

$$\text{SNR} = \sqrt{P_\tau T \eta_{\text{atm}} \eta_{\text{sys}} \frac{\pi D^2}{(4R)^2} \rho P_{\text{de}} \frac{1}{hv} n}, \tag{4}$$

where T is $\frac{M+1}{2}\Delta t$, Δt is the bit width, and $\frac{M+1}{2}$ is the number of signal "1" when modulated PN code length is M. So, T represents the entire sequence pulse width of signal "1". From Eq. (4), we can see SNR has a linear relationship with modulation sequence length, so we emphasize on the influence of system performance when adapt varied modulation sequence length.

A set of experiments were conducted in the lab using different length PN code streams under optical fiber delay method. The diagram of experiment setup is given in Fig. 1.

We proposed a different way to generate PN modulated pulses other than the common one[12]. A distributed feedback laser diode at 1550 nm in the optical communication module was modulated by a home-made field-programmable gate array (FPGA) circuit to generate the PN coded laser. The modulated laser pulses transmitted from the optical communication module was used as ranging source. Ranging resolution Δd is 20 cm according to the formula $\Delta d = \frac{c}{f}$, for light speed c is 2×10^8 m/s when transmit in fiber and modulation frequency f is 1 GHz (1-ns bit width). An optical attenuator was used to attenuate the signal to 1.96×10^{-18} J after transmit through a reel of about 5.2-m-long optical fiber simulating the ranging distance before coupling to the detector. InGaAs/InP APD single-photon detector (SPD), with a multimode fiber core of 62.5 μm and a diameter of 40 μm sensitivity area was operated in sine-wave gated mode with the same electronics design in Ref. [17]. The InGaAs/InP APD SPD had a detection efficiency of 10% at 30 kHz dark count rate when worked in free running mode. The avalanche signals were shaped to transistor-transistor logic (TTL) voltage pulses after being amplified and then was acquired by an oscilloscope. PN code length can be easily adjusted by sending control command to the FPGA circuit. So we modified PN code bits from 1023, 2047, 4095, to 8191, corresponding to 1.03, 2.047, 4.095, and 8.191 μs respectively under 1-GHz modulation rate. The MATLAB program was written to bin the TTL signals to digital stream by set proper threshold and then cross correlate the original sequence to the received signal. Target distance can be acquired by the time delay of peak location in the correlation function.

Figure 2 indicates the normalized cross correlation between the original PN code and the returned signal sequence of four different PN code lengths at a distance of 5.2 m. The received signals are accumulated 10 times to get a higher SNR. It is obvious that the SNR has a linear relation with PN code length which shows in Fig. 3

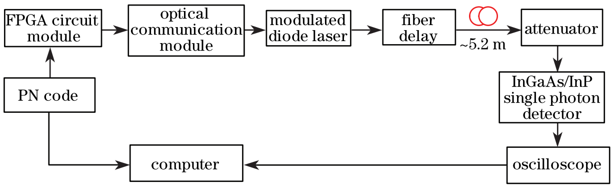

Fig. 1. Block diagram of optical fiber delay experiment.

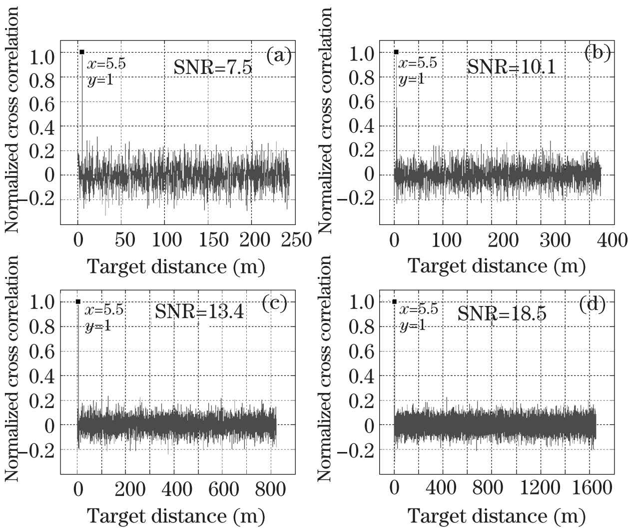

Fig. 2. (Color online) Normalized cross correlation between the original PN code and the signal sequence of different PN code length: (a) 1023, (b) 2047, (c) 4095, (d) and 8191 bits.

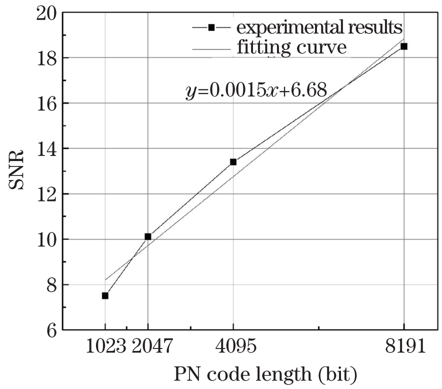

Fig. 3. (Color online) SNR under different PN code lengths and linear fitting curve.

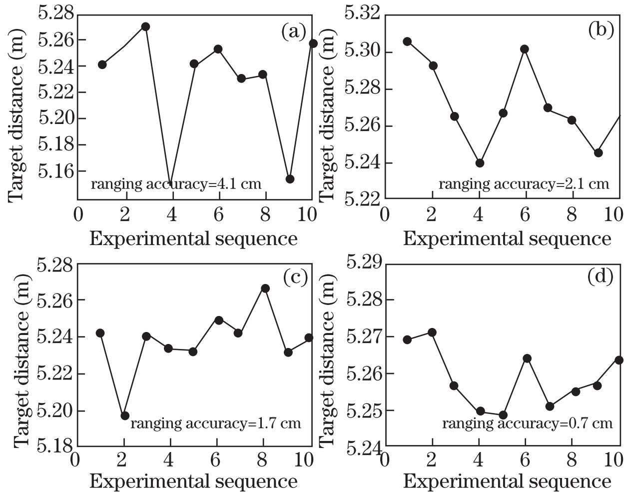

Fig. 4. (Color online) Distances of 10 times measurements and ranging accuracy under different PN code lengths: (a) 1023, (b) 2047, (c) 4095, and (d) 8191 bits.

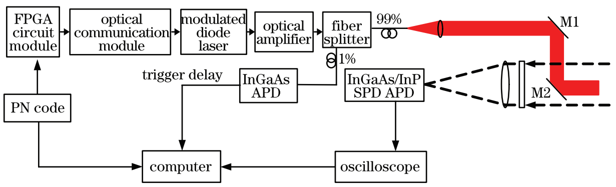

Fig. 5. (Color online) Block diagram of the photon-counting ranging system based on PN modulation fiber laser at 1550 nm and photon counting.

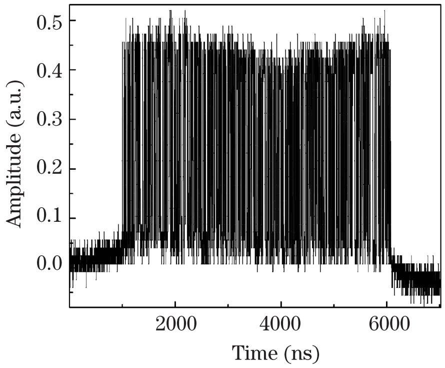

Fig. 6. Final output laser form after three-stage amplifier.

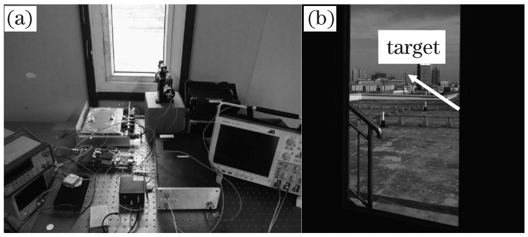

Fig. 7. (Color online) (a) Experiment setup and (b) target building.

and in accordance with theory analysis. We get 10 distances by ranging the target 10 times repeatedly at each different sequence lengths and found that ranging accuracy, calculating use the mean square root deviation method, improved from 4.1 to 0.7 cm which can be seen in Fig. 4. So the experiment results agree well with theory for ranging accuracy and SNR have an inversely proportional relationship.

Out-door ranging demonstration was implemented using the experiment setup showed in Fig. 5. An all fiber PN coded laser at 1550 nm based on a master oscillator power amplifier (MOPA) configuration was used as transmitter[18]. The modulated diode laser was amplified from 1.5 mW to 63.8 W by three-stage fiber amplifier and the final laser output form was displayed in Fig. 6. 1% of laser was coupled into InGaAs APD and used as the start trigger signal. The other 99% output channel from the fiber splitter was coupled into the transmitter-telescope. The optical transceiving system worked at coaxial mode. A 10-nm band-pass filter centered at 1550 nm was inserted in front of the receiver-telescope, with a diameter of 50 mm, to restrict background noise. The detected signals from the detector were recorded by oscilloscope with the same procedure as that of the optical delay test.

The ranging tests reported here were performed under bright condition. Experimental setup and the target building were shown separately in Figs. 7(a) and (b). Correlation calculating between the original PN stream and processed signal sequence was obtained in Fig. 8(a). The beginning peak was caused by back scatter of near field and the last one indicated the target distance of about 1.77 km. Ranging accuracy of 3 cm was acquired after the calculation of 10 distances showed in Fig. 8(b). The demonstration shows that PN code matching method is an efficient solution in high repetition frequency photon-counting ranging applications.

Some simulations were also carried out to demonstrate the feasibility of the system used for long distance probing. We assumed the requirement of SNR was 10 when ranging distance was 400 km. Simulation parameters list in Table 1. PN code length was set as 65535 limited by 10-kHz pulse repetition frequency. Receiver telescope aperture of 1 m and laser peak power of 110 W were selected by analysis according to radar equation. It is clear that space borne target distance of 400 km can be seen in Fig. 9 when SNR is 10. So we can come to the conclusion that PN code modulation will be a competitive method used for space-borne probing in the future.

In conclusion, a laser ranging system combing eye-safe high speed PN coded all-fiber laser and photon counting technique is proposed. The system is demonstrated in laboratory using different PN code length based on optical fiber delay experiments overs 5.2 m and in free space of a distance about 1.77 km with a 3-cm ranging accuracy. The performance of the

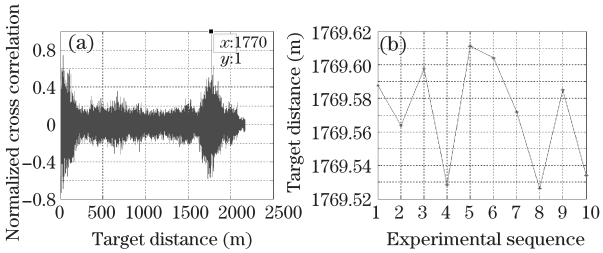

Fig. 8. (Color online) (a) Normalized cross correlation between the original PN code and the processed signal sequence; (b) distances of 10 times measurements.

Table 1. Simulation Parameters of Space Borne Lidar System

Parameters	Value
Range Distance (R)	400 km
Wavelength (λ)	1550 nm
Atmospheric Loss Factor (η_{atm})	0.5
Pulse Repetition Frequency (PRF)	10 kHz
System Loss Factor (η_{sys})	0.5
Target Reflectivity (ρ)	0.1
Detector Efficiency (P_{de})	10%
Transmitter Power (P)	110 W
Telescope Aperture (D)	1 m
PN Code Length (M)	65535

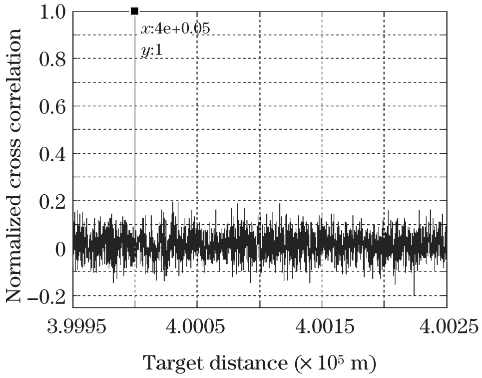

Fig. 9. (Color online) Normalized cross correlation of 400 km target distance.

system is improved as PN code length increased, so longer PN code length will be used as modulation signal in our future work. Simulation under space borne condition further proves that the system is a promising lidar scheme for long-distance application.

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