Non-linear frequency correction in frequency modulated continuous wave LADAR based on an optical frequency comb

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Abstract. Frequency modulated continuous wave (FMCW) LADAR has the advantages of non-contact, absolute distance measurement and no measuring blind area. However, the ranging precision often decreased because of the nonlinearity of tunable laser. In order to solve this problem, the method of the equispaced optical frequency non-linear frequency correction approach based on an optical frequency comb was proposed. Based on this method, we have constructed two sets of interference systems and obtained the ranging signal $f_0$ and heterodyne beat frequency signal $f_{\text{beat}}$ successfully.

1. Introduction

Recently, Laser Ranging and Detection (LADAR) has been widely used in the field of aerospace, automobile and other manufacture industry. Among many approaches, the frequency-modulated continuous wave (FMCW) LADAR is one of the best ways to achieve high precision absolute distance measurement in dozens of meters. Coherent detection of the beat frequency between the measuring and the reference laser is used to deduce the absolute distance with the resolution below 100 μm and the accuracy below 1 μm. The laser used in FMCW LADAR is often modulated linearly or sinusoidally.

Due to the frequency-tuning fluctuation, the noise in the modulator circuit and other reasons, the laser frequency can't be turned linearly and the beat frequency will be broadened. So the accuracy of FMCW LADAR will get worse. To improve the resolution and accuracy, the research of the FMCW LADAR is focused on two directions. One of the directions is to improve the performance of the laser, such as the linearity of frequency tuning, tuning bandwidth and linewidth. But due to the mode hop, the non-linearity of the control system and other reasons, the research has reached bottle neck. So some scientists turned to the other research direction, which is to correct the non-linearity of the laser frequency tuning.

The tunable laser is often compared with a fixed frequency laser to measure the non-linearity of the laser frequency by an interferometer [1]. But the performance is limited by the interferometer, in which the stability is hard to maintain. Iiyama proposed and demonstrated a linearizing method of optical frequency-sweep of a laser by use of a reference interferometer and an electric phase comparator [2]. The interference beat signal frequency of the reference interferometer is phase-compared with an external reference rectangular signal with a fixed frequency and the difference between them was used to control the laser frequency sweep to achieve the non-linearity frequency correction. This method needs the relative sophisticate control loop. In 1993, Glombitza demonstrated a principle, in which a broadened frequency due to the non-linearity swept frequency could be treated as one single frequency considering some negligible errors when the beat signal between the measuring and the reference light as the function of time was treated as the function of the swept frequency [3]. Based on this principle, several different approaches were proposed. Baumann demonstrated a comb-calibrated FMCW LADAR with the 130 μm resolution and a ~100 nm accuracy, in which a free-running frequency comb was used to measure the swept laser frequency and then the ranging signal was resampled [4]. Guang Shi proposed an equispaced-frequency resampling nonlinearity correction method, in which the extreme points of the beat signal between the reference laser and the delay reference laser were applied as the resample signal. This method didn't need to measure the absolute frequency and was easy to realize resample. But the number of the resample points was limited by the length of the delay fiber.

Here we demonstrated a new equispaced optical frequency resampling method for nonlinear correction, in which an assistant interferometer based on a free-running frequency comb and a frequency-swept laser was built and the points where the heterodyne frequency $f_{\text{beat}}=f_0/2$ were
used to resample the ranging signal. With the advantages of the high repetition rate, perfect
equidistant tooth spacing and traceability to the rf-standard, the frequency comb was used to
realize a perfect nonlinear frequency correction based on the equispaced optical frequency
resampling.

2. Non-linear frequency correction approach

FMCW LADAR is often based on the time-of-flight principle and the laser frequency was driven by
a triangular wave. The distance R between the measured object and the reference mirror can be
expressed as [5]:

\[ R = \frac{Tc}{4B} f_0 \]

(1)

Where T is the swept period of the tunable laser and B is the frequency tuning range. c is the speed
of the light in vacuum. \( f_0 \) is the frequency of the ranging signal between the reference and the
measured laser beam. The heterodyne voltage \( V_{LADAR}(t) \) of the ranging signal can be written as
[6]:

\[ V_{LADAR}(t) \propto \cos[\varphi(t) - \varphi(t - \tau)] = \cos[2\pi f_1 (t - \tau/2)] \]

(2)

Where \( \tau \) is the time delay to the local reference and the return signal and \( f_1(t) \) is the frequency of
the tunable laser. If the \( f_1(t) \) is ideally linear sweep, \( f_0 \) will be a constant through a Fourier
transform with respect to time of \( V_{LADAR}(t) \). Then we will get an exact distance R. But for many
reasons, the frequency sweep is not linear and the corresponding linewidth of \( f_0 \) will be broadened
[5].

Here we regard the \( V_{LADAR}(t) \) as a function of frequency \( f_1(t) \) rather than time. So the Fourier
transform will be an impulse function and the constant \( f_0 \) will be got again when the higher-order
terms of the Taylor expansion in the phase are ignored [3].

\[ V_{LADAR}(f_1) \propto \cos[2\pi f_1(t) \tau] = \sum_{n=0}^{N} \cos(2\pi f_1) \delta(f_1 - n\Delta f_1) \]

(3)

Where \( k = 2f_1(t_B)\tau \) and \( t_B \) is the time to start the sampling. \( N = 2f_1(t_B)\tau \), and \( t_E \) is the time to
end the sampling. \( \delta(f_1 - n\Delta f_1) \) is an impulse function.

\[ \delta(f_1 - n\Delta f_1) = \begin{cases} 
1 & f_1 = n\Delta f_1 \\
0 & f_1 \neq n\Delta f_1 
\end{cases} \]

(4)

From the formula 3, we can see that the transformed ranging signal was an ideal cosine signal,
which eliminates the influence of modulation nonlinearity and improves the resolution of
measurement. Based on this principle, the key to this approach is to obtain the resample signal
\( V_{LADAR}(f_1) \) and equispaced optical frequency(\( \Delta f_1 \)) points. The \( f_1(t) \) of tunable laser can be directly
measured by interferometer with optical comb [6]. This approach has direct traceability to the rf
but needs relative sophisticated signal processing system. One smart idea is to identify the extreme
point of the beat frequency signal from an assistant interferometer in which the reference tunable
laser is delayed by a section of fiber and then interfered with itself [7]. The time of the extreme
point is used as the resample signal to rebuild \( V_{LADAR}(f_1) \). But due to the length limitation of the
time-delay fiber, the resample rate is often just over a few times of the \( f_0 \). The accuracy would be
influenced because of a lack of the resample points and the environmental effect.

Here we use the optical frequency comb instead of the time-delay fiber to build an assistant
interferometer. Through this interferometer, \( f_1(t) \) is sweep across the comb teeth and the
heterodyne frequency signal \( f_{comb} \) is recorded simultaneously with the ranging signal. When the
\( f_{comb} \) equal to half of the repetition frequency \( f_{rep} \) of the comb, we resampling the ranging signal
\( V_{LADAR}(f_1) \), that is to say that \( \Delta f_1 = f_{rep}/2 \). Because the \( f_{rep} \) of the optical comb has perfect stability
and traceability to an rf-standard, we can get sufficient resample points to rebuild \( V_{LADAR}(f_1) \),
accurately.
3. Experiment setup and results

The schematic diagram of the experiment setup is shown in figure 1, consists of an optical frequency comb, a frequency modulated continuous-wave FMCW laser, two sets of interferometer, a high-speed acquisition card HSAC and so on.

The FMCW laser was a microelectromechanical systems based external cavity diode laser centered around 192 THz (1560 nm). This laser was swept triangularly over a bandwidth $B = 1.25$ THz/s. The optical frequency comb was a free-running, all polarization-maintaining 81.2 MHz Er-doped fiber oscillator, which mode-locked by a semiconductor saturable absorption mirror SESAM. The 3 dB bandwidth of mode-locked pulses was 9.8 nm with the central wavelength of 1560 nm. The average output power of mode-locked pulses was 2.5 mW with 120 mW of pump power. The FMCW laser was divided into two beams by a polarization beam splitter PBS. By adjusting a half-wave plate $\lambda/2$ at the front end of the PBS, about 80% (~20 mW) of the tunable laser was guided into the measuring interferometer. The remaining 20% (~5 mW) were launched into the assistant interferometer, combined with the output of the optical frequency comb. The interference signals from the assistant interferometer and the measuring interferometer were received by two avalanche photodiodes APD of the same type. The detected interference signals were synchronously sampled by the HSAC with a maximum sampling rate of 250 Ms/s. Finally, two interference signals were processed offline by a computer.

The measuring interferometer, a typical Mach-Zehnder type interferometer, was used to detect the ranging signal. The input tunable CW laser also was divided into two routes and then injected into the reference arm and measuring arm, respectively. The optical path of measuring arm was 3.5 meters longer than the reference arm through a pair of high reflector mirrors, corresponding to $f_0$ is about 15 kHz. The polarization of the laser beam was optimized by rotating half wave-plates in each route, and the two laser beams were then combined by a PBS. Adjusting the pitch of the optical mounts and rotating wave-plates carefully, the ranging signal was measured by a frequency spectrum analyser. As shown in figure 2(a), the signal-to-noise ratio SNR of the ranging signal was about 20 dB with a resolution bandwidth (RBW) of 100 Hz. Since the precision of a
FMCW LADAR was limited by the SNR of ranging signal, we must improve the SNR of ranging signal [6]. One feasible method is to replace the APD with a photoelectric balance detector. In addition, we can see from the figure 2(a) that because of the modulation nonlinearity of FMCW laser, the linewidth of the range signal was broadened significantly. The time-domain sequence diagram of the ranging signal was shown in the figure 2(b).

The assistant interferometer, also a typical Mach-Zehnder type interferometer, was used to measure the heterodyne frequency signal $f_{\text{beat}}$. By optimizing the polarization of two beams, the $f_{\text{beat}}$ signal was detected, as shown in figure 3(a). Because of the weak energy per tooth of the optical frequency comb, the maximum SNR of $f_{\text{beat}}$ signal was only about 12 dB, which will affect subsequent data processing. However, we believed that the SNR of $f_{\text{beat}}$ signal can be increased to over 30 dB by amplifying the energy of each tooth. The time domain sequence diagram of the signal was shown in figure 3(b). In the next work, we will go to increase the SNR of ranging signal and $f_{\text{beat}}$ signal and perform Fourier transform processing of the $f_{\text{beat}}$ signal to obtain the resampling points.

4. Conclusion
In summary, we have presented an equispaced optical frequency non-linear frequency correction approach based on an optical comb to improve the measure resolution of FMCW LADAR. The time points of the $f_{\text{beat}}$ equal to $f_{\text{rep}}/2$ of the comb were used to resample the ranging signal $V_{\text{LADAR}}(f_1)$. The reconstructed signal was an ideal cosine signal, which eliminates the influence of modulation nonlinearity and improves the resolution of measurement. This method is more convenient because it does not have to measure the frequency of CW laser directly, and has a wide application prospect in the field of large-scale precision measurement, such as major equipment manufacturing, space detection and so on. Besides, we demonstrate a ranging system, and have detected the ranging signal and the beat signal. Follow-up experiments will be reported in subsequent papers.

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