Linearizing Optical Frequency Chirp of a Laser Diode for Accurate FMCW Optical Ranging

Linearizing optical frequency chirp of a laser diode for accurate FMCW optical ranging

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***Abstract*—Optical frequency chirp of an external-cavity laser is linearized by optimizing the modulation waveform for long-range FMCW optical ranging system. The modulation signal of the laser is sampled with the interference signal of the auxiliary interferometer, and the sampled modulation signal is used as a new modulation signal. As a result, the optical frequency is linearly chirped. The linearization is realized at 50 kHz modulation frequency and the measurement range of up to 66 m optical fiber and up to 10 m in free space. The linearity of the optical frequency chirp is evaluated by the ranging resolution and the ranging accuracy of the FMCW optical ranging system, and the ranging resolution is almost the theoretical limit, indicating that the optical frequency of the laser is highly linearly chirped.**

***Index Terms*—FMCW optical ranging system, LiDAR, Optical frequency chirp, Laser modulation**

I. Introduction

Optical ranging systems have been widely used for land survey, medical diagnosis [1], [2], object profiling, optical fiber and waveguide diagnosis [3]–[5]. Although the ToF (Time of Flight) method is widely used for long-distance ranging, the FMCW (Frequency Modulated Continuous Wave) optical ranging system is also attracting attention for object profiling [6]–[8] and long-distance ranging [9]. Figure 1 shows the basic configuration of the FMCW optical ranging system. A laser diode is usually used as the laser source, and the optical frequency of the laser is chirped by modulating the injection current of the laser with a symmetric triangular wave. Figure 2 shows the instantaneous optical frequency of the reference light and the signal light reflected from the target, where f_m is the modulation frequency and $\tau = 2nL/c$ is the delay time of the signal light with the distance to the target L, the refractive index n and the light speed in vacuum c. Since there is a frequency difference f_B between the reference light and the signal light reflected from the target as shown in Fig. 2, the interference signal between the two lights has the beat frequency given by f_B. The beat frequency f_B is given as;

$$f_B = \frac{4nf_m\Delta F}{c}L \tag{1}$$

where ΔF is the optical frequency chirp range. The ranging resolution δL is usually defined as [7], [10];

$$\delta L = \frac{c}{2n\Delta F}. \tag{2}$$

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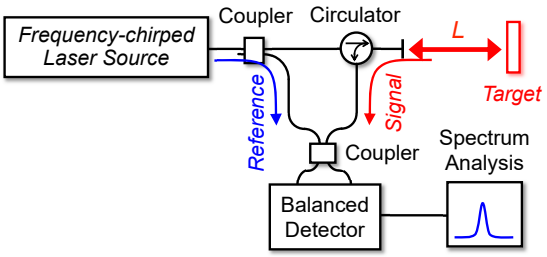

Fig. 1. Basic configuration of FMCW optical ranging system.

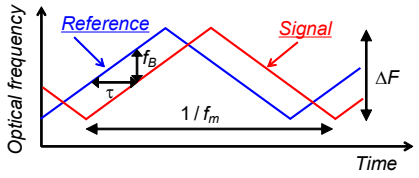

Fig. 2. Instantaneous optical frequency of reference and signal lights.

When the optical frequency of the laser is chirped by the injection current modulation with a triangular signal, the optical frequency is nonlinearly chirped due to response delay of the optical frequency change against the injection current change of the laser, and the ranging performance is seriously degraded [11]. To enhance the ranging performance, the k-sampling method has been demonstrated to eliminate the influence of the nonlinearity in the optical frequency chirp [7], [12]. In the k-sampling method, an auxiliary interferometer is configured and the ranging interference signal is sampled with the auxiliary interference signal, and the ranging performance is highly enhanced. However, a long fiber delay line, typically more than 500 m, is needed in the auxiliary interferometer for long-distance ranging to satisfy the Sampling theorem.

Linearization of the optical frequency chirp is also attractive method to enhance the ranging performance for long-distance ranging. The modulation signal for the optical frequency chirp is distorted so that the beat frequency of the auxiliary interference signal is constant in time. The proposed linearization methods are the optical and electrical phase-locked loop (OE-PLL) [13] and the iterative learning pre-distortion of the modulation waveform [14], and the optical frequency can be successfully linearized in both the methods. However in the OE-PLL, the lock range and the loop filter should be carefully designed to cover the beat frequency fluctuation, and the reported modulation frequency is 1 kHz. For the iterative learning pre-distortion, the reported modulation frequency is 4 kHz and the time to complete the iteration is 10 min.

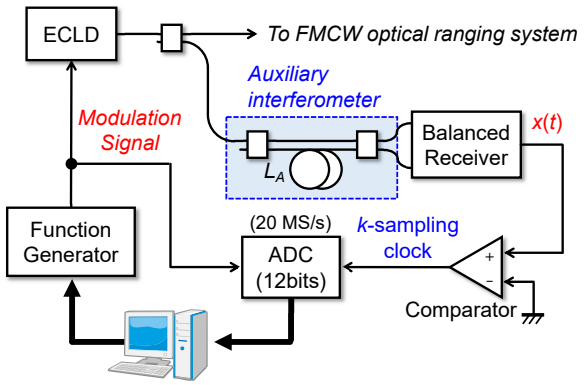

Fig. 3. System configuration for modulation waveform modification.

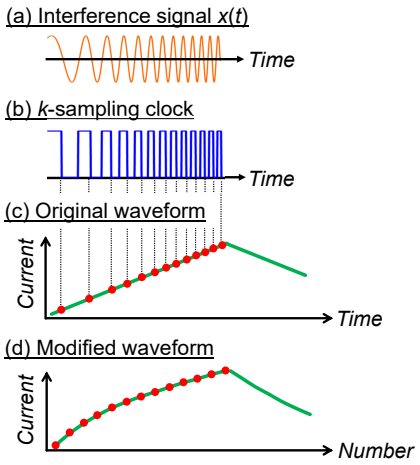

Fig. 4. Schematic procedure of modulation waveform optimization using k-sampling method.

Here we demonstrate linearization of the optical frequency chirp of a laser diode by modulation waveform optimization using the k-sampling method. The modulation frequency is increased up to 50 kHz and the time to complete the optimization is only a few seconds, and the ranging performance up to 66 m in fiber and up to 10 m in free space is discussed.

II. Procedure of Modulation Waveform Optimization for Linear Optical Frequency Chirp

Figure 3 shows the experimental setup. An external-cavity laser diode (ECLD) emitting at 1550 nm wavelength (Thorlabs, SFL1550S) is used as the laser source, and the injection current is modulated by the function generator (Agilent Technologies, 33522B) with a symmetric triangular waveform at a frequency of 50 kHz. The bias current is 140 mA and the modulation current amplitude is 120 $mA_{p\text{-}p}$. The measured spectral linewidth of the ECLD is about 200 kHz. A part of the laser light is coupled to the auxiliary interferometer with the differential fiber length $L_A = 15$ m, showing the free spectral range $\mathrm{FSR} = c/(nL_A) = 13.65$ MHz, where n is the refractive index of the optical fiber, and the interference signal is detected by the balanced receiver (Thorlabs, PDB150C).

Figure 4 shows the schematic procedure of the modulation waveform optimization using the k-sampling method. Due to the nonlinear optical frequency chirp of the ECLD, the beat frequency of the interference signal $x(t)$ is varied in time as shown in Fig. 4(a). The beat frequency is low just after the turning point of the modulation signal, and is gradually increased. The interference signal $x(t)$ is converted to the k-sampling clock by the comparator as shown in Fig. 4(b), and the modulation signal is sampled by the AD converter (ADC: Measurement Computing, USB-2020) using the k-sampling clock as shown in Fig. 4(c). The sampling interval is also varied according to the beat frequency fluctuation. The modulation signal is sparsely sampled just after the turning point of the modulation signal, and is gradually densely sampled. The sampled data are evenly arranged to form a new modulation signal. As a result, the modified modulation waveform is slightly curved as shown in Fig. 4(d). The modified modulation waveform data are then transferred to the function generator and are used as a new modulation signal. By repeating the process, the modulation waveform is optimized, and the optical frequency chirp of the ECLD is linearized.

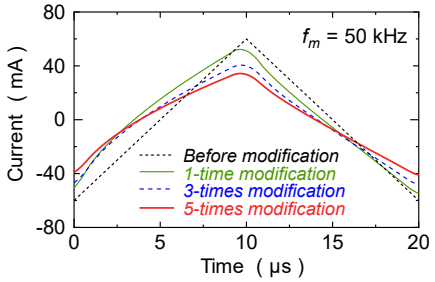

Fig. 5. Modulation waveform modified by proposed method.

Figure 5 is the modified modulation waveform by the proposed method. The modified modulation signal is curved as illustrated in Fig. 4(d). The number of sampled modulation waveform data in one period of the modulation signal is $300 \sim 400$ points, depending on the modification time. The number of the sampled data is limited by the bandwidth of the ADC. The sampled waveform data are smoothed by moving average with 8% averaging window to reduce the quantum error of the ADC. Due to the small number of the sampled data and the moving average, the amplitude of the modulation signal is decreased with the modification.

III. Demonstration of Optical Frequency Chirp Linearization

To confirm the linearity of the optical frequency chirp, the full-width at half maximum (FWHM) of the beat spectrum and the ranging accuracy are measured. The experimental setup is shown in Fig. 6. The modulation waveform is optimized by the proposed method for the frequency of 50 kHz. The target is a single-mode optical fiber, and the interference signal between the reference light and the reflected light from the far end of the fibers is measured. The interference signal in the 90% of the increasing section of the modulation signal is sampled by the USB oscilloscope (ADC: Picoscope, 5244B), and the power beat spectrum is obtained by the FFT with the Hann window. The beat spectrum is slightly broadened

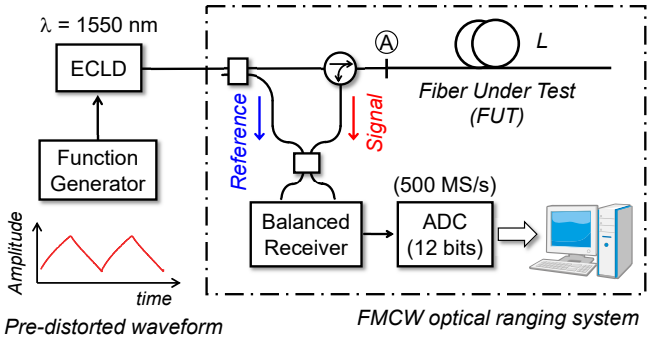

Fig. 6. Experimental setup for long-distance ranging using linearly optical frequency-chirped ECLD.

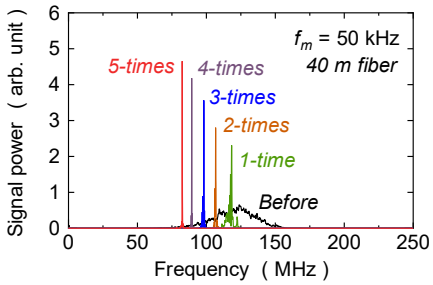

Fig. 7. Measured beat spectrum for 40 m-long optical fiber before and after modification.

due to the Hann window. The ranging resolution is evaluated from the FWHM of the power beat spectrum, and the FWHM, δL_{FWHM}, is given as;

$$\delta L_{\mathrm{FWHM}} = 1.44 \times \delta L = \frac{1.44\, c}{2n\Delta F}. \tag{3}$$

Figure 7 shows the beat spectrum for a 40 m-long optical fiber before and after modulation waveform modification. The beam spectrum becomes fine with repeating the modification, indicating that the linearity of the optical frequency chirp is improved with the modification. However the beat frequency is gradually decreased with the modification times due to the decreased modulation amplitude as shown in Fig. 5.

Figure 8 shows the FWHM (closed circles) and the ranging accuracy (closed squares) with the modification times. The ranging accuracy is defined by the standard deviation of 5000-times ranging for a 40 m-long optical fiber. The FWHM and the standard deviation are significantly improved by 2-times

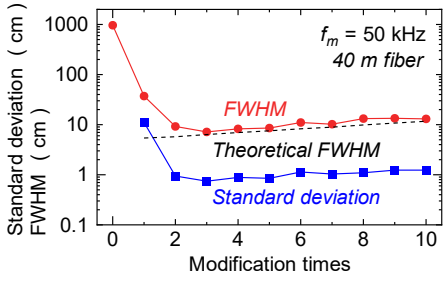

Fig. 8. Measured FWHM of the beat spectrum and standard deviation of beat frequency.

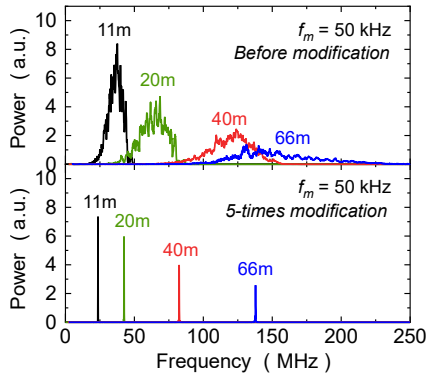

Fig. 9. Measured beat spectrum for various lengths of optical fiber before modification and after 5-times modification.

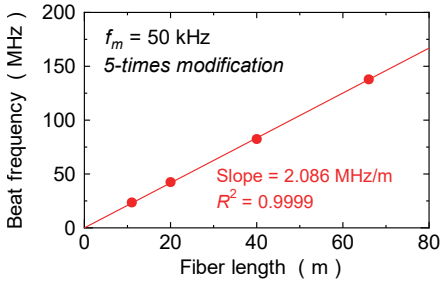

Fig. 10. Relation between beat frequency and optical fiber length after 5-times modification.

modification, and are minimum by 3-times modification. Then the FWHM and the standard deviation are slightly increased with the modification because the modulation amplitude is slightly decreased with the modification as shown in Fig. 5 and the resultant optical frequency chirp range ΔF is also slightly decreased with the modification. The dashed line is the theoretical FWHM calculated by eq. (3), where the optical frequency chirp range ΔF is given as $\Delta F = \mathrm{FSR} \times N/2$, where N the number of the sampled modulation waveform data. The experimental FWHM is almost the same with the theoretical FWHM after 3-times and more modification, indicating that the optical frequency is linearly chirped. Although the 3-times modification seems to be optimum because the FWHM and the standard deviation are minimum, there is a small side peak in the beat spectrum after 3-times modification as shown in Fig. 7. Hence the optimum modification time is 4-times or 5-times. The relative accuracy $(\text{standard deviation})/(\text{beat frequency})$ is 0.021% after 5-times modification. The process time for 5-times modification is only a few seconds.

Figure 9 shows the measured beat spectrum for various lengths of optical fiber before modification and after 5-times modification. The beat spectrum is significantly narrowed by 5-times modification, and the FWHM is narrowed. The result means that the optical frequency chirp is linearized. Figure 10 shows the relation between the measured beat frequency and the optical fiber length after 5-times modification. The beat frequency is proportional to the optical fiber length with the coefficient of determination $R^2 = 0.9999$.

Next, we measured the distance in free space. The target is a white panel, and the measured beat spectrum is shown

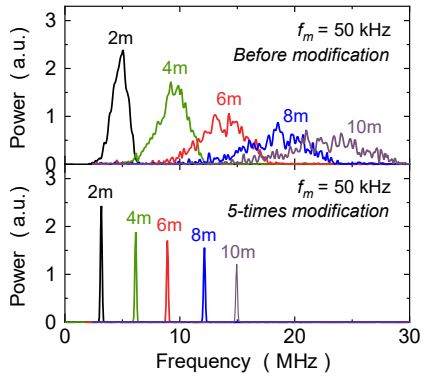

Fig. 11. Measured beat spectrum in free space before and after modification.

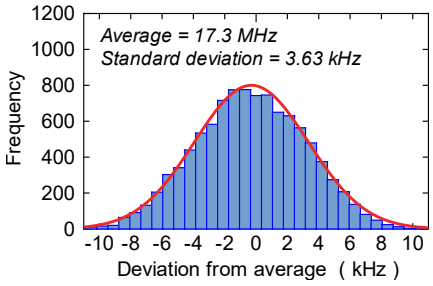

Fig. 12. Histgram of for 10000-times ranging for 10 m in free space after 5-times modification.

in Fig. 11. Although the distance is limited to 10 m due to the size of our laboratory, the beat spectrum after 5-times modification is significantly narrowed, and the FWHM after 5-times modification is 10 cm, which is almost the same as that shown in Fig. 8. The histogram for 10000-times ranging for 10 m after 5-times modification is shown in Fig. 12. The histogram is well described by the normal distribution (solid line) with the standard deviation of 3.63 kHz, which corresponds to 2.1 mm. Then the relative accuracy is 0.021%, which is the same as that for optical fibers.

Figure 13 shows the measured displacement for minute displacement around 8 m in free space after 5-times modification, where the distance to the white panel is mechanically changed using a manual translation stage. The beat frequency is measured 10000 times for each displacement, and the displacement is obtained from the beat frequency change. In Fig. 13, the closed circles are the averaged displacement and

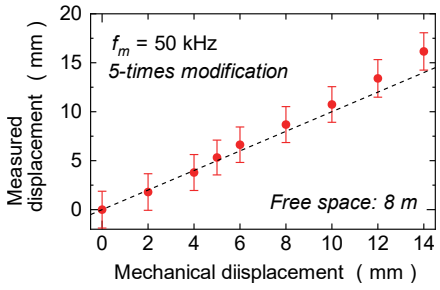

Fig. 13. Measured displacement for minute displacement around 8 m in free space after 5-times modification.

the error bars are the standard deviation, and the dashed line is the ideal relation. Although the measured displacement differs slightly from the dashed line due to the error in evaluating the beat frequency from the discrete beat spectrum, the measured displacement follows the mechanical displacement well.

IV. Conclusion

We have proposed and demonstrated linearization method of the optical frequency chirp of an ECLD for FMCW optical optical ranging system. The modulation signal for the optical frequency chirp is sampled with the auxiliary interference signal, and the sampled modulation signal is used as the new modulation signal. By repeating the process a few times, the modulation waveform is optimized and the optical frequency chirp is linearized. High resolution and high accuracy ranging results are demonstrated up to 66 m in optical fiber and up to 10 m in free space.

We can conclude that the proposed linearization method is very useful to realize high resolution and high accuracy long-range FMCW optical ranging system such as the FMCW LiDAR (Light Detection And Ranging).

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