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Pseudorandom modulation quantum secured lidar

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ABSTRACT

A new lidar scheme called pseudorandom modulation quantum secured lidar is proposed. The position and polarization of the photon are randomly modulated through electro-optic modulators controlled by pseudorandom codes to realize ranging and security. Using this ability to obtain the target distance is secure against the most primitive, intercept-resend attack, popularly known as "jamming". In order to jam our lidar system, the target has to disturb the delicate quantum state of the ranging photons, thus the statistical errors will be introduced, which can reveal the jamming activity. The formulas for estimating the signal-to-noise of our system are derived both in the presence and absence of jammers. Simulation result shows that, when there are no jammers, the range accuracy of centimeter level is obtained, and the observed range accuracy of the experiment is in agreement with this simulation value. However, the error of the received polarization can be viewed as random noise, which will descend the signal-to-noise ratio, and further decline the distance accuracy. The experimental results show that our system has a better ranging and anti-attack ability.

1. Introduction

With the rapid development of quantum mechanics, quantum communication [1,2], imaging technologies [3–5] and optical ranging [6,7] have been greatly enhanced in recent years, which become hot issues in the field of lidar. The quantum nature of light has been more and more widely applied in many fields, such as super sensitivity laser positioning [8–10], quantum interference [11], quantum radar [12–16] and so on. The quantum entanglement can not only improve the accuracy [17], but also guarantee the security [18] of distance measurement. However, the primary drawbacks of these schemes are the difficulties of creating the requisite entanglement and the sensitivity to loss [19]. Relative to the entangled photons, it is relatively easy to produce a single photon by attenuating laser pulse. Therefore, quantum security detection techniques based on single photon have attracted increasing attention. Malik et al. presented a quantum-secured imaging (QSI) system based on single photon quantum key distribution (QKD) protocol, in which they used a photon's position to image an object, while using the polarization of the photon for security [3]. Their proof-of-principle experiment demonstrated the excellent anti-attack ability of their scheme. Later, they reported a scheme of secure quantum lidar (SQL) [20] which used the same protocol as QSI for security. However, no further reports have been found since then.

In this paper, we present a new SQL system, called pseudorandom modulation quantum secured lidar (PMQSL) first. This lidar system ingeniously combines the classic random modulation method with the protocol of QKD, which makes the system possess not only good ranging accuracy and resolution, but also secured ranging. Here we use one electro-optic modulator (EOM) to control the position of the photon for ranging the distance of the target, while the polarization of the photon is governed by another EOM for security. The measurement of the distance of the target is secure against an attack through calculating statistical errors of the polarization of the photon. It is shown that we can get the range accuracy of centimeter level when there are no jammers, whereas the signal-to-noise ratio (SNR) and range accuracy will be descended in the presence of jammers. The observed range accuracy is then compared with the simulation value, which turns out they are in good agreement with each other. Finally, the proof-of-principle experimental results are shown and analyzed, which indicates that the system has a better ranging and anti-attack ability.

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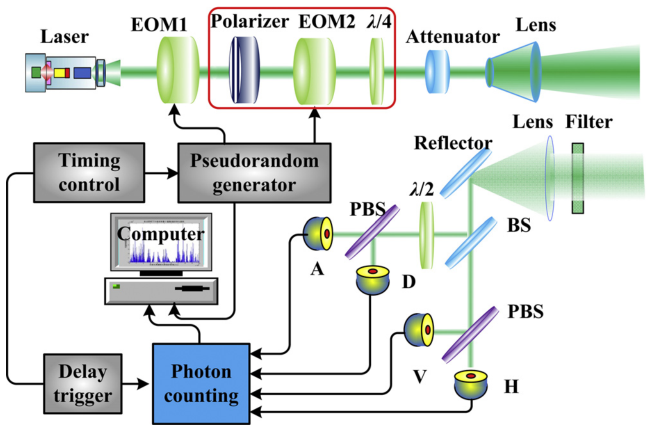

Fig. 1. Schematic of the PMQSL system.

2. The working principle of PMQSL

The principle of the PMQSL system is depicted in Fig. 1. The laser is pulse-position modulated by an electro-optic modulator (EOM1). These pulses are further randomly modulated to create the horizontal, diagonal, vertical, and anti-diagonal (|*H*>, |*D*>, |*V*>, and |*A*>) polarization states of the photon through a polarization modulated model. The polarization modulated model shown in the red solid box includes a polarizer, another electro-optic modulator (EOM2) and a quarter wave plate (λ/4). Passing through an attenuator, pulses with one detected photon on average are obtained and incident on the target through optical transmitting system. The signals from a pseudorandom generator are used as the reference signals and the trigger signals of the EOMs. Photons with different polarizations reflected from the target are collected by the receiving system and detected using four avalanche photodiodes (APDs) possessing single photon detectable sensitivity. A narrow-band filter is used to get rid of the background noise. The photon counter with threshold value discriminating circuit is used to judge the output electric pulses of the APDs. If the output of the APD is higher than the threshold, it is then regarded as code 1, otherwise code 0 is registered. A time controller is adopted to adjust the time period between adjacent codes of the modulation sequence. Simultaneously, the time controller is used to trigger the photon counter to record the echo signals.

Taking the 7th order M sequence for example, trigger signals of two electro-optic modulators are shown in Fig. 2. Fig. 2(a) expresses the trigger signal of EOM1, in which '1' represents transmitting signal pulse and '0' no signal pulse. Fig. 2(b) shows the trigger signal of EOM2 which is re-edited according to the same sequence as Fig. 2(a) using other software. Here '0' represents none operations for EOM2, whereas random numbers '1', '2', '3' and '4' with equal probabilities correspond to the operations of horizontal, diagonal, vertical, and anti-diagonal polarization, respectively. EOM1 and EOM2 change synchronously.

The distance of the target can be extracted through the cross-correlation operation between the reference sequence and received sequence. The error rate (see Section 3.2) of polarizations is obtained through comparing the received codes with the reference codes. If the eavesdropper actively jams our system, he must affect the quantum states of ranging photons and introduce statistical errors, which will reveal his jamming activity.

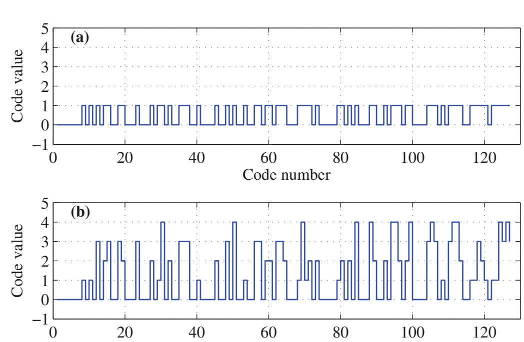

Fig. 2. Modulation sequence of EOM1 and EOM2.

3. Theoretical analysis

3.1. Ranging principle based on pseudorandom modulation

The ranging principle of PMQSL is based on random modulation technique. The random modulation is a technique in the time domain, which is a typical way to recover the weak signal buried in random noise. This technique enables us to use a low power laser as the lidar source. The transmitting signal is modulated by the digital pulse codes, usually consisting of on and off. The nth order M-sequence a_i (with elements 1 or 0) adopted in our system is generated by a set of n-stage shift registers. The total number of the elements of the nth order M-sequence is given by $N = 2^n - 1$, where the numbers of 1 and 0 are $(N+1)/2$ and $(N-1)/2$, respectively. However, the probabilities of 1 and 0 are approximately equal when $N \to \infty$. As another expression of the M sequence, we denote a'_i with elements 1 and -1 connected with a_i by the relation $a'_i = 2a_i - 1$, where a'_i is defined as the reference sequence. Given that the transmitting power is expressed as P_t, the receiving power P_r for the modulation code 1 takes the form of

$$P_r = \frac{P_t \eta_a \eta_s \rho D^2}{\left(8R^2\right)} = \Re P_t \tag{1}$$

where η_a, η_s, D, R and ρ are the atmosphere transmittance, optical system transmittance, receiving aperture, target distance and target reflectivity, respectively. Thus $\Re = \eta_a \eta_s \rho D^2 / \left(8R^2\right)$ is the response function of the system.

For the same target, the response function of all a_i is equal, so the received signal satisfies

$$Y = \sum_{i=0}^{N-1} y_i = \sum_{i=0}^{N-1} \left(P_t a_i \Re + n_i\right) \tag{2}$$

where n_i is the background noise. The cross-correlation between y_i and a'_i is expressed as

$$S_j = \sum_{i=0}^{N-1} y_i a'_{i-j} = \Re P_t \sum_{i=0}^{N-1} a_i a'_{i-j} + \sum_{i=0}^{N-1} n_i a'_{i-j} \qquad j = 0, 1, 2, \ldots, N-1 \tag{3}$$

And the cross-correlation between a'_i and a_i is given by

$$\begin{matrix} \sum_{i=0}^{N-1} a_i a'_{i-j} = (N+1)/2, & j \bmod N = 0 \\ \sum_{i=0}^{N-1} a_i a'_{i-j} = 0, & j \bmod N \neq 0 \end{matrix}. \tag{4}$$

Therefore, the maximum of S_j which includes the target distance information can be expressed as

$$S_{j\,\max} = \frac{(N+1)\Re P_t}{2} + \sum_{i=0}^{N-1} n_i a'_{i-j}. \tag{5}$$

To illustrate our results, a simulation result of distance measurement using the PM method is shown in Fig. 3. Here a 10th