All Fiber Coherent Doppler Lidar for Space Craft Safe Landing

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***Abstract*—Recent advances in fiber optic component technology and digital processing components have enabled the development of a new coherent doppler lidar (CDL) system based upon a fiber optic FMCW, which has small size and light weight. CDL can give high precision velocity measurements data and range measurements data which support space craft safe landing. We designed and implemented a CDL of all-fiber structure in this article. First of all, FMCW ranging theory was described. Second, the CDL architecture of the system was discussed. Last , we introduced radar fiber Coupling and signal processor part, which include signal acquisition hardware, signal processing of dedicated FFT based on FPGA. The experimental program and experimental results were presented in the paper. We analyzed the experimental results carefully. From the results, the project has the advantage of large velocimetry range (-100m/S~+100m/S) and high velocimetry accuracy (0.5%). It completely meted the requirement of Space Craft Safe Landing.**

Keywords: coherent detection Lidar Doppler Speed measureformatting;

I. INTRODUCTION

Coherent doppler lidar has been widely used in the 1960s [1] [2], which can be used to measured range, speed of moving targets, wind speed and vibrations. The performance of the coherent radar has advantages compared to the direct detection radar. It has strong anti-jamming capability, high detection sensitivity and access to large amount of information, which are important direction of future development of lidar.

The structure of coherent doppler lidar is complex and bulky, which limited its application before the year of 2000. With the development of laser technology, in particular, the tunable diode laser technology, which leads to coherent laser radar can be realized compact in size. Master oscillator power-amplifier (MOPA) structure of the coherent light source has frequency modulation function in distributed feedback semiconductor (DBF) lasers and erbium doped fiber amplifier (EDFA), which is a new type emission source of coherent radar. The emergence of the source caused coherent laser radar technology innovation, which made it possible to achieve frequency modulation continuous wave coherent doppler lidar[3].

We introduced Structural theory and key technologies of frequency modulated continuous wave coherent doppler lidar in detail and experimental results are presented in this paper.

II. THE STRUCTURE AND PRINCIPLE

The frequency modulated（FM） continuous wave CDL block diagram shown in Figure 1.

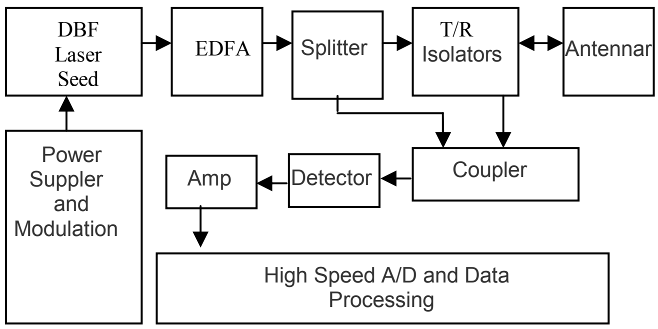

Figure 1 FM continuous wave CDL block diagram

In Figure 1, distributed feedback semiconductor laser seed source is driven by the laser power and modulation circuit . Seed source laser modulated by frequency is amplified by the erbium-doped fiber amplifier and is transformed into 1W single-frequency modulated laser. Beam splitter divides the laser into two beams, one beam pass through the transceiver isolators to the common aperture optical antenna radiation to detect the target, the echo signal reflected from the target reach the coupler finally by antenna transceiver isolator; another beam is local oscillator laser. The local oscillator laser and signal laser be merged into a beam of laser in couplers and the detector output signal enters by the amplifier into a high-speed data acquisition and data processing unit, then after computing gets the target speed.

Set the frequency of the signal beam and reference beam for and, the electric field intensity that beam reaches the cathode surface of beam detector are as follows:

$$E_1 = E_{01}\cos(2\pi f_{sig} + \phi_1) \quad (1)$$

$$E_2 = E_{02}\cos(2\pi f_{ref} + \phi_2) \quad (2)$$

In the above formula, and were respectively the amplitude of the two beams on the photocathode surface. And were the initial phase of the two beams. The two beams mixing on the photocathode surface, the synthetic electric field intensity as follows:

$$E = E_1 + E_2 = E_{01}\cos(2\pi f_{sig} + \phi_1) + E_{02}\cos(2\pi f_{ref} + \phi_2) \quad (3)$$

Proportional to the square of the electric field intensity of the beam and intensity of beam:

In the above formula, k is a constant, ϕ is the difference of initial phase of the two beams. The first is DC component which can be isolated in capacitor, and the second is the AC component in which $f_{if} = f_{sig} - f_{ref}$ is the detector output of the IF.

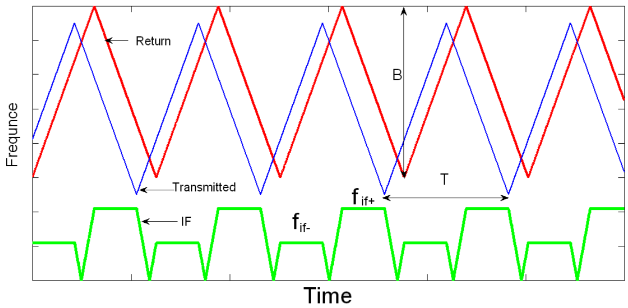

Figure 2. FM continuous wave CDL frequency domain Trasmitted,return and IF waveforms.

Shown in Figure 2, the laser Transmitted by the system is linear FM wave and the echo is also a linear FM wave. Signal beam relative to the reference optical frequency maxima and minima in the delay of the time of the horizontal axis reflects the distance of the target, the difference in the frequency of the vertical axis reflects the movement speed and direction of the target .According to Figure 2, it is easy to get the following equations:

$$f_{if-} = |f_R - f_d| \quad (4)$$

$$f_{if+} = |f_R + f_d| \quad (5)$$

According to (4) and (5) can be obtained:

If $|f_D| < f_R$ then:

$$f_R = \frac{f_{if+} + f_{if-}}{2} \quad (6)$$

$$f_D = \frac{f_{if+} - f_{if-}}{2} \quad (7)$$

If $|f_D| > f_R$ then:

$$f_R = \frac{|f_{if+} - f_{if-}|}{2} \quad (8)$$

$$f_D = \begin{cases} \frac{f_{if+} + f_{if-}}{2} (当 f_{if+} > f_{if-}) \\ -(\frac{f_{if+} + f_{if-}}{2})(当 f_{if+} < f_{if-}) \end{cases} \quad (9)$$

The distance and speed of the target can be obtained according to the following equation (8) and (9):

$$R = \frac{Cf_R * T}{4B} \quad (10)$$

$$v = \frac{\lambda}{2} \bullet f_D \quad (11)$$

III. key technology

A. Fiber coupling technology

The signal of FM continuous wave CDL detect is beam of reflected scattered laser by target. Detection system with the optical path is different from common detection system, the target scattered light is not directly from the lens converging to the detector, but conferencing to the fiber end. The interface technology of space light and fiber is one of the key technologies in the system. The signal received from FM continuous wave coherent laser speed radar is often very weak, about 10^{-13}W, so the key of coupling the space light and fiber is the coupling efficiency. Only as far as possible to improve the coupling efficiency from echo to the fiber can achieve the far distance.

. The signal beam coupled into the fiber is the same with the local oscillator light, the electromagnetic field distribution on the optical fiber end face is zero-order Bessel function, for the convenience of calculation using the Gaussian distribution to approximate [4].

$$A_1(r) = A_s(r) \approx e^{-(\frac{r}{r_0})^2} \quad (12)$$

r is the radial distance from any point of the fiber end face to the center, r_0 is the mode field radius of the base mode. The most important conditions to achieve efficient coupling of single-mode optical fiber is to meet the matching of the mode field. In the mode field matching conditions, the laser sent by the output fiber of FM continuous wave coherent laser speed radar is the same with echo wave light field distribution (amplitude and phase) of Incident optical fiber of lens focus to obtain the highest coupling efficiency. The light coupling efficiency depends on the match of the signal light in front of the wave of the focal plane and the core of the fundamental mode. The percentage of the energy of the coupling incident optical fiber as follows:

$$\rho = \frac{|\iint A_1(r) M^*(r) d^2 r|^2}{\iint A_1(r) A_1^*(r) d^2 r \bullet \iint M(r) M^*(r) d^2 r} \quad (13)$$

In the above formula, M(r) is the plane wave electromagnetic field distribution in the focus of receiving lens. From (14) and (15) can get[5]:

$$\rho(\alpha) = 2[\frac{e^{-\alpha^2}(1 - e^{-\alpha^2})}{\alpha}]^2 \quad (14)$$

Among:

$$\alpha = \frac{\pi}{2} \frac{d}{f} \frac{\omega_0}{\lambda} \quad (15)$$

In the above formula, d and f, respectively, are the diameter and focallength of the coupling lens. When α = 1.121, ρ up to 81.45%.Through the design of appropriate parameters of the lens, making the Airy spot field focused by echo is nearly the same with the fiber end mode field. At this point, d/f = 0.213 for the coupling system of 1.55μm . For this parameter, we have designed Cassegrain same aperture transmitting and receiving optical antenna, as shown in Figure 3.

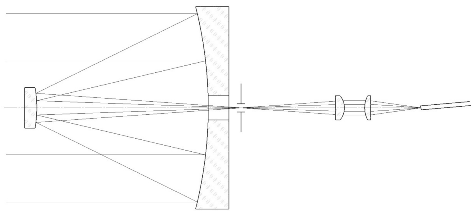

Figure 3 Efficient fiber-coupled optical antennas

B. high-speed data acquisition and processing technology

In the CDL, the output signal from the detector is amplified, pre-processed by low-pass filter and converted to digital signal by the AD converter, and then is processed by the fast Fourier transform (FFT, Fast Fourier Transforms) to improve the adaptability of noise and signal processing speed and, ultimately, we get the frequency of the spectral peaks.

According to the principle mentioned by the previous section, assume that the target velocity is 100m/s and the maximum signal frequency deteceted by the front-end detector is set to 129MHz, so in accordance with the Nyquist sampling theorem, the system sampling frequency is required at least 258MHz. Generally the sample rate is required four times maximum signal frequency for engineering applications in order to get the real signal. So the system selects an AD chip that has sampling frequency of 550MHz, 10bit resolution equivalent to 9.1 bit. This fully satisfies the system application. In addition, the system also uses a high-stability clock generator and low-noise front-end analog amplifier to improve signal to noise ratio. The high-speed data acquisition and processing system is shown in Figure 4

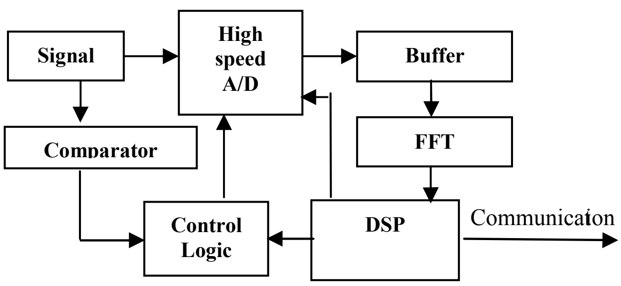

Figure 4 High-speed data acquisition and processing system

We use the fast Fourier transform to process the data. Frequency range and resolution of the FFT on the frequency axis (x axis) depends on the sampling rate and data record length (sampling points). The frequency points or lines in the power spectra is N / 2, N is the number of points contained in the signal sampling records. All the frequency interval is consistent. This interval is often called the frequency resolution or FFT resolution determined by the following formula:

$$F_R = \frac{F_{Sample}}{N} = \frac{1}{N \bullet t_{Sample}} \qquad (16)$$

Doppler data contains the information that is the average speed in T (the length of time) and the number of sampling points is:

$$N = T * F_{Sample} \qquad (17)$$

According to (16) and (17) , in the case of Doppler velocimetry within 1ms and the data sampling rate of 550MHz, the FFT method can obtain power spectrum with 0 to 225MHz range and 1kHz resolution. That is able to mesure the speed from -100m/S to 100m/S and the accuracy can be up to 0.1%.

High-speed A/D part consists of front-end anti-aliasing filter, variable gain amplifier, low-jitter clock and high-speed analog to digital IC, shown in Figure 5.

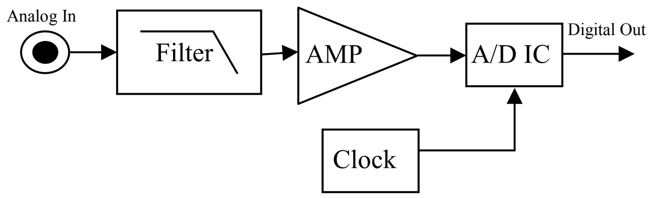

Figure 5 High-speed A/D part Schematic.

In high-speed A/D part,the jitter of clock is very important for system signal to noise ratio. Clock jitter will be converted to the white noise of the signal jitter by the jitter of the ADC itself and acquisition jitter of the clock generator, the respective RMS re-composition of the total jitter RMS:

$$Jitter_{Total} = \sqrt{(Jitter_{ADC})^2 + (Jitter_{clock})^2} \qquad (18)$$

The SNR contribution of total jitter is

$$SNR_{Jitter} = 20\log_{10}[\frac{1}{2\pi f_{in} jitter_{total}}] \qquad (19)$$

The ADC jitter is 350fS, if clock jitter is 500fs,so we can get

$$SNR_{Jitter} = 66dB .$$

We controled clock jitter less than 500ps, to ensure that the SNR will be greater than 66dB when other factors not considered. In this project, we used ultra-low noise amplifier, the input votage noise is 1.1nV/√Hz. High-speed A/D part achieved 550MHz sampling rate and SNR greater than 59dB.

FFT is completed by the large scale FPGA. We have adopted a parallel computing structure.Spent a total of 512 multipliers in FPGA. By the test, 32K point FFT actual computation time of 212μS. DSP can find f_{if+} and f_{if-} in data FFT results and compute the target speed.

IV. Experimental Results

In order to test the performance of the FM continuous wave CDL, we use a rotating flywheel to build the experimental platform. Then we use a tunable laser that can control the frequency difference of laser, aiming at the edge of the flywheel that has some known speed. The reflected signal light and a local oscillator light are coupled into an optical fiber and received by the detector. Finally, the signal is sampled and processed by some algorithms to compute the line speed of the flywheel. Flywheel with high-precision servo motor driving and shaft angle encoder calibrating, the relative accuracy of 0.1%.The signal waveform is shown in Figure 6. The experimental results are shown in Figure 7 and Table 1. By comparison of different speed settings of the flywheel and the actual measurement value, the signal processing system is able to get the correct measurement results.

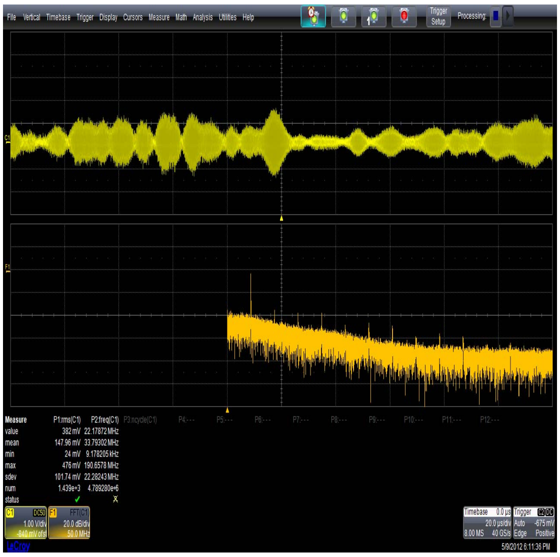

Figure 6 test waveform (top) and FFT results (under)

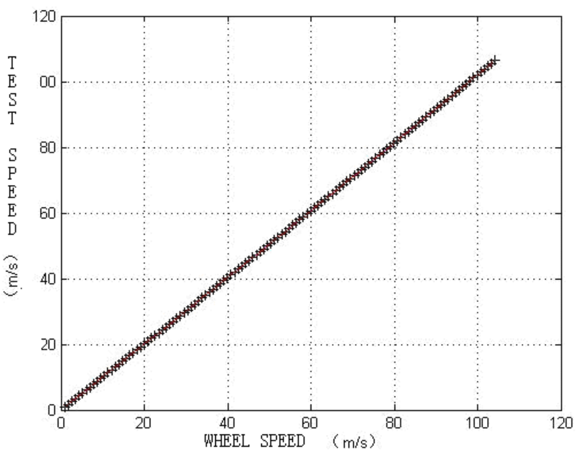

Figure 7 Test data

Table 1 Test data

No.	Speed 1 (m/S)	Speed 2 (m/S)	Speed 3 (m/S)	Speed 4 (m/S)	Speed 5 (m/S)
1	1.741	21.783	30.398	39.183	49.705
2	1.7483	21.923	30.521	39.521	49.929
3	1.7441	21.762	30.475	39.231	49.670
4	1.7358	21.814	30.329	39.342	49.611
5	1.7476	21.806	30.559	39.402	49.917
Variance	0.0051	0.0625	0.0936	0.1351	0.1471

No.	Speed 6 (m/S)	Speed 7 (m/S)	Speed 8 (m/S)	Speed 9 (m/S)	Speed 10 (m/S)
1	63.401	70.48	82.639	91.293	106.22
2	63.358	70.413	82.876	91.802	106.107
3	63.674	70.163	82.476	91.261	105.649
4	63.59	70.713	82.574	91.619	105.792
5	63.579	70.546	82.308	91.047	105.363
Variance	0.1347	0.2015	0.2094	0.3020	0.3466

V. Conclusion

The FM continuous wave CDL has character of high precision and high dynamic range, from a few centimeters per second to a few hundred meters per second can be accurately measured. The CDL can accurately distinguish between the speed of the positive and negative polarity. So the CDL can be used for space craft safe landing, autonomous navigation, and other fields.

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