Journal of Applied Sciences

ISSN 1812-5654

science alert

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Journal of Applied Sciences 8 (2): 316-321, 2008
ISSN 1812-5654

Modified Phase-Shift Measurement Technique to Improve Laser-Range Finder Performance

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Abstract: In this study, a new technique for improving the performance of laser phase-shift range finders is presented. The phase measurement is performed by using a new method to extract the phase-shift data from the peak of the received and transmitted intermediate frequency signal amplitudes. The pulse-width modulation is used to minimize the noise effects of electronic circuits and enhance the accuracy of signal amplitude measurement. The two most advantages of the proposed system over others are its ability of proper isolation which reduces crosstalk and its independency to the frequency thermal drift. Theoretical calculations and experimental results have shown accuracy better than 2 mm over measuring distance range of 0.3-163 m.

Key words: Crosstalk, heterodyne, laser range finder, phase shift, pulse width modulation

INTRODUCTION

Optical measurement systems based on the semiconductor laser diodes are widely used in the industrial applications because of their performances, small size, easy to drive and low cost. The measurement of the phase-shift between the transmitted and received signals that is based on heterodyne detection is well adapted to medium range distance measurement, but is limited by the frequency thermal drift and the crosstalk occurring between the emitting and receiving circuits (Bosch and Lescure, 1997; Hashemian *et al.*, 1994; Journet *et al.*, 1996, 2001; Mohammad Nejad and Olyaee, 2002; Poujouly and Journet, 2001). For example, the maximum error due to the crosstalk corresponding to modulation frequency of 16.6 MHZ and photoelectric signal-to-induction ratio of 30 was reported about 5 cm at 10 m (Bosch and Lescure, 1997). By reduction of the modulation frequency to 230 kHz, the effective electrical isolation of circuits can be achieved and the crosstalk effect would be reduced considerably.

In the present study, we develop a modified heterodyne phase-shift range finder. The simulation and experimentation results indicate that the accuracy is obtained better than 2 mm for a distance range of 0.3-163 m.

MATERIALS AND METHODS

This study is based on the various measurements and simulations on the modified laser phase-shift range finder. The complete system is designed, simulated and implemented in the Optoelectronic and Laser Laboratory of Iran University of Science and Technology during 2006-2007.

The basic operation of laser phase-shift range finder is based on sinusoidal modulation of laser intensity and conversion of the flight time, due to propagation of light, into phase-shift. The phase-shift measurement between the optical signal reflected from the target and the reference signal emitted by the laser diode permits the determination of distance d, as:

$$\Delta\varphi = 2\pi f_0 \tau_d = 2\pi f_0 \frac{2d}{c} \tag{1}$$

Where:
$\Delta\varphi$ = The phase-shift
τ_d = The propagation time
f_0 = The modulation frequency

The phase-shift measurement with high resolution can be achieved by heterodyne detection technique. By using the heterodyne technique, the phase-shift can be written as:

$$\Delta\varphi = 2\pi T_x/T_{IF}$$

Where:
T_{IF} = Period of intermediate frequency signal
T_x = Time corresponding to high pulse width of rectangular wave train

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Therefore, d can be determined by (Poujouly and Journet, 2001):

$$d = \frac{\lambda_0}{2} \cdot \frac{T_x}{T_{IF}} \tag{2}$$

The accuracy in the phase-shift measurement is affected by several factors such as the crosstalk effect, the accuracy and instability of laser diode frequency, the local frequency and resolution of phase detection. In order to introduce the new technique to minimize the above mentioned parameters effects, we express the driver signal of the laser diode as:

$$S_D(t) = K_1 \cos(\omega_0 t + \varphi_1) \tag{3}$$

Where:
K_1 = The amplitude of the laser driver current
ω_0 = The angular frequency
φ_1 = The initial phase

The received signal after passing through an AGC circuit can be expressed as:

$$S_R(t) = K_2 \cos(\omega_0 t + \varphi_2) \tag{4}$$

Where:
K_2 = The amplitude of the received signal

The local signal is also given by:

$$S_L(t) = K_3 \cos((\omega_0 \pm \omega_{IF})t + \varphi_0) \tag{5}$$

Where:
ω_{IF} = The intermediate angular frequency
K_3 = The amplitude of the local signal

The local signal is multiplied by the driver signal of laser diode and, in parallel path, by the received signal. Therefore,

$$S_{DL} = \frac{K_1K_3}{2}\{\cos[(2\omega_0 \pm \omega_{IF})t + \varphi_1 + \varphi_0] + \cos(\mp\omega_{IF}t + \varphi_1 - \varphi_0)\} \tag{6}$$

$$S_{RL} = \frac{K_2K_3}{2}\{\cos[(2\omega_0 \pm \omega_{IF})t + \varphi_2 + \varphi_0] + \cos(\mp\omega_{IF}t + \varphi_2 - \varphi_0)\} \tag{7}$$

These signals are sent to the Low Pass Filters (LPF) and as a result, Eq. 6 and 7 can be rewritten as:

$$S_{DL} = K\cos(\varphi_1 - \varphi_0) \times \cos(\omega_{IF}t) \tag{8}$$

$$S_{RL} = K'\cos(\varphi_2 - \varphi_0) \times \cos(\omega_{IF}t) \tag{9}$$

Where:
$K = K_1K_3$
$K' = K_2K_3$

We use a peak detector circuit to extract the peak amplitudes of signals that contain the phase data. The difference phases (φ_1-φ_0) and (φ_2-φ_0) are measured in the processing unit and as a result the phase-shift (φ_2-φ_1), corresponding to the propagation of laser beam, can be calculated.

Figure 1a shows the main parts of the modified laser range finder. The system is composed of four main blocks. The first block is composed of three electrically isolated units. The laser diode amplitude is modulated by a sine-wave signal with frequency of 230 kHz and the unambiguous range with respect to the frequency of modulation is about 163 m. The amplitude modulation index is about 2% to decrease the crosstalk effect. The main device in oscillation unit is a 66.240 MHZ crystal oscillator. We use the divider circuits to produce 230 kHz and 207 Hz frequencies which they are the frequencies

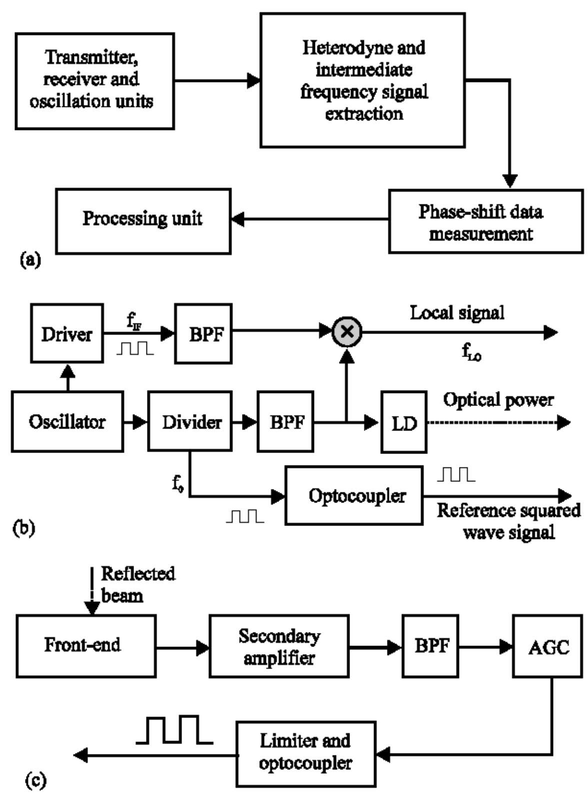

Fig. 1: (a) The block diagram of the system including (b) transmitter and oscillator units and (c) receiver unit

of the laser diode driver and the intermediate signal, respectively. A multiplier IC is used to mix the main harmonics of mentioned frequencies and produce the local frequencies. The block diagram of transmitter and oscillator units is shown in Fig. 1b.

The block diagram of the receiver unit is illustrated in Fig. 1c. In this unit a front-end circuit based on the transimpedance amplifier (Alexander, 1997; Graeme, 1995) with 2.05 MHZ bandwidth is used. The front-end converts the incident modulated laser beam to an electrical signal. In the transimpedance amplifier the 18 A/W Si-APD at 910 nm peak sensitivity wavelength is used. The APD's breakdown voltage is about 180 V and its temperature coefficient of breakdown voltage is 0.2 V/°C.

In order to have a good resolution for the phase-shift measurement, it is necessary to use the heterodyne phase detection technique. In the new heterodyne technique each of transmitted and received signals, which are converted to square wave signals, are mixed with a local signal. The frequency of local signal is (230 kHz±207 Hz) and is obtained by mixing of reference and intermediate signals in the oscillation unit (Fig. 1b). According to the Eq. 8 and 9, after low-pass filtering, two signals with intermediate frequency are extracted.

Figure 2 shows the proposed configuration to eliminate the measured phase. In the proposed configuration, when the analog switch S_2 is activated, the local signal will be mixed with reference signal. In this case, after low-pass filtering, the intermediate frequency can be written as:

$$S_{IF_1} = KG_{LPF}\cos(\varphi_1 - \varphi_0) \times \cos(\omega_{IF} t) \qquad (10)$$

Where:
G_{LPF} = The gain of active low-pass filter

In the same way, if S_1 is activated, the signal is given by:

$$S_{IF_1} = KG_{LPF}\cos(\varphi_1 - \varphi_0 - 90) \times \cos(\omega_{IF} t) \qquad (11)$$

The reference signal passes initially through a unity gain -90° phase-shifter, before mixing with local signal. In the both cases, the amplitude of intermediate frequency signal is measured.

By dividing the measured signal amplitudes, $\tan(\varphi_1$-$\varphi_0)$ is produced which is independently from K and G_{LPF} parameters. In similar way, by activating S_3 and then S_4 analog switches, $\tan(\varphi_2$-$\varphi_0)$ will be resulted. Finally the amount of phase-shift (φ_2-φ_1) can be calculated in processing unit. This method is a way to make the phase-shift measurement independent from environmental conditions. A differentiator circuit is used to implement a unity gain -90° phase-shifter.

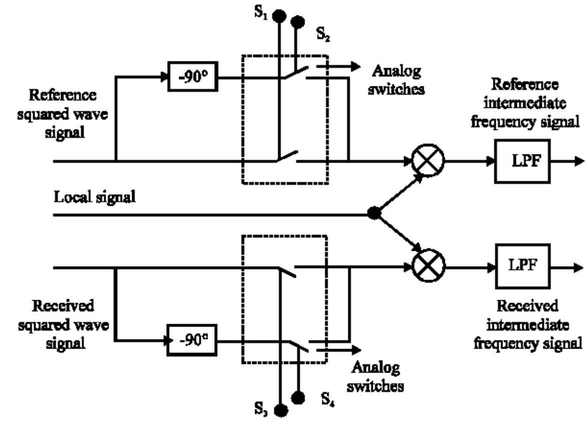

Fig. 2: The modified heterodyne technique

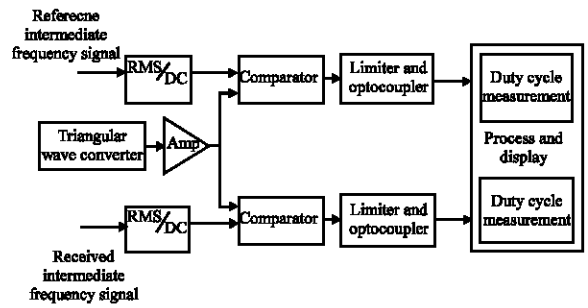

Fig. 3: The block diagram of the designed system for accurate DC signal measurement

On the other hand, a fast RMS to DC converter is used to implement the Pulse-Width Modulation (PWM) for phase-shift data extraction. The output of this circuit is linearly proportional to the peak of sinusoidal intermediate frequency signal. In order to achieve an accurate DC signal measurement and minimize the noise effects, the PWM is used. The block diagram of the designed circuit for accurate DC signal measurement is shown in Fig. 3.

The duty cycles of reference and received signals containing the phase-shift data are measured by the processor. We can express the phase-shift in accordance with measured duty cycles as:

$$V = V_m(2.Du - 1) \qquad (12)$$

Where:
V_m = The peak amplitude of triangular waveform
Du = The measured duty cycle

From Eq. 8 and 9, it can be seen that the measured phase-shift is frequency-independent. This leads to remove the phase-shift error due to the frequency thermal

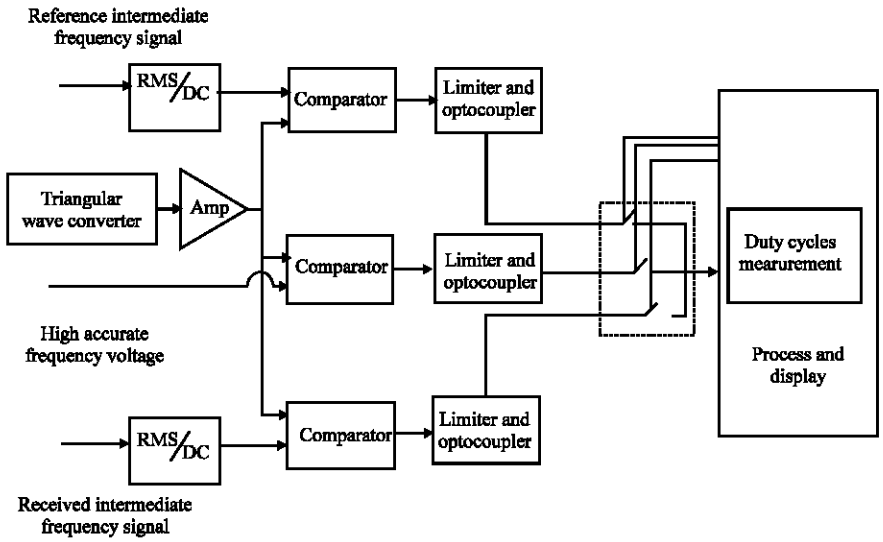

Fig. 4: The designed configuration for sensitivity reduction to the amplitude of triangular signal

drift. Equation 11 shows that the accuracy of the measurement is depending on the stability and accuracy of the peak amplitude of the triangular signal. In order to remove this limitation, we use the configuration shown in Fig. 4. In this configuration the instant amplitude of V_m is measured with respect to a high accurate reference voltage, before measuring the amplitude of the DC signals. The instant value of V_m is accurately calculated by the processor then used in each DC voltage measurement process.

The value of phase error due to the electronic delay time is constant and can be eliminated by system calibration. The range finder measures the target range relative to a reference range. The accuracy of the measurement is dependent on the accuracy of the reference range. If $\Delta\varphi_{REF}$ is the phase-shift corresponding to the reference range, R_{REF} then the calibrated range is given by Hashemian *et al.* (1994):

$$R = R_{REF} + \frac{c}{4\pi f_0}(\Delta\varphi - \Delta\varphi_{REF}) \tag{13}$$

Where:
c = The speed of light in vaccum
f_0 = The frequency of laser modulation signal
$\Delta\varphi$ = The measured phase-shift

In the processing unit, the amounts of phase-shift and the target range are calculated based on Eq. 12-13. As mentioned earlier, since the frequency of triangular waveform is 200 Hz, it is possible to average the measured voltage results. The processor produces the required commands for selection of the specified input and uses the software method to average the measured results. This leads to increase the measurement accuracy without any considerable increasing in the measuring time.

The other distance measurement accuracy limitation is resulted from resolution of phase detection. If we consider $T_x = NT_{count}$ in Eq. 2, where, T_{count} and N are the period of counter clock pulse and the number of counted pulses, respectively, then Eq. 2 can be rewritten as:

$$d = \frac{T_x}{T_{IF}}\left(\frac{\lambda_0}{2}\right) = \frac{f_{IF}}{f_{count}}\frac{\lambda_0}{2}N \tag{14}$$

Where:
$f_{IF} = 1/T_{IF}$
$f_{count} = 1/T_{count}$

If the error due to the thermal drift in f_{count} is neglected, the total frequency thermal drift is given by:

$$\Delta d = \frac{\Delta f_{IF}}{f_{count}}\frac{\lambda_0 N}{2} - \frac{f_{IF}}{f_{count}}\frac{c\Delta f_0}{2f_0^2}N \tag{15}$$

Where:

$$\Delta f_{IF} = f_{IF}\left(\frac{ts_0}{60}\right) + f_0\left(\frac{ts_1 - ts_0}{60}\right)$$

and

$$\Delta f_0 = f_0\left(\frac{ts_0}{60}\right)$$

are frequency thermal drifts versus temperature in the laser driver and intermediate signals, respectively and tS_i is the temperature stability in the crystal frequency, per million over 60°C temperature variation range (Mohammad Nejad and Fasihi, 2006).

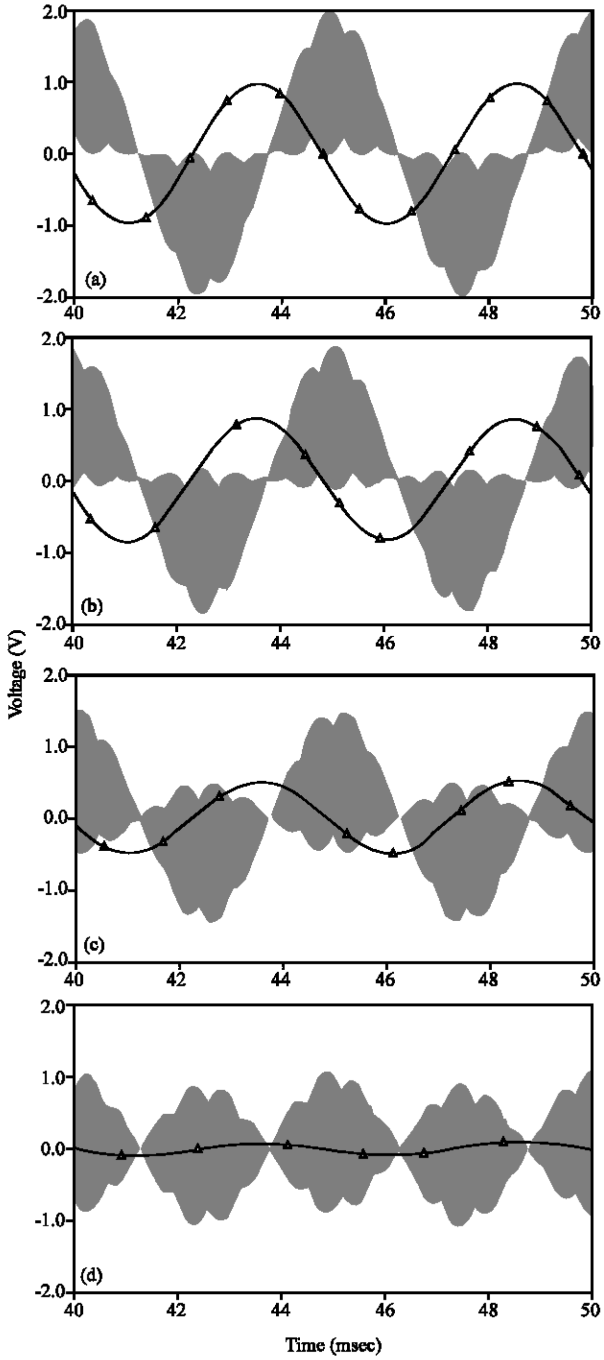

Fig. 5: The simulation results of the modified phase-shift detection circuit. The phase-shifts between local and receiver signals are (a) 5°, (b) 30°, (c) 60° and (d) 85°

RESULTS AND DISCUSSION

The simulation results about front-end circuit indicate that the unity gain and the input capacitance are 34 MHZ and 6 pf, respectively. A 1.78 pf compensation capacitor can produce 44° phase margin. The total front-end output RMS noise is about 531 μVrms. On the other hand, the simulation results of the modified phase-shift detector are shown in Fig. 5. The solid curves indicate the multiplication of the local signal by the received signal and the sinusoidal wave corresponds to the intermediate frequency signal. In this simulation it is assumed that the initial phase of local signal is zero and the initial phases of received signal is 5°, 30°, 60° and 85°. The amplitudes of these signals contain the phase data that should be extracted and processed.

As shown in Fig. 3, the amplitude of the triangular wave signal is adjusted to a desired level and compared with a DC signal in a fast comparator circuit. The amplitude of the triangular wave signal must be greater than the maximum amplitude of DC signals. The comparator outputs have the duty cycles corresponding to the DC signal amplitudes. The typical frequency of the triangular wave signal is about 200 Hz.

The experimental results based on a 100 ns processor indicate that the accuracy of ±100 μV in DC signals is measured. The accuracy of ±100 μV in DC measurement is corresponded to a resolution of ±2 mm over the measuring distance of 0.3-163 m. The signals with specified duty cycles corresponding to $V_0 = 0$ and V_1 are shown in Fig. 6.

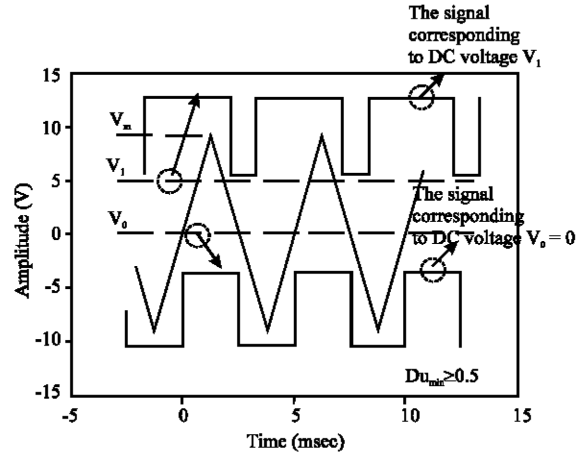

Fig. 6: The signals with specified duty cycles corresponding to the DC amplitude

The experimental result of the measurement error corresponding to the distance range of 142.6 m is also shown in Fig. 7. The lower curve corresponds to the measurement error versus DC voltage without averaging and the upper curve shows the reduction of error after averaging of fifty samples.

The distance measurement error in a distance range of 0-163 m is simulated as shown in Fig. 8. In this

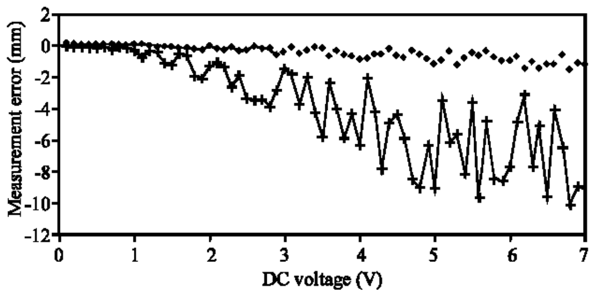

Fig. 7: The distance measurement error versus DC voltage

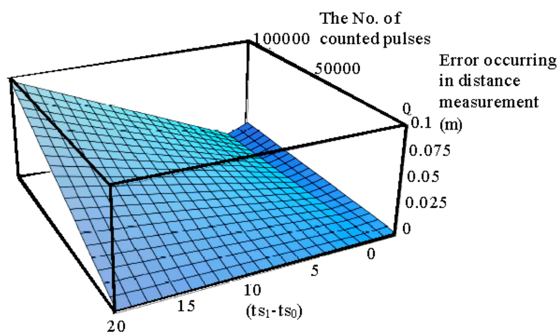

Fig. 8: The distance measurement error due to the thermal drift difference in the range of 0-163 m

simulation, it has been assumed that ts_0 = 2 ppm and (ts_1-ts_0) varies from -2 to 20 ppm. In addition, the laser driver frequency, intermediate frequency and the counters clock pulse are measured as f_0 = 230 kHz, f_{IF} = 207 Hz and f_{count} = 66.24 MHZ, respectively.

CONCLUSIONS

A new design for improving the performance of the laser phase-shift range finder has been presented. By using a new heterodyne technique, the peak amplitudes of intermediate frequency signals contain the phase-shift data. By converting the reference and received signals to square waveform and using a complete electrical isolation between transmitter and receiver circuits, the crosstalk effect is considerably reduced. Accurate measurement of the peak amplitude of the intermediate frequency signal is achieved by using the RMS to DC converter and PWM modulation. The experimental results of DC signal measurement is shown accuracy of ±100 μV. In addition, the accuracy of the proposed range finder over a distance of 163 m is limited to ±2 mm.

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