P8 FMレーザーレーダーにおける非線形周波数変調の分解能への影響

Influence of Nonlinear Frequency Modulation on Resolution in Chirp Laser Radar

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Abstract The nonlinear frequency modulation (FM) influences the resolution of chirp (FM-CW) laser radar systems for rang measurements. A simulated calculation of nonlinear FM in a homodyne system has been made and the result indicates that the FM nonlinearity affects seriously on the side lobe level especially when the frequency of nonlinear FM variation is same as the chirp frequency, and the side lobe level increases with the nonlinearity. The nonlinearity requirement for homodyne system is deduced.

1. Introduction

Coherent laser radar (CLR) has played an important role in laser radar due to its high sensitivity and much available information. With the development of diode pumped single longitude-mode solid laser to infrared range laser technology, the CLR is not limited to 10.6μm laser and has been extended to near infrared and visible region. The CLR can be applied in almost all fields involved environmental monitor, meteorology and ranging applications. since solid-state lasers and diode lasers have a wide tunable spectrum, this advantage has made high resolution range measurement in coherent chirp laser radar. Gernarally, high resolution in the pulsed laser radar requires very narrow pulse width, and makes the system complex and the signal process in time domain complicated. Coherent laser radar with linear frequency modulation may have a simple construction and signal processed in frequency domain different from that of time domain, and the range information can be determined by the heterodyne frequency. So FM-CW coherent laser radar has an intrinsic feature for velocity and range measurements where the signal is processed in frequency domain.

Since linear FM coherent laser radar presents some advantages especially on the signal process and simple construction, it has been widely applied for many years in accurate ranging, coherent laser reflectometry[1], compact coherent laser radar[2-4], etc. In term of conventional radar theory, however, the accuracy and resolution is determined by modulation band width and modulation frequency. Laser frequency modulation can be realized by inner or external cavity using AO (acoustic optical) or EO (electronic optical) device or other devices, whichever modulation device is used in laser system, the output frequency can not be exactly changed linearly with time. The nonlinear frequency modulation will undoubtedly affect the laser radar performance. If the nonlinear laser frequency changes coincident with the chirp frequency, the amplitude of the nonlinear item significantly increases the side-lobe level and therefore influences the resolution of the laser radar. This paper concentrates on deducing the nonlinearity requirement for a linear FM coherent laser radar system and shows simulated results. The popular frequency-domain processing is used for the system and simulation.

2. Chirp signal analysis

To understand the essence of homodyne detection in laser radar it is helpful to present it as the simple squaring process as shown in Figure 1. Ignoring the laser phase noise and initial phase, and assuming no Doppler shift in the returned signal, the LO and returned laser fields, E_{LO} and E_s, can by written respectively as

$$\begin{aligned} E_{LO} &= E_{LO}^0 \cos[2\pi f(t)t] \\ E_s &= E_s^0 \cos[2\pi f(t-\tau)t] \end{aligned} \tag{1}$$

where τ is the delay time of laser beam in the whole path, $f(t)=f_0+\mu t$ is the lasing frequency, μ is the frequency ramp rate which is a constant by $\mu=B/T$, B and T are modulated width and modulation period, respectively. So, if the LO and the returned signal have matched phase fronts over the detector surface, the output field power mixture is:

$$\begin{aligned} I \propto &< |E_{LO}+E_s|^2 > = < |E_{LO}|^2 > + < |E_s|^2 > \\ &+ 2E_{LO}E_s\{\cos[2\pi(f(t)-f(t-\tau))t] + \cos[2\pi(f(t)+f(t-\tau))t]\} \end{aligned} \tag{2}$$

By introducing a electronic filtering after detector, we can extract the term with intermediate frequency $f_{IF}=f(t)-f(t-\tau)=\mu\tau$ which carries all information of targets. That frequency directly corresponds to the delay time τ and, hence, the range of targets.

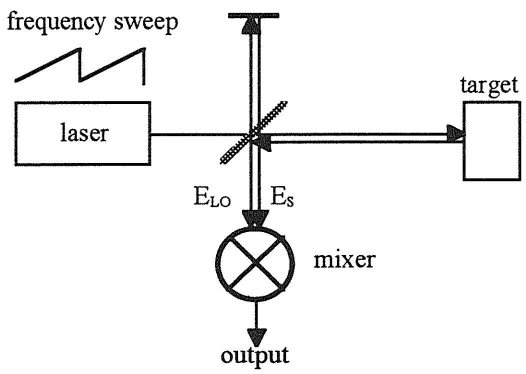

Fig. 1 Optical homodyne detection block-diagram

Linear frequency modulation scheme in laser radar system is a realistic situation, in many cases modulated laser frequency nonlinearly changes. Assuming the modulated slope μ is a time function, $r(t)$ is a relative slope error of μ within T, therefore the $\mu(t)$ can be written by

$$\mu(t) = \mu[1+r(t)] \tag{3}$$

where, $0 \le |r(t)| << 1$. The intermediate frequency, thus, is given by

$$\begin{aligned} f_{IF}(t) &= f(t) - f(t-\tau) \\ &= \mu\tau[1+r(t)+(t-\tau)r'(\xi)] \approx f_{IF}[1+r(t)] \end{aligned} \tag{4}$$

where $r'(\xi)$ is the derivative with respect to the time and ξ is a time between $t-\tau$ and t. We have neglected the higher order small term in Eq.(4). Generally the nonlinear frequency term changes with cosine rule[5], which can be given by

$$r(t) = r_{\max} \cos(2\pi f_m t) \tag{5}$$

where $r_{\max}$ is the maximum relative slope error, f_m is the frequency of $r(t)$. From the Fourier transfer process, this nonlinear term will produce a pair of lobes positioned f_m from the expected spectrum on both sides, with the relative amplitude $(\mu\tau/2f_m)r_{\max}$ to the main lobe. Let $f_m=1/T$, where the side lobe is placed at a resolution element near the main lobe, and if the level of the relative amplitude is enough, in this case it is hard to determine whether the nonlinear modulation or another small scattering target causes the side lobe spectrum. To eliminate the influence of the nonlinear frequency modulation, we restrain the amplitude level introduced by the nonlinear frequency term into the side lobe level of the received signal spectrum

$$s \geq \frac{\mu\tau}{2f_m} r_{\max} \tag{6}$$

where s is the side lobe level. From Eq.(3) and Eq.(5), we have $\Delta\mu=\mu r(t)$, the maximum frequency difference to nonlinear chirp is $\Delta B=\Delta\mu T=\mu T r_{\max}\approx B r_{\max}$. The nonlinearity of the frequency modulation is defined as the frequency deviation devided by the modulation width, therefore the maxmium nonlinearity of the chirp laser radar is required by

$$\eta = \frac{\Delta B}{B} = r_{\max} \leq \frac{2sf_m}{\mu\tau} \tag{7}$$

where τ is corresponding with the range R by the relation of $R=c\tau/2$, c is light velocity. The side lobe level in a given laser radar system parameters is known, so the Eq.(7) can be explained that the linearity of a chirp laser radar is determined by modulation parameters, i.e. modulation frequency and modulation slope. The linearity can be improved by increasing the chirp frequency and/or decreasing the chirp ramp rate.

3. Calculation

The FFT method of simulating the effect of the nonlinear FM laser signal on the resolution has been used, which is popular for chirp signal processing. As an example, we choose the laser system parameter with B=240kHz, T=1ms and τ=0.02ms (corresponding R=3000m). Three different nonlinearity of laser frequency modulation, η=0, 0.01 and 0.05, was calculated as shown in Fig.2. From Eq.(6) we can easily get the requirement of nonlinearity by the laser system parameters within about 0.8%. If the nonlinearity is more than this condition, the effect of the nonlinear FM on the side lobe level becomes clear and large. Comparing the linear FM (η=0) and nonlinear FM (for instance, η=5%), we can clearly predict that when the side lobe level is increased closed to the main lobe by the nonlinear frequency modulation, the laser radar may report a wrong result at the position of side lobe. This will decrease the reliability of laser radar.

4. Conclusions

A chirp coherent laser radar system requires a stringent linear frequency modulation. The maximium nonlinearity is limited by some modulation parameters and detecting range. The nonlinearity modulation of FM laser radar can very much affect on the level of side lobe, even possibly higher than that of the main lobe. So previously knowing the nonlinearity of frequency modulation of a chirp coherent laser radar is necessary for the system designation and the evaluation of the laser radar. Increasing modulation frequency and/or detecting short distance can relax the requirement of the nonlinearity.

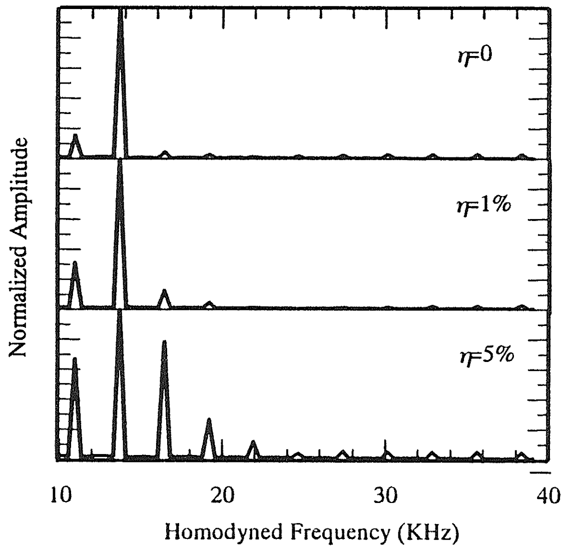

Fig. 2 Computed homodyne spectrum with the nonlinearity of frequency modulation η at 0, 1% and 5%

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