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# Study on the resolution improvement of a range finder using the chaotic frequency characteristics of a laser diode

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**Abstract.** An optical range finder system that relies on laser diodes' frequency noise, instead of intensity or frequency modulations, and its improvement in resolution are reported. The distance to the target is measured by calculating the cross-correlation of two signals reflected from the target and reference mirrors. These two signals are converted from the laser diodes' frequency noise signals by frequency/intensity converters, such as a Fabry–Perot etalon. We obtained the distance to the target by checking time lags between the target and reference beams at the highest correlation coefficient. We also measured the change in the correlation coefficient around the peak sampling point by adjusting the reference-path length, achieving a resolving power of $\pm 3$ mm.  [DOI: 10.1117/1.OE.56.6.064101]

Keywords: laser diode; frequency noise; optical range finder; correlation coefficient.

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## 1 Introduction

Optical range finders have been the subject of much discussion in fields such as mobile robotics and cloud measurement.[1,2] The development of low-cost, high-resolution optical range finders looks set to have a significant impact on countless scientific endeavors. Range finder systems, which use a random-noise modulated signal, have been discussed in the fields of microwave radar and Lidar systems.[3–7] Lidar systems fall into two specific categories: pulse systems and CW systems. The pulse system has been widely used for a commercial range finder. The system has an advantage that a high S/N ratio can be obtained with a high-peak pulse output even if the target is not a reflecting mirror. The random-noise modulated signal Lidar is a CW system that enjoys widespread use due to its high S/N ratio, coupled with low power consumption, as compared with pulse devices. Therefore, employing CW laser diodes as optical sources for the random-noise-modulated signal Lidar is effective. When a high-resolution measurement is required, this system depends on high-speed devices to randomly modulate laser output. As a method that does not need a high-power output and a high-speed modulation, a chaotic Lidar has been reported.[8–10] It utilizes a chaotic intensity signal generated by the optical feedback to a semiconductor laser. However, due to the feedback condition, the oscillation state also changes to a state other than chaos.[11] It makes the construction of the optical setup difficult. Using the laser diode's high-speed frequency noises—whose amplitude and bandwidth are much larger and broader than other lasers—[12,13] as a random signal, we believe that high-resolution optical range finders can perform admirably, without the need of any specialized high-speed modulation equipment or complex optical alignment.

The objectives of this work are to develop a high-resolution optical range finder using laser diode's wide frequency noise characteristics from a low frequency to a few GHz. The laser diode frequency noise characteristics-based optical range finder system was described previously.[14–16] The distance to the target is measured by calculating the highest cross-correlation of intensity noise signals, which are converted from the laser diode's frequency noise signals through the frequency/intensity converters, such as Fabry–Perot etalon or atomic absorption lines, reflected from the reference and target mirrors.

Because our system uses signals sampled by ADC, however, range resolution is limited by sampling time. To improve resolving power, we also measured changes in the correlation coefficient around the peak by changing the reference path length. As a result, we achieved a resolution of 3 mm using a simple optical setup consisting of a laser diode, a frequency/intensity converter, a fast photodetector, and a fast A/D converter (ADC). Range resolution is improved by a factor of 10, over the previous value of 30 mm, which was limited by the ADC's sampling rate of 10 GS/s.

In Sec. 2, we describe the principle of our measurement method and the basis of a resolution improvement. Section 3 shows the experimental setup of measurement. Section 4 presents the experimental results of our measurement without and with a resolution improvement. Section 5 draws the comparison of the measurement result with the commercial range finder. Section 6 describes conclusions.

## 2 Principle of the Method

The principle of our method has been described in previous reports.[14–16] The Rb absorption line is used as an optical

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frequency discriminator to convert laser diode frequency noises into the random intensity-modulated signal. The steep slopes of the Doppler-broadened absorption curve are also visible on both sides of the resonance frequencies. The laser oscillation frequency is tuned to these regions, where the side slope of the Doppler-broadened absorption line is steep, because the amplitude of frequency noise signals is effectively converted to changes in intensity, according to the principle of slope demodulation.[14] With our system, the distance to the target is measured using the "time-of-flight" of a random noise-modulated frequency signal, determined by calculating cross-correlation between two signals that have passed through reference and target paths. Reading the peak of the cross-correlation waveform, we recognize a time-lag between the reference and target beams. We then calculate the optical path difference by multiplying the optical velocity $c$ (m/s) by the obtained time delay. Because our system uses signals sampled by ADC, resolution is limited by sampling time as described above. We improved on this using the shifts of the correlation coefficients near the peak sampling point because they correspond to the brief optical time delay differences between the reference and target signals. Compared to our former experimental setup, the reference prism becomes movable to allow for the reference optical-path length to be adjusted by more than the range resolution. When the reference path is changed, the correlation coefficients around the peak also change.

## 3 Experimental Setup

Figure 1 shows the experimental setup for presented optical range finder. The 780-nm band laser diode (DL-7140, Sanyo) is driven with a constant current around 50 mA. The threshold current of this laser is 25 mA. The output power on this bias current is about 10 mW. The laser oscillation wavelength is tuned around 780.02 nm, which corresponds to a resonance frequency of a Rb-D2 line. The Rb absorption line is used as an optical frequency discriminator to convert laser diode frequency noises into the random intensity modulated signal. The steep slopes of the Doppler-broadened absorption curve are also visible on both sides of the resonance frequencies. The laser oscillation frequency is tuned to these regions, where the side slope of the Doppler-broadened absorption line is steep, because the amplitude of frequency noise signals is effectively converted to changes in intensity, according to the principle of slope demodulation.[17–19]

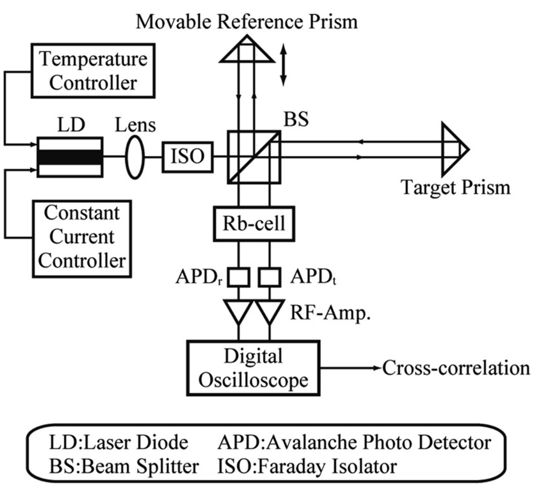


**Fig. 1** Experimental setup.

The wavelength of the laser diode is sensitive to changes of ambient temperature. If the mode hopping occurs from the ambient temperature change, since the oscillation frequency deviates from the Rb absorption slope, the frequency discrimination is not performed. In our experiment, since the laser oscillation wavelength must be at a slope region in a Doppler broadened Rb absorption curve that has about 500 MHz full-width at half-maximum at room temperature, the ambient temperature of the laser diode is monitored and controlled by a thermistor and a peltier device at around 17°C within 0.01 K. The optical isolator is directed to prevent the optical feedback. The laser beam is split into the reference and target paths, and they are reflected by 45-deg prisms. Lights reflected from each prism pass through the Rb-cell to discriminate the laser frequency noise. The laser's center oscillation frequency is detuned from the resonance frequency of a Rb-$D_2$ line to its slope region in a Doppler-broadened Rb absorption curve for high-efficiency frequency discrimination. Several percent absorbance is measured in our Rb-cell. The intensity change, that is, the converted frequency noises, is detected by high speed two Avalanche photodiodes (APDs), whose bandwidth is from DC to 1 GHz (Hamamatsu S12023-02). The RF-amp (LPA-G39WD) with a 40-dB gain and bandwidth ranging from 50 MHz to 8 GHz is used to amplify the AC part of electric signals on APDs. The amplified electric signal is sampled by a 4-GHz bandwidth high-speed digital oscilloscope with a 10-GS/s sampling rate. The time delay between the reference and target signals is calculated by waveform cross-correlation with a correlation length of 0.25 $\mu$s, and the correlation results are averaged with a time constant 25 $\mu$s. The time delay is determined from the correlation time corresponding to the peak of correlation waveform. The fundamental time resolution is restricted by sampling time $\tau_s = 0.1$ ns and the fundamental range resolution $\tau_s = 30$ mm at this sampling time.

## 4 Results

### 4.1 *Signal Characteristics and Correlation Coefficient*

We measured the optical path difference, using the experimental setup shown in Fig. 1. Figure 2 shows the reflected signal from a target prism, which is observed through the Rb-cell by the $APD_t$, as shown in Fig. 1, and displayed on a digital oscilloscope. This waveform showed high-speed white noise-like changes, so we observed its spectrum via the fast APD in our experiment.

Figure 3 shows three detected spectra: (a) "laser on:" the frequency noise spectrum of a laser beam detected through the Rb-cell, i.e., the optical frequency discriminator, (b) "laser on &Rb off:" the spectrum of a laser beam detected without Rb-cell, and (c) "laser off:" the background noise of the APD and the RF amplifier without a laser beam. We can see that (b) "laser on &Rb off" conditions demonstrate the contribution made by the laser's intensity noise. The amplitude of the frequency noise-discriminated signal of (a) is about 20 dB higher than the amplitude of (b) "laser on &Rb off" and about 30 dB higher than the background noise detected in (c) "laser off." The spectrum of the frequency noise signals distributed from the RF amplifier's 50-MHz cut-off frequency is roughly 1.5 GHz. We suspect

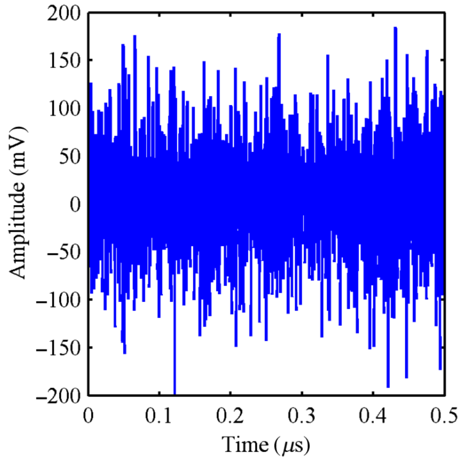


**Fig. 2** Frequency noise discriminated signal waveform.

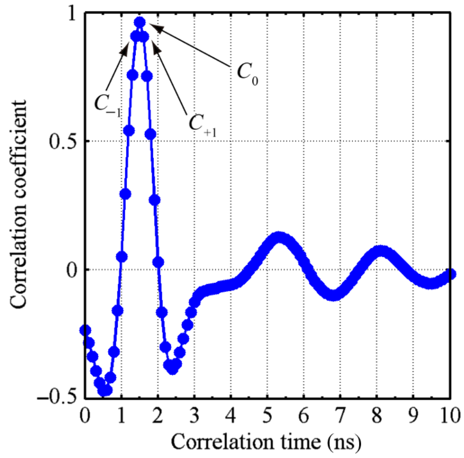


**Fig. 4** Cross-correlation waveform between the reference and target signals.

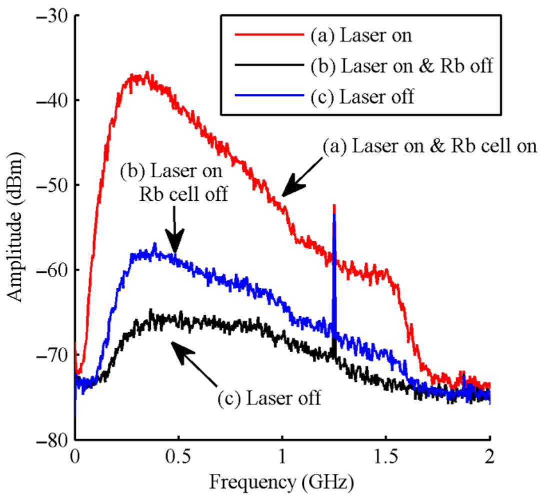


**Fig. 3** Observed noise spectrum.

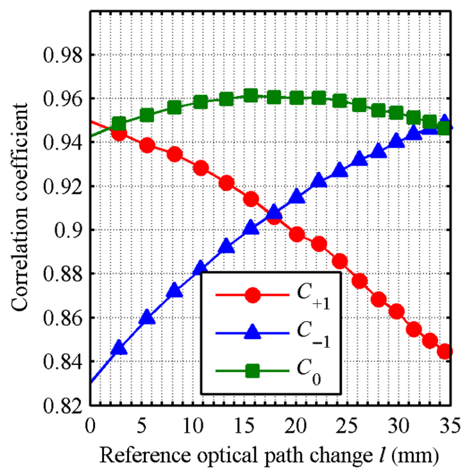


**Fig. 5** Change of correlation coefficients near the correlation waveform peak.

that the APD circuit's bandwidth may be responsible for the drop in the spectrum's magnitude over than 1.5 GHz.

Figure 4 shows the result of the cross-correlation calculation between the reference and target beam digitalized intensity signals. A high-correlation coefficient of ~0.95 is obtained without defeating spurious noise. Reading the correlation time corresponding to the correlation waveform peak, the result of the time delay was 1.5 ns, and the calculated distance was 450 mm.

### 4.2 *Improvement of Range Resolution*

We measured the shift of correlation coefficients around the correlation waveform's peak by changing the reference optical-path length. Figure 5 shows correlation coefficients when the reference optical-path length $l$ (mm) is adjusted. We define the correlation waveform's peak and its neighbors as $C_0$ and $C_{\pm 1}$, respectively (Fig. 4). According to the calculation described in Sec. 3, the time-delay 1.5 ns of $C_0$ corresponds to the optical path difference $L = 450$ mm, and the delay values $C_{-1}$ and $C_{+1}$ correspond to optical path differences $L = 420$ and 480 mm, respectively. As shown in Fig. 5, correlation coefficients $C_0$ and $C_{\pm 1}$ shift by changing the reference optical-path length.

Since $C_0$ shows the highest value when the optical path difference is exactly 450 mm, Fig. 5 gives the optical path difference as $L = 450$ mm at $l = 18$ mm. On the other hand, the optical path difference slightly shifts from $L = 450$ mm, at the other $l$, so $C_0$ peaks at $l = 18$ mm.

Correlation coefficient $C_{\pm 1}$ increases and decreases monotonically with any changes in the reference optical-path length $l$. $C_{-1}$ increases with the reference optical path change $l$. The reason is that the optical path difference $L$ decreases by increasing the reference optical-path length $l$ in this experimental setup. At $l = 34$ mm, the value $C_{-1}$ reaches its peak value of $C_0$. The fact that $C_{-1} = C_0$ means that the optical path difference $L$ is located precisely in the middle of a 420- to 450-mm field. Therefore, $L = 435$ mm at $l = 34$ mm. Similarly, the optical path difference at $l = 2$ mm is estimated to be $L = 465$ mm. However, there is a 32-mm gap between $l = 2$ mm and $l = 34$ mm, where it should be just 30 mm, due to a degradation of the S/N ratio caused by temperature variations that negatively affect the lasers' oscillation frequencies.

By adjusting the reference optical-path length $l$ within the range resolution and observing the shift in the correlation value near the correlation waveform's peak, we can measure the optical path difference $L$ even more precisely than the resolution expected by ADC's sampling rate.

### 4.3 *Normalized Correlation Coefficient*

We calculate the normalized correlation coefficient $C_{\pm 1}/C_0$, as shown in Fig. 6. Least squares-based linear fitting is applied to these values. It is understood that the normalized correlation coefficient $C_{\pm 1}/C_0$ changes linearly with variations in the reference optical-path length $l$. Normalized correlation coefficient $C_{\pm 1}/C_0$ equals $C_{-1}/C_0$ at $l = 18$ mm, where correlation coefficient $C_0$ is highest (Fig. 5). The optical path difference $L = 450$ mm at $l = 18$ mm.

The average precisions of the optical reference path change $l$ calculated from dividing the standard error of estimation of regression line by the slope of regression line are 324 and 134 $\mu$m for $C_{+1}/C_0$ and $C_{-1}/C_0$, respectively. Using this linear shift in the normalized correlation coefficient, we can measure optical path difference $L$ with precision.

Even if a slower ADC sampling rate of 5 GS/s is used, this linear normalized correlation coefficient can be obtained. The shift of normalized correlation coefficient $C_{+1}/C_0$, at

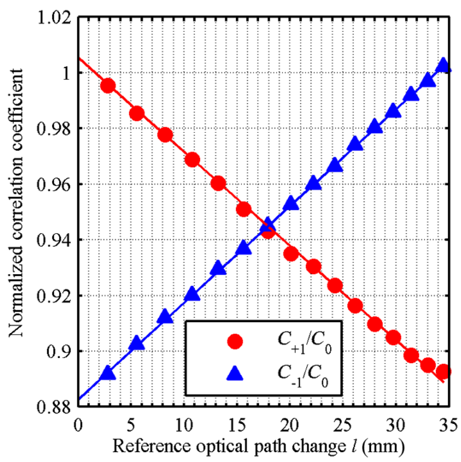


**Fig. 6** Change of normalized correlation coefficients at the ADC's sampling rate of 10 GS/s.

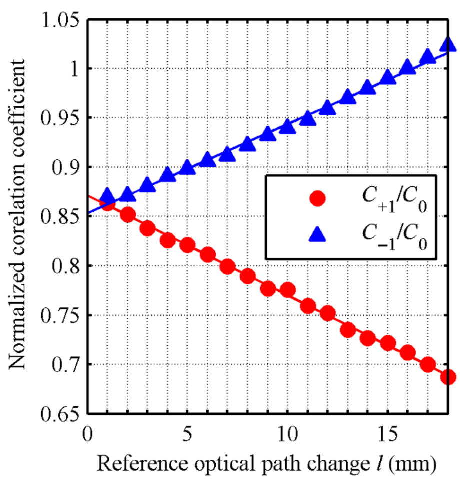


**Fig. 7** Variation of normalized correlation coefficients at the ADC's sampling rate of 5 GS/s.

a sampling rate of 5 GS/s, is shown in Fig. 7. The range resolution is 60 mm at 5 GS/s. Figure 7 describes an optical path difference of 0 to 30 mm, half of the calculated range resolution. The change of normalized correlation coefficient at 5 GS/s shows a similar characteristic to that of 10 GS/s. The average of horizontal values of the precision in each of the optical path difference $l = 220$ and 328 $\mu$m for $C_{+1}/C_0$ and $C_{-1}/C_0$, respectively.

## 5 Analysis

To verify the accuracy of our measurements, we compared them with those of a commercial laser range finder (PLR15, BOSCH) whose measurements are accurate to $\pm 3$ mm.

The commercial range finder is attached to a stage behind the target prism. In this experiment, we measured the distance ($\Delta L$) between the positions of $x_1$ and $x_2$ using both systems.

We measured the target position $x_1$ with two systems. The obtained correlation waveform is shown in Fig. 8, and the optical path difference $L_{p1}$ is determined to be 450 mm.

Then, to obtain an accurate measure of optical path difference $L_{p1}$, we used the method discussed in Sec. 4 to adjust the reference optical-path length, every 2 mm over a total of 20 mm, and obtained the revised normalized correlation coefficient shown in Fig. 9. The horizontal axis in Fig. 9 shows a distance shift $l_1$ from the optical path difference $L_{p1}$, which is obtained from the correlation waveform peak in Fig. 8. The "measurement point" noted in Fig. 9 is the value of $C_{+1}/C_0$ in Fig. 8. To determine the optical path difference precisely from this point, we add the distance ($l_1$) noted in Fig. 9 to the optical path difference $L_{p1}$. The distance $l_1$ read from Fig. 9 is $-13.02$ mm. As a result, the optical path difference measures $L_{T1} = 436.98$ mm. After this measurement is completed, the reference prism is moved back to its original position.

Next, the target prism was moved distance $\Delta L$ (20 mm) to position $x2$, as measured by the aforementioned laser range finder. Figure 10 shows a correlation waveform and the optical path difference $L_{p2}$, measured to be 390 mm. Figure 11 also shows a shift in the normalized correlation coefficient $C_{\pm 1}/C_0$. The distance $l_2$ read from Fig. 11 is 7.36 mm. According to our tests, the optical path difference measures $L_{T2} = 397.36$ mm.

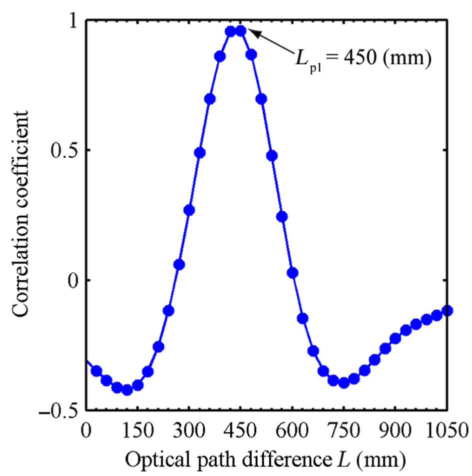


**Fig. 8** Correlation waveform at the original target prism position.

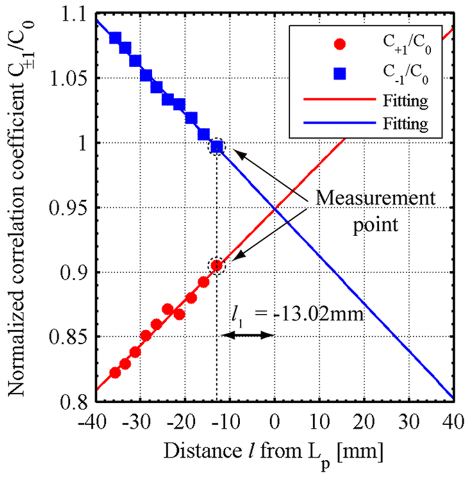


**Fig. 9** Changes of normalized correlation coefficient $C_{+1}/C_0$ at the original target prism position.

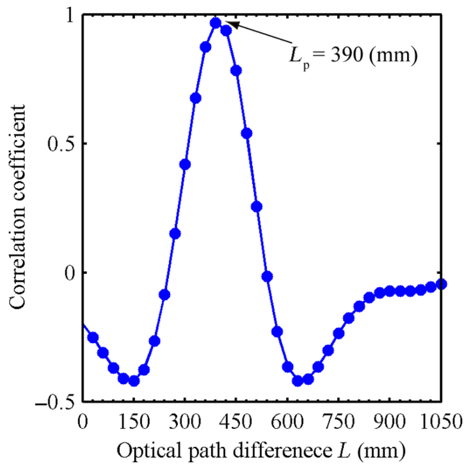


**Fig. 10** Correlation waveform after moving the target prism.

Additionally, when the target is moved $\Delta L$, $2\Delta L$ is added to the target optical-path length. Thus, the distance $\Delta L$ between position $x_1$ and $x_2$ is determined to be $\Delta L_T = |L_{T2} - L_{T1}|/2 = 19.81$ mm. Since our measurement results are consistent with those of the commercial range finder

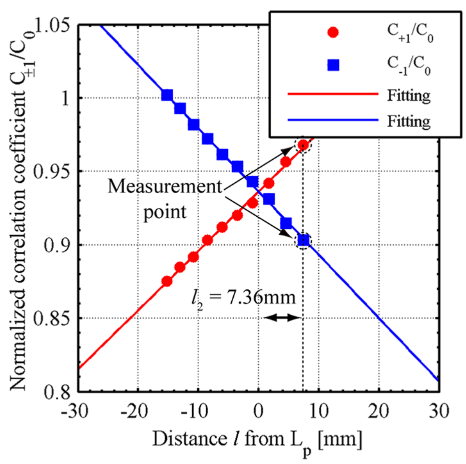


**Fig. 11** Change of normalized correlation coefficient $C_{\pm 1}/C_0$ after moving the target prism.

whose accuracy is $\pm 3$ mm, the validity of our method with $\pm 3$ mm resolution appears to be confirmed.

## 6 Conclusion

The objective of this work is to develop a high-resolution optical range finder that uses random signals generated from laser diodes' frequency noise. Modulated signals travel along reference and target paths, with differences between the two determined by calculating cross-correlation. However, when an ADC is used to sample the signal, resolution is limited. If we adopt a sampling rate of 10 GS/s, resolution is limited to $c\tau_s/2 = 15$ mm. To overcome this, we used the linear relationship of the normalized correlation coefficient $C_{\pm 1}/C_0$ versus the reference optical-path length change. Comparing results obtained using our method and those of the commercial laser range finder, we confirmed a range resolution of $\pm 3$ mm of our method. Furthermore, our system should have a higher resolution because of the measurement result of average precision 300 $\mu$m. We will confirm the resolution of our method with a more accurate reference system. It is hoped that this high-resolution optical range finder, which requires no high-speed modulators or other complex mechanics, will take pride of place among the various low-cost distance–measurement applications currently available.


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