Multi-target real-time ranging with chaotic laser radar

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We demonstrate the feasibility of multi-target real-time ranging with a chaotic laser radar. The used chaotic laser is emitted by a semiconductor laser with optical feedback. We design a proof-of-concept experiment based on the correlation detection and realize the range measurements of two targets simultaneously. The range resolution of 9 cm between two targets is achieved, which is limited by the bandwidth of the used real-time oscilloscope. A preliminary experiment of chaotic laser coherence is carried out to verify the high resolution of the chaotic lidar.

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Laser ranging has attracted extensive attention recently[1−6]. In the traditional laser radars (lidars), range finding can be performed with short-pulsed or modulated continuous-wave (CW) laser. To be able to use the CW lasers for range-resolved measurements, a pseudorandom code modulated CW lidar was firstly proposed by Takeuchi *et al.*[1]. Then a pseudorandom code modulated CW lidar using a semiconductor laser was demonstrated[7]. In this technology, the target detection is based on the feature of delta-like function of the correlation between the transmitted signal and the received reflection. The range resolution is determined and limited in the range of several tens of meters by the modulation speed and pseudorandom code rate[1,7]. In order to obtain higher resolution, an expensive external modulator is necessary.

Compared with pseudorandom/random code modulated CWs, the noise-like optical chaotic waveforms generated by nonlinear dynamical semiconductor lasers[8] have bandwidths larger than 10 GHz and good correlation properties that ensure great range resolution and unambiguity[9,10]. Furthermore, it is highly resistant to mutual interference from a similar system since the laser source produces a unique chaotic laser signal. Range measurement using a chaotic laser pulse train from a semiconductor laser with optical feedback was realized by Myneni *et al.*[2]. In 2004, Lin and Liu proposed the concept of chaotic lidar and studied the performance of a CW chaotic lidar in detail[3]. The chaotic lidar system has all the advantages that a modulated CW lidar has by using a diode laser as the light source, and the needs of expensive high-speed code generation and modulation electronics no longer exist. But the previous studies demonstrated the feasibility of the chaotic lidar technique and only single target was included. In this letter, we emphasize the multi-target ranging using chaotic lidar. A proof-of-concept experiment is designed to verify the ability of multi-target real-time ranging of the chaotic lidar.

The diagram of the laboratory experimental arrangement is shown in Fig. 1. The chaotic laser is generated by a 778-nm single-mode semiconductor laser (Sharp LT024MD0) with optical feedback from an external reflector. In the semiconductor laser with optical feedback, the chaotic state characteristics depend on the controllable operational parameters, i.e., the pump current, the feedback intensity, and the delay time. Under a fixed external cavity length, complex high dimensional chaotic state can be obtained by adjusting the feedback intensity and the pump current. In this setup, the external reflector is placed at a distance of 20 cm from the semiconductor laser. The optical feedback intensity can be adjusted by alternating the angle of the half-wave plate (HWP) with the polarization beam splitter (PBS).

The chaotic laser output is then split into reference and signal light by a 50:50 beam splitter (BS). An optical isolator (OI) is placed after the chaotic laser transmitter (the part in the dashed frame in Fig. 1) to prevent unwanted optical feedback. The reference light is detected by a 1-GHz-bandwidth high-speed photodetector (PD1, Newport 818-BB-21) and the signal light is directed to the targets. Two mirrors (M1 and M2) are used as the targets, which are placed at different ranges with respect to the transmitter. At the wavelength of 778 nm, about 40% of the signal light is back reflected and 60% is transmitted through M1. The reflectivity of M2 is 92%. The two reflected light beams from the surfaces of both targets are deflected by 90° at the BS and detected by a single photodetector (PD2), which is the same as PD1.

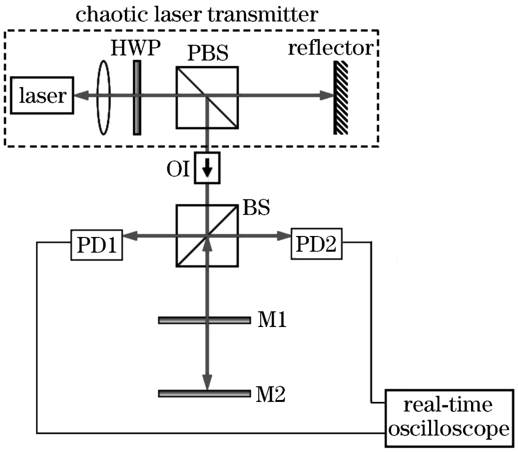

Fig. 1. Experimental setup of multi-target real-time ranging using chaotic laser.

The waveforms detected by PD1 and PD2 are recorded by a real-time oscilloscope (Tektronix TDS3052) with 500-MHz bandwidth and 5-Gs/s sampling rate. Then their cross-correlation can be calculated by using a computer.

In the experimental arrangement, a set of signal and reference waveforms are obtained, and the peak of the cross-correlation trace of them is used as zero reference. This reference point is positioned 1 cm behind the edge of the BS. Two mirrors are 12 and 82 cm away from the zero reference point. Thus, the separation between two targets is 70 cm. From the cross-correlation trace of the reference and signal waveforms shown in Fig. 2, two delay time intervals of 0.8 and 5.4 ns are indicated by the locations of two peaks of the cross-correlation trace. Thus two target distances of 12.0 and 81.5 cm are measured simultaneously. Accordingly, the separation between two targets is measured to be 69.5 cm. The results are in accordance with the experimental arrangements. In chaotic lidars, the full-width at half-maximum (FWHM) of the correlation peak and the peak sidelobe level (PSL, the ratio of the maximum sidelobe to the peak of the correlation trace) are used to quantify the performance. For both targets, with a 0.6-ns FWHM of the cross-correlation peak, a 9-cm range resolution is achieved. And the PSLs of two targets are −15.9 and −14.9 dB, respectively. Note that the peak value of the second target is lower than that of the first target, which is caused by the signal detection loss.

Figure 3 shows the correlation traces for the target separations of 12 and 9 cm. From the correlation trace with solid curve in Fig. 3, the separation between the peaks is measured to be 12.0 cm. Although the nearer target shows a lower value, it can still be distinguished from the sidelobes easily. But when the separation between two targets is 9 cm, two targets cannot be distinguished. From the correlation trace with dashed curve in Fig. 3, we can only obtain one peak and the time width of the profile is doubled.

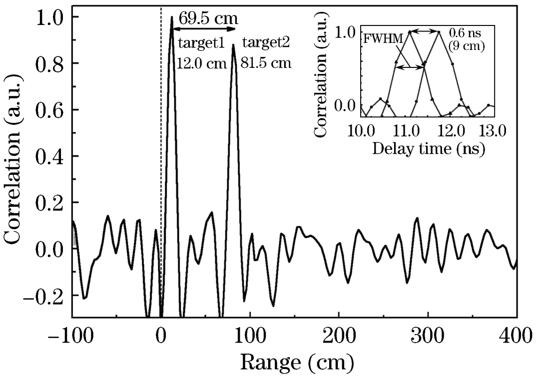

Fig. 2. Cross-correlation trace of two-target real-time ranging with target separation of 69.5 cm. The inset shows the FWHM of the peak of the same correlation trace.

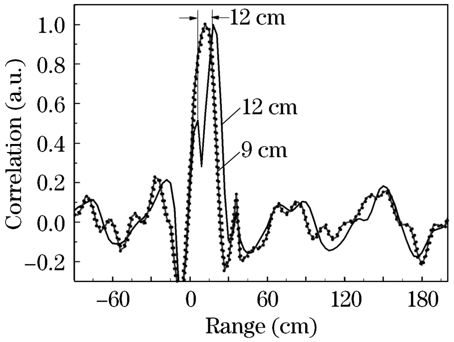

Fig. 3. Cross-correlation traces of two-target real-time ranging when the separations between two targets are 12 and 9 cm, respectively.

The experimental results are limited not by the spectral bandwidth of the chaotic laser but by the bandwidth of the used real-time oscilloscope. We have theoretically demonstrated that enhanced bandwidth of the chaotic lidar can substantially improve the range resolution of the lidar[11]. Our simulation results show that the range resolution can be improved from 1.5 to 0.75 cm, corresponding to the chaotic bandwidth improvement from 4.0 to 11.8 GHz. Our result also indicates that the PSL decreases as the signal-to-noise ratio (SNR) increases[12]. Thus, increasing the bandwidths of the electronic devices used in the experiment should provide a significant improvement in performance. In order to eliminate the bandwidth limitation from the electronics and fully utilize the broad bandwidths of chaotic waveforms, the method of chaotic laser coherence can also be adopted[3,13]. We use a Michelson interferometer to interfere the signal light with the reference light, as shown in Fig. 4. One of the arms as the reference (M4) is mounted on a piezoelectric transducer (PZT). With this element, the path length of the Michelson interferometer is varied so that its output power varies between constructive ($P_{\max}$) and destructive ($P_{\min}$) interference when the path difference is in the range of the coherence length. In this way, we measured the visibility $V_{(l)}$,

$$V_{(l)} = \frac{P_{\max} - P_{\min}}{P_{\max} + P_{\min}}, \tag{1}$$

where l is the length difference of the two paths of the Michelson interferometer. $V_{(l)}$ is measured as a function of the length mismatch between the two arms of the interferometer. We measured the power using the real-time oscilloscope in the step of 10 μm. We set a mirror M3 at the distance of 10 cm to the BS, and translated M4 in the line of sight, and the coherence envelopes are obtained and plotted in Fig. 5. As can be seen, a distance of 10 cm is measured from the peak, while a 4-mm range resolution is achieved deriving from the FWHM of the peak. So the range resolution is enhanced significantly despite the bandwidth limitation of the electronics. The range resolution of the multi-target measurement is consistent

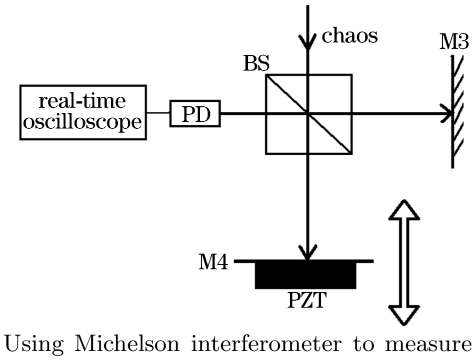

Fig. 4. Using Michelson interferometer to measure the visibility $V_{(l)}$.

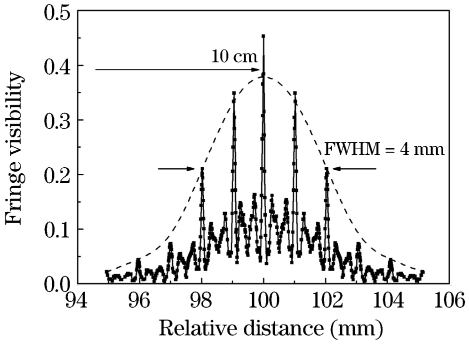

Fig. 5. Measured fringe visibility trace by interfering the chaotic signal and reference light.

with the range resolution of the single-target case.

In conclusion, we designed a proof-of-concept experiment to show the feasibility of multi-target real-time ranging using chaotic laser generated by a semiconductor laser with optical feedback. To enable practical utilization of this concept in tracking lidar, more actual conditions should be considered. For multi-target detection, the transmitted signal should be a scanning beam and a rapid switching/scanning optical delay line in the reference channel is needed.

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