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Time-of-flight range detection using low-frequency intensity modulation of a cw laser diode: application to fiber length measurement

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Abstract. This paper describes a simple optical range detector in the time-of-flight (TOF) category using a cw laser diode emitting at 1.55 μm. The principle of operation combines TOF with frequency-modulated cw methods. The main originality of this method consists in measuring the time delay between two signals without using the time variable. The forward current of the laser diode is modulated by a low-frequency triangular signal. The emitted and received signals are compared, and the amplitude difference gives a readout signal whose peak-to-peak amplitude is proportional to the TOF. An application to optical fiber length measurement is given. [DOI: 10.1117/1.2977794]

Subject terms: ranging; phase measurement; modulation; signal processing.

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1 Introduction

Laser range finders can be classified in three categories, of which each uses a particular property of the laser light:

- Self-mixing interferometry[1,2] uses reinjection of the beam reflected by the taget in a laser diode cavity. The light interference in the cavity is detected at the laser diode's back face photodiode. Laser coherence is required.
- Frequency-modulated continuous-wave (FMCW) range finding[3] with coherent detection uses high-frequency intensity modulation of a laser source. This produces frequency sidebands in the optical spectrum. The backscattered signal is then combined with the incident signal (which plays the role of a local oscillator) in a Michelson interferometer. The interference (heterodyne detection) produces a beat whose period is proportional to the distance from the target. The high modulation frequency does not allow direct modulation of the diode forward current without degrading its performance and requires that the beam modulation be carried out by an electro-optic device external to the laser cavity. On the processing level, the signal is digitized and a fast Fourier transform is used to measure the beat period and thus determine the distance. This category of range finder requires a highly monochromatic optical source.
- With range finding by time-of-flight (TOF),[4–6] a light pulse is emitted and a clocked electronic device measures the time interval between the input and return pulses. This principle requires a high-speed optical source operated in a pulsed mode with a short rise time of about 0.6 ns. On the detection level, this method needs an ultrafast and high-sensitivity photodiode (e.g., an avalanche photodiode) with excellent turn-on and turnoff behavior. The electronic time interval measurement circuit[7] must typically have a bandwidth about 15 GHz. The TOF technique is defined by start and stop signals and needs high resolution timing of pulses. This problem can be solved by integrated detecting and processing with sophisticated timing discriminator circuits.

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Commonly, the modulation of the cw used in radar or lidar techniques requires operations in the frequency domain (see for example Refs. 8 and 9). In this paper, we describe a simplified and inexpensive TOF range finder[10,11] employing a cw light source with low-frequency (LF) intensity modulation. The objective of this approach is to overcome the difficulties encountered with the high-frequency bandwidth requirement of conventional TOF range finders. In addition, no condition is imposed on the coherence of the laser emission.

2 Principle

The input cw signal S_E is a LF triangular waveform as shown in Fig. 1, and is used to modulate the forward current injected into the laser diode. The threshold and the amplitude of the driver current S_E are adjusted to correspond to the linear section of the laser diode emission curve as shown in Fig. 2, which ensures that optical intensity emitted by the laser diode is matched to S_E. After a propagation distance d, the light is collected on a photodiode. Figure 1 shows how the received signal S_B has the same triangular form and the same frequency as S_E. But S_B is delayed with respect to S_E by a time T_F corresponding to the propagation distance:

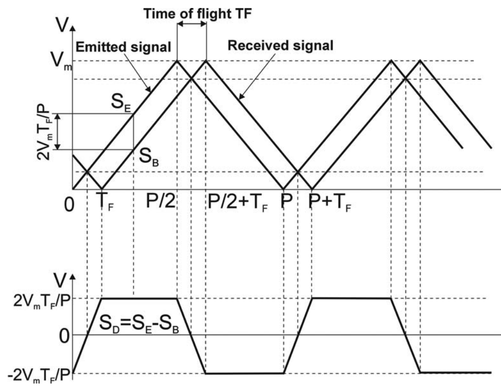

Fig. 1 Top: Schematic representation of input and output signals. LF-intensity-modulated optical signal is emitted by the laser diode and is matched to S_E (amplitude V_m and period P). Received signal S_B is delivered by the photodiode after propagation. The delay T_F corresponds to the TOF in the propagation medium. Bottom: Readout signal S_D obtained as difference between S_E and S_B.

$$T_F = \frac{d}{c}, \tag{1}$$

where c is the velocity of the light in the propagation medium.

The receiver regenerates the original amplitude level by using digital processing. The signal S_E with period P and amplitude V_m can be described by

$$S_E(t) = \frac{2V_m t}{P} \qquad (0 \leqslant t < P/2), \tag{2}$$

$$S_E(t) = -\frac{2V_m t}{P} + 2V_m \qquad (P/2 \leqslant t < P). \tag{3}$$

The received signal $S_B(t)$ is delayed with respect to $S_E(t)$:

$$S_B(t) = \frac{2V_m t}{P} + \frac{2V_m T_F}{P} \qquad (T_F \leqslant t < P/2 + T_F), \tag{4}$$

$$S_B(t) = -\frac{2V_m t}{P} + \frac{2V_m (P + T_F)}{P} \times (P/2 + T_F \leqslant t < P + T_F). \tag{5}$$

The comparison between $S_E(t)$ and $S_B(t)$ gives a new signal $S_D(t) = S_E(t) - S_B(t)$:

$$S_D(t) = \frac{2V_m T_F}{P} \qquad (T_F \leqslant t < P/2), \tag{6}$$

$$S_D(t) = -\frac{2V_m T_F}{P} \qquad (P/2 + T_F \leqslant t < P). \tag{7}$$

Thus S_D is a LF trapezoidal signal, as shown in Fig. 1, with linear leading and trailing edges. The peak-to-peak amplitude of the signal $S_D(t)$ is equal to

$$S_{D\text{pp}} = \frac{4V_m T_F}{P}. \tag{8}$$

The result is independent of the time variable t and is proportional to the time delay T_F between S_E and S_B.

Only linear slopes of the transmitted (S_E) and received (S_B) signals are used with this method, and thus distortions of the leading edges of the signal S_D have no influence on the result.

With this measurement principle, the maximum value T_F is given by

$$T_{F\,\max} = P/2, \tag{9}$$

and the maximum range $d_{\max}$ is

$$d_{\max} = \frac{cP}{4}. \tag{10}$$

The coefficient

$$\gamma = \frac{4V_m}{P} \tag{11}$$

can be considered as an amplifying coefficient, which can be adjusted by varying the ratio between the amplitude V_m and the period P of the input signal S_E. Within the range limit, if V_m is constant and if the propagation length is short, one chooses a high frequency to increase the peak-to-peak amplitude of S_D.

3 Experimental Setup and Measurement Process

An experimental validation of this technique has been performed by determining the length of a monomode optical fiber wrapped around a bobbin. The commercial supplier information indicates that the fiber length is nominally 500 m.

The measurement chain is shown in Fig. 3 and consists of the following components:

- The emitter is a multimode laser diode (Avanex A1905 LMI) emitting cw radiation (13 mW max; 0.17 mW/mA; wavelength 1.55 μm). The forward current of the laser diode is modulated by a triangular signal S_E delivered by a digital function generator with variable frequency. The LF forward current is directly injected into the biased laser diode. The required dc bias current is set in the linear region (Fig. 2).
- The pigtailed laser diode is connected to the fiber under test through a 2×2 coupler (output 1).
- A mirror is positioned at the end of the fiber to reflect the light.
- Output 2 of the coupler is connected to an InGaAs photodiode, which delivers the signal S_E emitted by the laser diode before propagation in the fiber.
- Output 3 of the coupler is connected to a similar InGaAs photodiode, which delivers the signal S_B emitted by the laser diode after propagation in the fiber.

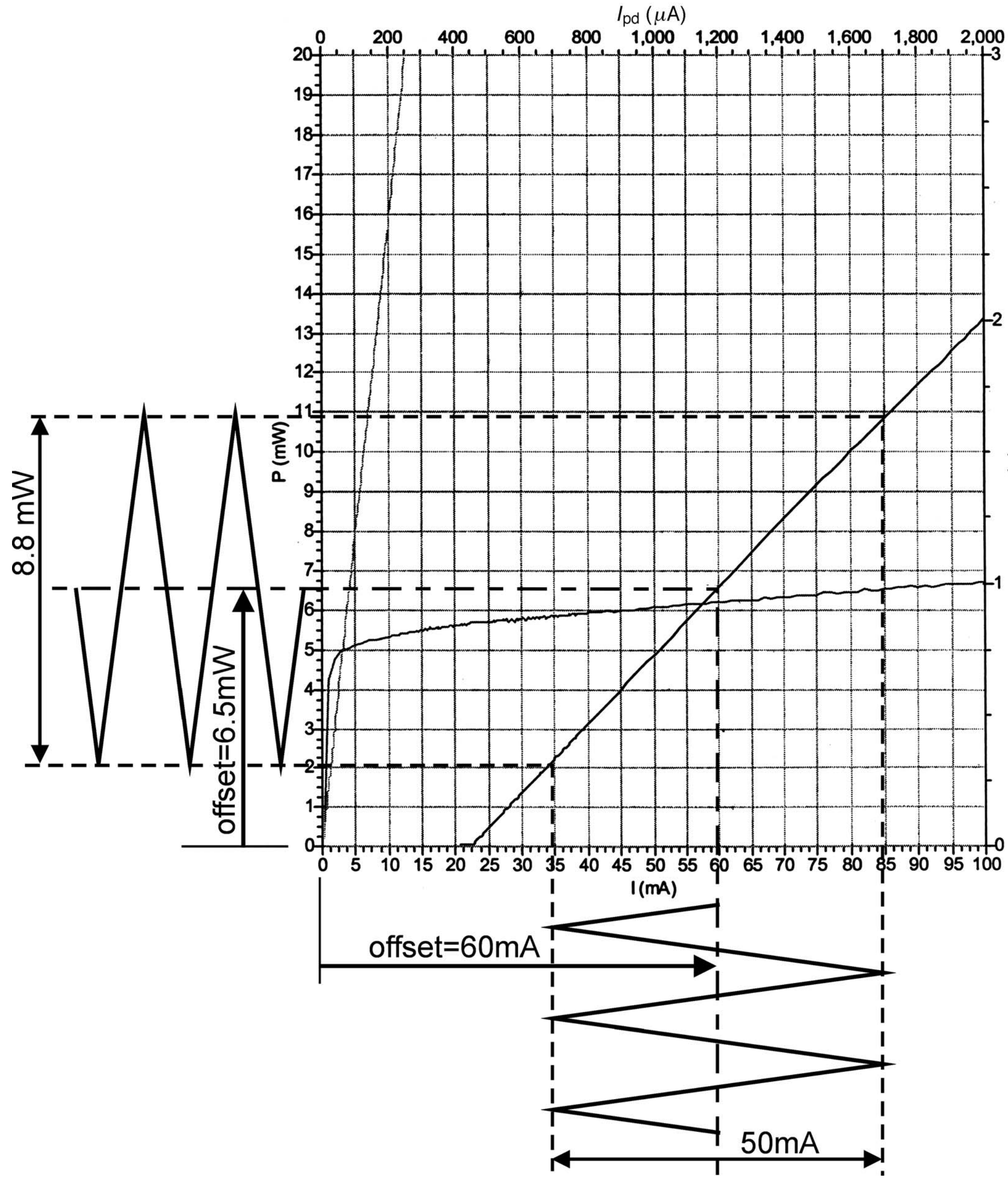

Fig. 2 The modulation of the forward current of the laser diode along the linear part of the laser *P-I* response curve, as shown, yields an optical signal that reproduces the electrical modulation signal.

The outputs of the InGaAs photodiodes (Thorlab D400) are connected to an acquisition card. The amplitudes versus time values of the signals are converted to data files and recorded in computer memory. For each measurement, 50 waveforms of signals are recorded. Each waveform has 5-ms length and 1-ns sampling period. Statistical processing is used to avoid random perturbations.

The first step of the measurement process consists in a setup calibration without the fiber bobbin, as shown in Fig. 4, where the mirror is placed directly at output 1 of the coupler. This operation allows removal of any possible phase-shift difference between photodiode 1 and photodiode 2 due to capacitive effects in analog detection and preamplification devices.

Over the range of modulation frequencies employed (0.5 to 20 kHz), the delay time between photodiodes is less than 0.1 ns. The frequency response of the detection circuits was observed to be flat with no phase-shift variation versus frequency. Phase-shift variation can thus be considered as negligible compared with the delay time due to propagation in the fiber.

Digital subtraction ($S_E - S_B$) yields the signal S_D, which is shown as the bottom trace in each panel in Fig. 5. Software, developed in MATLAB, allows comparison and adjustment of the amplitudes of S_E and S_B to make them equal. A simple method to equalize those amplitudes consists in computing the slope of the top of the signal S_D as shown in Fig. 5. The data in the files corresponding to S_E and S_B are adjusted to reduce this slope to near zero. This method avoids possible errors due to the distortion of S_B,

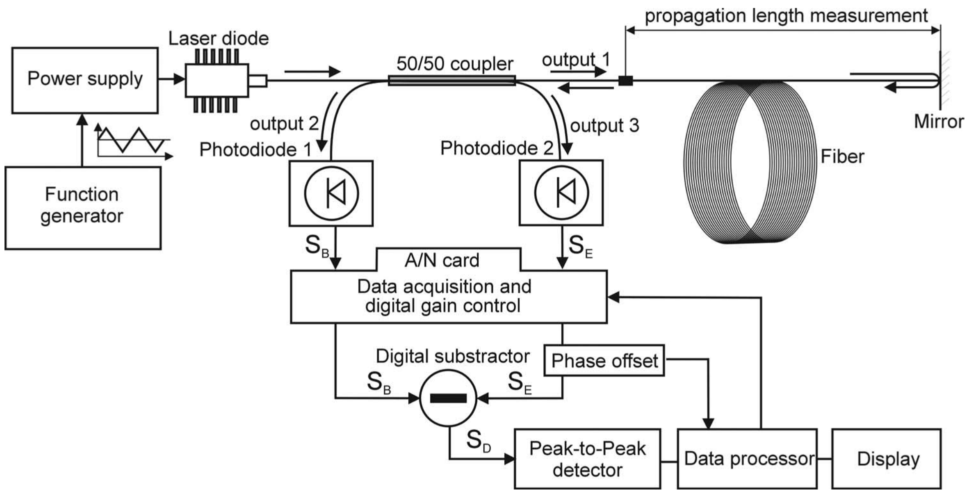

Fig. 3 Experimental setup to measure the length of a propagation medium. The fiber is connected at the coupler output, and a mirror at the fiber output reflects the signal towards the detector.

especially those associated with the smoothing of the leading edge of the triangular function due to the frequency response of the laser diode and detectors.

Peak-to-peak detection of the signal S_D gives the value $S_{D\mathrm{pp}}$, from which T_F can be obtained as

$$T_F = \frac{S_{D\mathrm{pp}}P}{4V_m}, \tag{12}$$

and a simple computation then gives the value of the fiber length:

$$d = \frac{1}{2}(cT_F). \tag{13}$$

The factor $1/2$ in Eq. (13) corrects for the effect of the mirror, which doubles the actual fiber length.

However, the precision of the measurement depends directly on the SNR. It is important to use the specific properties offered by this method to increase the level of the signal without significantly increasing the noise.

Previously, it was indicated that the amplitude of S_D can be adjusted by means of a geometrical amplification coefficient γ [Eq. (11)]. This geometrical gain is a function of the modulation period. In this case we consider as noise the errors due to the distortion of the profile of the optical signal when the modulation period decreases, as well as random fluctuations of emitter and detectors. In view of the low modulation frequencies, the amplitude and phase jitter of the laser diode can be neglected.

Another way to increase the amplitude of S_D consists in imposing an arbitrary phase shift on the reference signal S_E. This method can be also considered as a geometrical amplification of S_D without noise. The phase bias T' can be introduced as a numerical function with an accuracy better than a nanosecond. It is deducted from T_F to obtain the value of d:

$$d = \frac{1}{2}c(TF - T'). \tag{14}$$

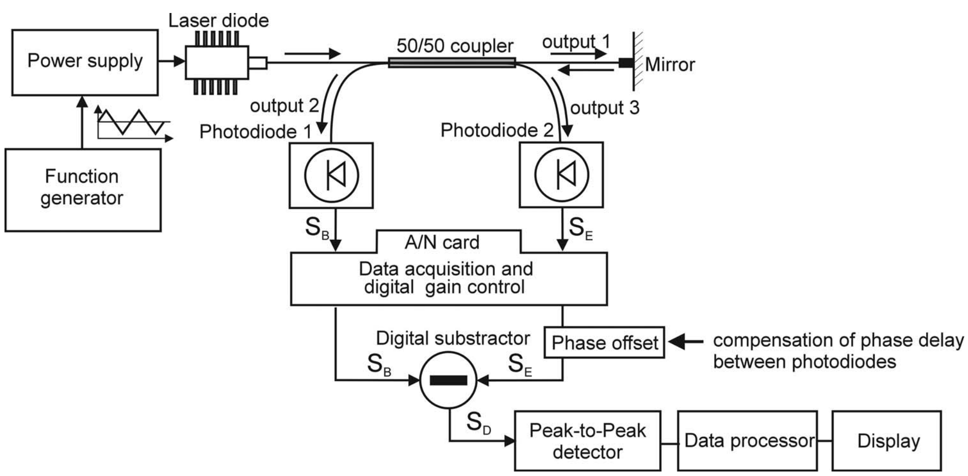

Fig. 4 Calibration operation to detect and cancel a possible phase error induced in analog detection components by capacitive effects. The fiber is removed and the mirror is placed at the coupler output.

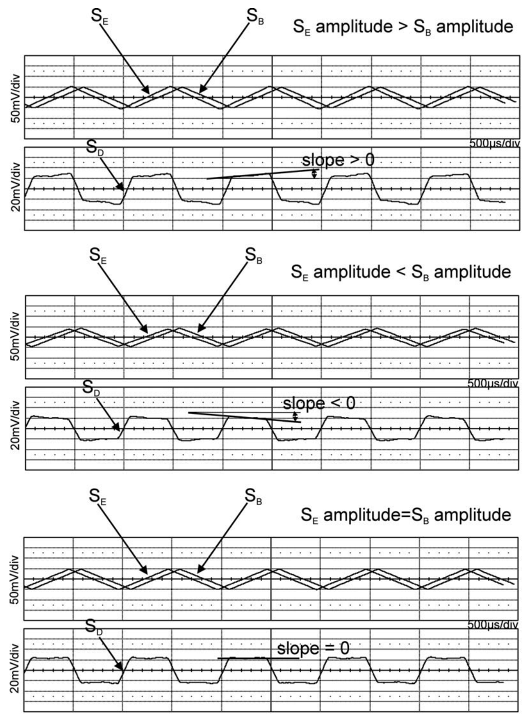

Fig. 5 The principle of operation requires that the amplitudes of S_E and S_B be equal. This is checked by observing the slope of the top of the signal S_D. A computing loop determines the coefficient that yields proper adjustment of the amplitudes S_E and S_B.

For example, a comparison between measurements without phase shift and with a phase offset equal to $P/8$ is shown in Fig. 6. The phase offset results in an increase of the SNR by nearly an order of magnitude from 18 to 167.

The measurement of the fiber length is shown in Fig. 7. The specific experimental conditions are: frequency modulation at 1 ± 0.001 kHz; optical signal amplitude 8.8 mW; electrical signal amplitude delivered by photodiode, 140.16 ± 0.07 mV; additional phase offset of S_E, $P/8 = 125 \pm 0.001$ μs; peak-to-peak amplitude $S_{D\text{pp}} = 72.7 \pm 0.2$ mV.

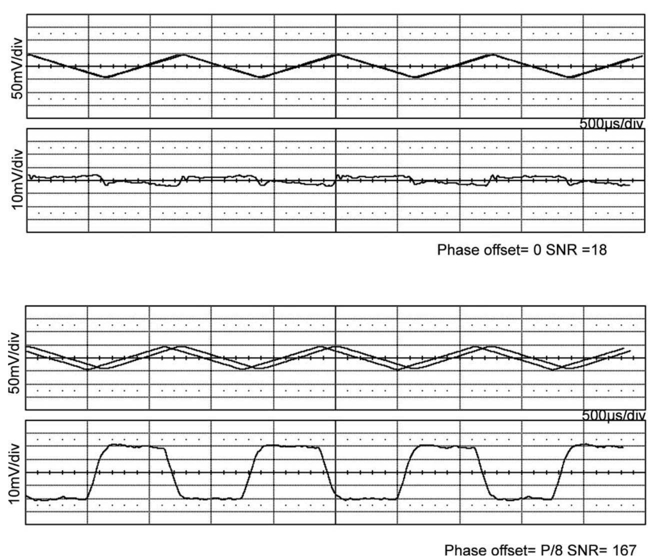

Fig. 6 Combined with a judicious choice of the modulation frequency [see Eq. (10),] the provision of a phase offset between S_E and S_D allows one to increase (by a simple geometric effect) the level of S_D and consequently to improve the SNR.

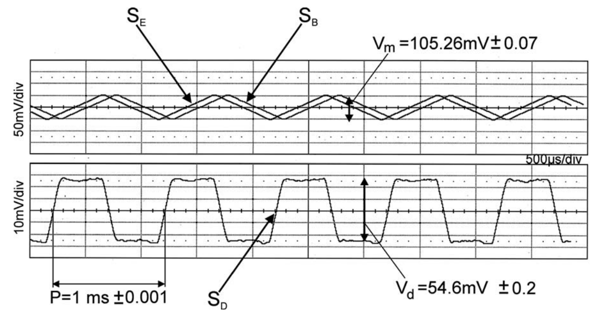

Fig. 7 The knowledge of the peak-to-peak amplitude of S_D gives the information needed to compute the TOF and consequently the length of the propagation medium.

From these data the fiber length can be evaluated to be: 483 ± 2 m, representing a 0.4% error.

4 Discussion and Conclusion

The error in the length measurement, estimated to be 0.4% for a fiber length of 483 m, has the same order of magnitude as that of a measurement obtained with a commercial optical time-domain reflectometer (OTDR) using pulses with 10-ns duration and using the classical TOF principle. It is appropriate in this context to discuss the advantages and disadvantages of our technique compared with the widely used OTDR. An important advantage of our technique is that our measurement error decreases for longer fiber lengths. This is in contrast to OTDR systems, where pulse distortion due to fiber dispersion reduces accuracy for longer lengths. On the other hand, our setup does not allow the localization of small modifications of the refractive index in the fiber core. The resulting dead zone is determined by the maximum value of the modulation frequency of the forward current of the diode that allows maintaining a linear conversion of electric intensity to light power, which yields a typical length of 20 m for our parameters, compared to 2 m for a high-quality OTDR. However, our approach using LF modulation of a cw laser source is ideally suited for measurements of long distances where short dead-zone lengths are less critical, and for such cases it possesses significant advantages associated with its simplicity and low cost.

The novelty of this range detection method is its simplicity. The experimental setup presented in this paper uses a cw laser diode emitting at only 13 mW, and modulated in a frequency bandwidth ranging between 500 Hz and 50 kHz. It uses only standard components operated in the 1.5-μm telecommunication window. The distance information is obtained by measuring the peak-to-peak magnitude of the output signal. The signal processing is simplified, without pulsed or high-frequency signals, compared with other categories of range finders. Intensity modulation by LF with linear slopes allows direct control of the forward current of the laser diode without degrading its performance. Furthermore, LF cw intensity modulation avoids other problems: dispersion of the transmitted signal due to the propagation medium, profile distortion of the output signal due to capacitive effects in electronic receiver devices, and spatiotemporal instabilities of optoelectronic components in turn-on and turn-off. The operation of the range finder is not concerned with the carrier wave, but only with the associated modulation envelope. Consequently, it is independent of the source spectrum (profile and bandwidth), so that this principle can be easily adapted to microwaves or acoustic waves for other applications.

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