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A method to enhance the SNR of pulsed heterodyne LADAR based on radio frequency modulation

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ABSTRACT

The performance of conventional incoherent pulsed LADAR is limited by the emitting power of laser as well as the sensitivity of detector, which makes it hard to increase the operating range. In this paper, a set of pulsed heterodyne LADAR design is proposed by combining efficient radio frequency modulation in laser pulses and pulsed heterodyne detection. Finally, the SNR of this design is analyzed, which shows a superiority of 7 dB to 12 dB over conventional incoherent pulsed LADAR and a better appeal to long-range detection.

1. Introduction

Operating range is an important performance index of LADAR, yet has also the bottleneck of traditional LADAR development. Conventional incoherent pulsed LADAR detects the distance of target by the flight time of laser pulse, whose performance is limited by transmitting power, volume of laser source and sensitivity of the detector and thus is caught in an unbreakable barrier in operating range. Aiming to solve this problem, many methods are put forward such as phase encoding pulsed ranging [1], FM/CW ranging [2,3] and pulse compression ranging [4–6]. However, there are flaws in these systems respectively such as the ranging frame frequency limitation of corresponding pulsed coded sequence, leakage of signals of FM/CW system, and the sophistication of the transmit-receive system of pulse compression LADAR besides the problem of sidelobe and range – velocity coupling. In addition, all the method mentioned above utilize continuous wave or broad pulse laser source, which makes them limited by the laser source power observably. Therefore, seeking out an effective way to enhance the operating range of pulsed ranging LADAR has a profound significance.

Vallet proposed a pulse modulated LADAR system based on mode-locked laser source and acousto-optic devices in order to improve both range and velocity accuracy in direct detecting [7]. Inspired by that, a Radio Frequency Modulated Pulsed Heterodyne (RFMPH) LADAR system is proposed based on radio frequency modulation utilizing acousto-optic devices combining with electric heterodyne detection theory in this paper. The SNR is enhanced in this system by mixing the target echo and local electrical signals, and then the operating range and other performance index are enhanced in proportion.

2. Radio frequency modulated pulsed heterodyne LADAR

The schematic of Radio Frequency Modulated Pulsed Heterodyne LADAR is shown in Fig. 1. The operating principle of this system is similar to the conventional FM/CW radar: two signal generator are adopted to produce two frequency-steady signals f_1 and f_2 respectively; f_1 is used to drive two acousto-optic frequency shifters (AOFSs), which provide a frequency shift $f_1 = f_{AO1} = -f_{AO2}$ respectively in two laser paths, thus makes the pulse generated by the laser source RF-modulated by $\omega_M = 2f_{AO} = 2f_1$ after NPBS2 acting as a combiner. Then the modulated pulse is transmitted to the object region after expanded and shaped by the optical emitting antenna. The other signal $f_2 = f_L$ is used as local oscillator to mix with light current of echo signal responded by the APD detector, and then filtered by a narrow band filter. At last, the difference in frequency signal whose frequency $\Delta f = f_2 - 2f_1$ is acquired, and the range information of the target could be obtained after digital processing.

3. Radio frequency modulated laser pulse

The recognized concept of radio frequency modulated laser pulse means that the intensity of a laser pulse is modulated by a signal whose frequency is in radio band. The structure of the system to generate radio frequency modulated pulse is shown in Fig. 2, the

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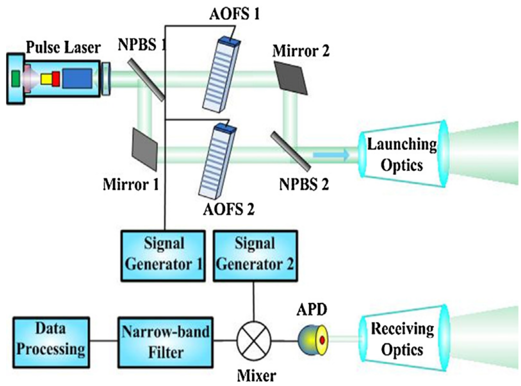

Fig. 1. The schematic of Radio Frequency Modulated Pulsed Heterodyne LADAR.

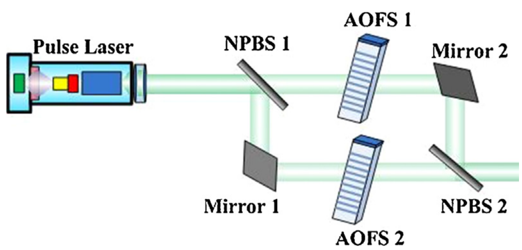

Fig. 2. Principle of generating radio frequency modulated pulses.

optical field distribution of a Gaussian laser pulse generated by laser source with full width at half maximum (FWHM) T, peak power P_m and frequency f_0, can be expressed as:

$$E_0(t) = \sqrt{2P_m \exp[-\frac{(x-t_0)^2}{2\sigma^2}]} \cos(2\pi f_0 t + \varphi_0) \tag{1}$$

In formula (1) the FWHM T and the standard deviation of Gaussian function σ satisfy $T = 2\sqrt{2\ln 2}\sigma$.

The pulse generated by laser source is split into two pulses by a non-polarized beam splitter (NPBS), whose intensity ratio of is $\beta_1 : \beta_2$. These two pulses transmit through two AOFSs respectively whose driving frequency are both $f_{AO1} = f_{AO2} = f_1$. The angles of AOFSs are adjusted to concentrate the energy of the diffraction light on +1 order and −1 order respectively, with an energy diffraction rate $\xi_1 = \xi_2 = \xi$. By keeping the same length of the two light paths, the optical field distribution of the two pulses can be obtained as:

$$E_1(t) = \sqrt{2\xi \frac{\beta_1}{\beta_1+\beta_2} P_m \exp[-\frac{(x-t_0-\tau)^2}{2\sigma^2}]} \times \cos[2\pi(f_0+f_1)(t-\tau)+\varphi] \tag{2}$$

$$E_2(t) = \sqrt{2\xi \frac{\beta_2}{\beta_1+\beta_2} P_m \exp[-\frac{(x-t_0-\tau)^2}{2\sigma^2}]} \times \cos[2\pi(f_0-f_1)(t-\tau)+\varphi] \tag{3}$$

Then a second NPBS is utilized to combine the two pulses, with the energy loss ignored, the output light intensity of the pulse after coherent addition is:

$$P_0(t) = \frac{1}{2}E_s^2(t) = \frac{1}{2}[E_1(t)+E_2(t)]^2 \tag{4}$$

Considering that the optical frequency f_0 cannot be responded by the detector, the high frequency part can be regard as direct current component and ignored, then the expression of the output pulse could be obtained as:

$$P_0(t) = \xi P_m \exp[-\frac{(x-t_0-\tau)^2}{2\sigma^2}]\{1+m[1+\cos(4\pi f_1 t - 4\pi f_1 \tau)]\} \tag{5}$$

where, $m = \frac{\sqrt{\beta_1\beta_2}}{\beta_1+\beta_2}$ is called modulation depth with a maximum 0.5. It is showed in formula (5) that the Gaussian pulse generated by the laser source is modulated by a radio frequency signal whose frequency is $f_M = 2f_{AO}$.

According to the principle of pulsed radio frequency modulation referred above, the corresponding parameters are selected as follows: FWHM is $T = 30$ns; modulation frequency is $f_1 = f_{AO} = 80$ MHz; the energy diffraction efficiency of acousto-optic crystal is $\eta = 0.9$, normalized splitting ratio is $\beta_1 : \beta_2 = 0.5 : 0.5$. Then the normalized shapes of the pulse generated by laser source and after modulation in time domain could be calculated as shown in Fig. 3.

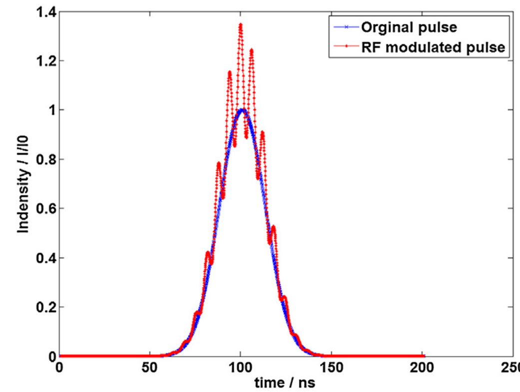

Fig. 3. Shapes of normalized pulse signal before and after radio frequency modulation.

From Fig. 3 it is found that the peak power of the normalized radio frequency modulated pulse $P_{0,max}/P_{max}$ is greater than 1. Besides, the diffraction efficiency and modulation frequency also have an impact on the SNR of system.

4. The enhancement of SNR

According to the LADAR equation, the echo intensity of an area target received by the receiving antenna of LADAR can be expressed as:

$$P_s(t) = \frac{P_0(t)T_1T_2\gamma^2\rho_1A_r}{R^2} \tag{6}$$

where, P_s and P_0 are receiving and emitting intensity respectively; T_1 and T_2 are the transmission factor of emitting and receiving optic system respectively; γ^2 represents the attenuation of the signal caused by atmosphere; ρ_1 is the average reflectivity of the target; A_r is receiving aperture; R is the distance between LADAR and target. At last, the photoelectric detector responds the echo and outputs photocurrent correspondingly:

$$I_s^2(t) = \left(\frac{\alpha e}{h\nu}\right)^2 G^n P_S^2(t) \tag{7}$$

where, α and G are quantum efficiency and gain of the detector respectively. Considering that thermal noise and quantum noise are far more predominant than other noise output by the detector, and both of whose power spectrums distribute uniformly on the entire bandwidth as Gaussian white noise, then the average value of noise could be calculated as:

$$\overline{I_n(t)}^2 = 2e\left(\overline{I_S(t)}+\overline{I_b(t)}+\overline{I_d(t)}\right)G^nB + \frac{4kT}{R}B \tag{8}$$