A New High Accuracy Time-Of-Flight Range Finder with Q-Switching Nd:YAG Laser

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Abstract: In this paper, design, simulation and implementation of a new high accuracy Time-Of-Flight range finder is presented, and various possible errors are also discussed. In this design a Q-switch Nd:YAG laser as a source and an avalanche photodiode as a detector have been used. The optics of the system, including optical filter with $ZnS/\text{MgF}_2$ structure having quality factor of 2.53 has also been designed and implemented. Considering the transmitted power of 1.5MW, the lowest detectable optical power at the APD input, ignoring the noise, was 10nW. Also in this design an appropriate algorithm is designed to reduce the measurement error.

Keywords: Time-Of-Flight, Laser Range Finder, Q-Switch, Nd:YAG Laser, Optical Filters.

1-Introduction

Three major techniques are usually being used for range finding processes. These techniques are: Interferrometry, Phase-Shift and Time of Flight (TOF). The interferrometry technique is generally used for short distances and it has a very high accuracy [1-3]. The phase shift technique is used to measuring the intermediate distances up to several hundreds of meters [4]. However, other techniques such as FMCW\textsuperscript{1} or the combination of interferrometry and phase shift techniques could also be used to measure the intermediate distances with high accuracy [5-8]. But, none of these techniques could be used to measure distances above 1km, since in these techniques continuos wave (CW) or burst lasers are used. On the other hand, to detect the reflecting wave from long distances, lasers having relatively high powers are required. Also, the use of high power lasers with continues wave or burst is impossible. Hence, for measuring distances above 1km, the use of pulsed lasers are necessary. As the repetition of the transmitter power increases, the system becomes complicated and also cooling becomes inevitable. If however, the repetition rate decreases, the detection of a moving target become very difficult. It is therfore necessary to compensate between the maximum distance to be measured, the repetition rate and the system’s complication.

In this paper, design and implementation of a TOF range finder with deviation of about $\pm 5m$ and repetition rate of up to 20Hz is presented. Beside the electronic circuitry, the optical portion of the system was also designed and simulated. The designed system was tested in the range 300m to 20km by using a Q-switched Nd:YAG laser having 1.5MW pulse power with 1.06 $\mu \text{m}$ wavelength. The test results were satisfactory.

2-TOF Laser Range Finder Operation Principals

In a TOF laser range finding system, the round trip time measurement of a short powerful laser pulse is used to determine the distance. With reducing the pulse width of the signal, the output power of the laser signal could be increased to several MW and the signal to noise ratio could be increased

\textsuperscript{1} Frequency Modulation Continuous Wave
considerably. The more important sections of the designed system are:
a) The transmitting section including, the Q-switch, the HV source to drive the flash tube, the repetition rate controlling part, the cooling system and the transmitter optics.
b) The receiver analog section including, the APD detection parts, the low-noise and wide-band preamplifier, the converter, the limiter and the receiver optics.
c) The receiver digital section including, the isolating circuit, the processing and the interface circuits.

As can be seen from fig.1, the output beam from the transmitter is directed toward the target, and its reflection is collected by the receiver optics. Since the laser beam travels a distance of 2r, the receiving power is usually very small. The relation between the received power at the optic section, \( P_{inc} \), and the distance r, is defined as [9]:

\[
P_{inc} = \frac{\rho \tau S}{\pi r^2} P_{opt}, \quad \tau = \tau_c \cdot \tau_{opt}
\]

where, \( \tau \) is the transmitting coefficient (which is equal to the multiplication of transmitting coefficient of the optics and the transmitting coefficient of the media), \( \rho \) is the scattering coefficient of the target (\( \rho = 1 \) for a perfect mirror and is equal to zero for a black body), \( P_{opt} \) is the laser output power and \( S \) is the receiver optic area. As is given by equation (1), the received power by the optics of the receiver is proportional to the square of the distance from the target, \( r \). Considering 1% for the target reflection and 75% for the transmission of the media, in a maximum distance of 20Km measurement by a 1.5MW laser source, the reflecting power will be 70.3nW only.

It can also be seen from fig.1 that, a START signal is simultaneously introduced to the processing circuit through a p-i-n diode. As the START signal is received, a counter is activated, until the STOP signal arrives. After travelling a distance of \( 2r \), the laser beam, trough the optics, arrives on the APD having high responsivity and a short rising time. In order to stop the counter, the APD photocurrent is converted into a voltage signal and is amplified. If the clock pulse frequency is \( f_{clk} \), the distance between the target and the transmitter is,

\[
r = \frac{C N}{2f_{clk}}
\]

3-Design and Implementation of the TOF System

3.1 The Transmitting Circuit

The main function of the transmitting section is to produce a relatively powerful short period pulse, adjust its repetition rate and also produce the START signal. The schematic drawing of the transmitter circuit is shown in fig.2. The main sections of the system are:
a) The laser (including the Nd:YAG laser media, the polarizer, the Q-Switch crystal, the cavity mirrors, the flash lamp and a p-i-n diode).
b) The 4.5KV supply.
c) The driver and repetition rate regulator.
d) The laser cooling system.

As can be seen from fig.2, using a Q-Switch and the related driving and oscillating circuits, the repetition rate is adjusted in the range of 1-20Hz. On the other hand, the laser output pulse variation is adjusted to the range 10-15ns, which in turn, causes the laser cavity output power to vary. In accordance to the measured 15mJ energy, the output power could be adjusted from 1.0 to 1.5MW.

The Nd:YAG laser was pumped by a Flash Tube. For the Flash Tube excitation a 4.5KV source was used. Since the cavity power generation is high, the laser cavity need to be cooled by an especial cooling system. The starting signal was produced by a silicon PIN diode having dark current \( I_d = 10nA \) and a rising time of \( \tau_r = 5ns \). When triggering the Q-Switch and directing the laser pulse out of the cavity, a current pulse is produced by the diode and implied to the processing section to start the counting.

3.2 The Receiver Section

The receiver is to receive a small portion of the main beam and also the reflected signal from the target, to produce the START and STOP signals to measure the round trip time of the beam and convert it into digits presenting the distance. The range finder receiver consists of two analog and
digital sections. The block diagram of the analog section is presented in fig.3. As is shown in the figure, the reflected beam is being detected by an APD having responsivity of $28A/W$ at the wavelength of $\lambda = 1060nm$. Since the APD is in the current mode of operation, the output signal is amplified by a wide band preamplifier having an input impedance of $50\Omega$. The amplifier output signal is given by,

$$V_o = P_{inc} \cdot \Re Z_t \cdot A_v$$

where, $P_{inc}$ is the received optical power on the APD, $\Re$ is the APD responsivity, $Z_t$ is the transimpedance gain of the preamplifier and $A_v$ is the amplifier voltage gain. From the designed circuits, the ratio of the output voltage to the power received by the APD equals $1.4MV/W$.

The amplifier output is implied to a comparator to allow the increase of the output to the desirable level. The signal comparison level due to the minimum received power ($10nW$) is considered to be $14mV$. This in turn will reduce the system’s noise effects. The pulswidth of the signal is then increased by a monostable and the STOP signal of the counter is implied to the optocoupler. It then is implied to the digital section of the circuit.

Furthermore, it is required that the preamplifier gain to be proportional to the received optical power. This can be accomplished by variation of the APD responsivity with respect to the biasing voltage. The varying the bias in the range 320-351V for this APD, the responsivity varies between 18.5A/W to 123.1A/W. If $\Re$ is the responsivity of the APD and the transimpedance gain is $Z_t$, then,

$$A_v = \frac{V_o}{P_{inc}} = \Re Z_t$$

From this equation, the total gain will vary in the range of 920 KV/W to 6.17MV/W.

At the digital section (fig. 4), to measure the round trip time of the signal, a 16 bit counter having the clock pulse of 300MHz is being used. Considering the clock pulse frequency, the resolution obtained from (3) becomes 0.5m. The data obtained from the counter is inputted to an 8bit micro controller, and according to this data and the ERROR and PAUSE signals, the proper phrase is presented on the LCD. If for any reasons, the one cycle output signal of the laser is not received by the detector, an ERROR signal will be produced. The lack of receiving signal could have many reasons such as the target is located very far, the beam is being greatly absorbed by the transmitting media, the target being a very absorbing object and so on. The signal generation is the responsibility of a retrigable monostable. With the implementation of the received signal period the monostable output stays low for the least repetition of 1Hz. Otherwise, the monostable output returns to the High condition. As is shown in fig.4, a selector is employed to estimate the desired range for the user. This will greatly eliminate the possible mistakes, which may happen in finding the range. If the measured distance is not in the selected range, a PAUSE phrase will be shown on the LCD.

Since the delay time related to the electronic circuits in the START and STOP paths are not equal, it is necessary to eliminate this time difference, since it may some deviations in the measurements. The time difference could be eliminated either by hardware or by software. However, it should be noted that, due to the changes caused by extensive heat or the effect of time, the deviation may be reproduced in the software elimination procedure. For this reason, we have employed the hardware procedure and a calibration circuit is placed after the amplifier of the START path. It should be noted that the counter employed to measure the roundtrip time of the laser beam, acts upon the rising edge of the pulse and hence, in the calibration circuit the duty cycle of the START pulse is changed. This in turn will displace the falling edge of the START signal and therefore, changes the time interval between the START and the STOP signals.

4-The Noise Consideration In the Range Finding Path

Detecting the minimum receiving power is also related to the system’s noise. The circuit output noise (optical) can be greatly eliminated by designing and implementing proper optics for the circuit. The main internal noise is the one created in the receiver STOP channel. Due to the isolation of the analogue section from other parts, the noise effect of the other parts is being curtailed. The switching noise of the 4.5KV flash lamp of the laser is being eliminated by EMI filters. The noise related to the digital section is eliminated by separating the source and the ground from the analogue section of the receiver. However, the main noise related to the receiver channel is the noise of the preamplifier, which is given by,
\[
\langle i_\text{n}^2 \rangle = \frac{4KT}{R_{eqi}} \left( \frac{\pi}{2} \Delta f_i \right) 
\]

where \( k \) is the Boltzmann constant, \( T \) is the absolute temperature, \( R_{eqi} \) is the preamplifier's input impedance, and \( \Delta f_i \) is the system bandwidth, which is 100MHz. Considering the 50\( \Omega \) impedance for the preamplifier’s input, the input current noise is 228nA. The equivalent optical power will then become,

\[
P_{\text{inc}} = \frac{\langle i_\text{n} \rangle}{\Omega} 
\]

(7)

Considering the 28\( A/W \) responsivity for the APD, the minimum detecting power becomes 12.7nW.

It is well known that signal-to-noise ratio (S/N) is one of the main elements determining the resolution of the system. For our system, the relation between the resolution of the system and the S/N could be presented by [10],

\[
\delta_d = \frac{C}{2} \frac{\langle n \rangle}{dU/dt} = \frac{0.35C}{2B.\text{SNR}} 
\]

(8)

where \( dU/dt \) is the slope of the time dependent pulse and \( \langle n \rangle \) is the rms noise value. For repetition rate of \( N \) (1<\( N <15 \)), Equation (8) changes into,

\[
\delta_d = \frac{0.35C}{2\sqrt{N}.B.\text{SNR}} 
\]

(9)

It should be noted that the signal to noise ratio rate is considered only for the STOP path. This is because the START path is small and its noise effect can be neglected. Hence, equation (9) could be changed into,

\[
\delta_d = \frac{0.35C}{2\sqrt{N}.B} \left[ \frac{1}{(\text{SNR}_{\text{START}})^2} + \frac{1}{(\text{SNR}_{\text{STOP}})^2} \right]^{1/2} 
\]

(10)

Figure (5) shows the resolution in terms of signal to noise ratio. Considering the resolution of the digital section obtained from equation (3) to be 5m, the minimum required signal to noise ratio obtained for the worst case (\( N=1 \)) from equation (3) becomes 0.1. However in practical situation, the \( \text{SNR}_{\text{START}} \) is larger and the total resolution will be limited to that of the digital section.

5-Simulating The Optical System

The optical part is one of the important sections in a range finding system. A proper optics not only collects and focuses the incident beam, but also it could be designed to filter and eliminate the undesired radiation arriving at the receiver input.

Fig.6 shows the range finder’s optical section. As is shown in the figure, the beam reflected from the target, is directed to the detector by the lens and a filter. The lens is made of a crown glass having an absorbing range of 10\( \mu \text{m} \) and is covered with an antireflection layer of MgF2 of 1.38 reflectivity. The thickness of the antireflectivity layer is \( d = 1\mu \text{m} / 4n = 0.18\mu \text{m} \). The layer is not only to optimize the detectivity, but also acts as a filter. The reason for using the above mentioned glass is that, it is not soluble in water, it has the shortest (1\( \mu \text{m} \)) passing stripe and is a very good absorber of the wavelengths above 3.5\( \mu \text{m} \) (the heat radiation wavelengths). In interference filters used in this design, with the use of thin layers of dielectric materials of different thickness, one can design a Fabri-Perot filter. The transfer matrix of the beam provides the emission of the layer as follows [11],

\[
\left[ \begin{array}{cc} A & iB \\ iC & D \end{array} \right] = \prod_{m=1}^{N} \left[ \frac{\cos \delta_m}{\sin \delta_m} \right] \left[ \frac{i \mu_m}{\mu_m} \frac{\sin \delta_m}{\cos \delta_m} \right] 
\]

(11)

\[
\delta_m = \frac{2\pi n_m d_m \cos \theta_m}{\lambda} 
\]

(12)

For polarization of P; \( \mu_m = \frac{n_m}{\cos \theta_m} \)

(13)

For polarization of S; \( \mu_m = n_m \cos \theta_m \)

(14)

And,

\[
T = \frac{4\mu_1 \mu_2}{(\mu_1 + \mu_2)^2 + (\mu_1 \mu_2 B + C)} 
\]

(15)

In the above equations, \( n \) is the refractive index, \( A \) is the radiation angle, \( d \) is the layer thickness, \( m \) stands for the layer number and \( T \) is the emission power.

The glass used for the substrate has \( n_s = 1.5 \), and \( \text{MgF}_2 \) of \( n = 1.38 \) is used as the layer of low refractive index and \( \text{ZnS} \) with \( n=2.29 \) is used as the high refractive index layer. The selected materials for layers have relatively high melting temperatures and are relatively tough and indissolvent in water. In the simulation carried out for 5 layers, a quality factor \( Q = 1.59 \) was obtained. As is shown in fig.7b, by repeating the epilayers, a filter having \( Q = Q_1 Q_2 = 2.53 \) was obtained. On the other hand, since a thin metal layer on a transparent dielectric is a good reflector for \( IR \) and also is a good transmitter for visible radiation, a direct observation of the target is possible. In Fig.7a the transmission curve for the optical filter is also presented. For the Nd:YAG
laser wavelength the transmission coefficient is 99.7%.

In this design an appropriate algorithm is designed to reduce the measurement error. Considering the sampling rate 20Hz and the 2sec for refreshing the display, there will be 40 samples in each display. By omitting the out of range data, the measuring error is considerably reduced. Fig.8 presents the measured data for approximate distance of 1.17Km. For primary data the average and standard deviation are 1185.57m and 114.95, respectively. After processing the data changes to 1175.23m and 2.92 respectively.

Conclusion:

In this paper design, simulation and implementation of a TOF laser range finder was presented. All the transmitting and receiving circuits were designed and simulated. Based on theoretical and simulation results, the different sections of the system were designed and assembled. A 1.5MW Nd:YAG laser having operating wavelength of 1.064 µm was used as the source, and an APD was used as the detector. The range finding error was ±0.5m and the sampling rate was 1-20Hz.

References

Fig.1: Schematic representation of a time-of-flight range finder system.

Fig.2. Schematic presentation of the transmitter circuit for a TOF laser range finder.
**Fig. 3:** Schematic presentation of the analogue section for the receiver.

**Fig. 4:** The block diagram of the digital section for the receiver.

**Fig. 5:** Receiver resolution in terms of signal to noise ratio.

**Fig. 6:** The range finder optics.

**Fig. 7:** a) Transmission curve and b) The designed filter with layers of ZnS and MgF₂ of quality factor=2.53.

**Fig. 8:** Measured data for distance of 1.17Km.