Optimized design of laser range finding system using the self-mixing effect in a single-mode VCSEL

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An optimized design of laser range finding system using the self-mixing effect in a single-mode vertical-cavity surface-emitting laser (VCSEL) is proposed. In order to improve the ranging accuracy and expand dynamic measurement range, we apply difference frequency analog phase-locked loop (PLL) instead of fast Fourier transform (FFT) to process signal, and choose the optimum triangular wave frequency $f_{\rm m} = 500$ Hz and small modulation current $\Delta I_{\rm p-p} = 0.28$ mA to modulate single-mode VCSEL. The experiment results show that, without controlling the laser's temperature, the ranging accuracy is better than 2 mm and the measurement dynamic range is as large as 50—500 mm when the sampling time is 0.1 s and the room temperature is 0—55 °C.

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Range finding using the self-mixing effect in a laser has been well studied[1−3]. Compared with laser diode (LD), the single-mode vertical-cavity surface-emitting laser (VCSEL) has the advantages of single mode, circular beam shapes, lower threshold current, low power consumption, low cost, and so on, which make it suitable for a wide range of applications.

Generally, the emitting power of single-mode VCSEL is small (no more than 1 mW), and the backscattered light is extremely weak. The signal-to-noise ratio (SNR) of self-mixing photoelectric signal is low and the envelope modulation is severe. The accuracy using fast Fourier transform (FFT) to process such signal is not satisfiable. However, analog phase-locked loop (PLL) can improve ranging accuracy obviously for its good characteristics of tracking fundamental wave frequency, narrow band pass filtering, and high amplitude modulation (AM) rejection ratio[4]. But the lock-in range of normal analog PLL is only about $20\% f_0$, here f_0 is the center frequency of its voltage controlled oscillator (VCO), so the measurement dynamic range is very narrow. The difference frequency analog PLL has wide lock-in range which can expand the measurement range obviously. Both the frequency $f_{\rm m}$ and amplitude ΔI of modulation triangular wave current for VCSEL are important to the ranging accuracy, so it is necessary to optimize these parameters.

The self-mixing effect is firstly reported by Rudd[5]. It occurs when the light emitting from the laser hits a target and is reflected back into the laser cavity. This causes the periodic changes of laser light output frequency, linewidth, threshold gain, and output power, all of which relate to the phase of the backscatter laser light. We can utilize the standard internal power monitoring photodiode, which is built into the commercial LD package, to observe the output power regulation.

The LD is modulated by periodic triangular wave current, so the distance to the target $L_{\rm ext}$ can be obtained by calculating the number of differentiated power waveform sharp peaks in the modulation period, the relationship is formulated as[6]

$$L_{\rm ext} = \frac{c}{2\Omega m p_{\rm avg}} = \frac{c}{2\Omega m} \cdot f_{\rm avg}, \qquad (1)$$

where c is the velocity of light, Ω represents the frequency modulation coefficient in GHz/mA, m is the slope of the modulation triangular wave current in mA/s, $p_{\rm avg}$ is the overall average spacing between consecutive peaks of the self-mixing beat signal, $f_{\rm avg}$ is the average frequency of beat signal, and $f_{\rm avg} = 1/p_{\rm avg}$. The following equation can be used to calculate $f_{\rm avg}$ in experiment

$$f_{\rm avg} = \frac{N_{T_{\rm m}}}{T_{\rm m}} = N_{T_{\rm m}} f_{\rm m}, \qquad (2)$$

where $T_{\rm m}$ and $f_{\rm m}$ are the period and frequency of modulation triangular wave respectively, $N_{T_{\rm m}}$ represents the number of the best signal waveforms corresponding to $T_{\rm m}$.

Figure 1 shows the self-mixing beat signal and modulation triangular waveforms of a single-mode VCSEL. As shown in the figure, there are several evident problems in the beat signal. Firstly, the signal envelope modulation is severe, and sometimes the AM coefficient is near 1; secondly, there are obvious interferences in the beat

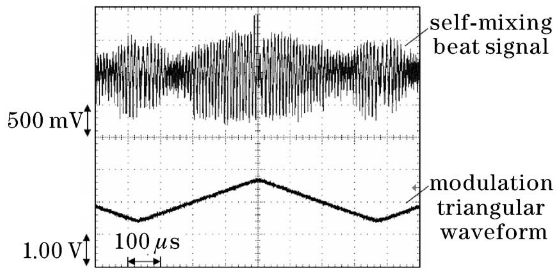

Fig. 1. The self-mixing beat signal and modulation triangular waveforms of a single-mode VCSEL with laser operating current $I = 8$ mA, optical frequency excursion $\Delta f = \pm 29$ GHz, $f_{\rm m} = 1.3$ kHz, $L_{\rm ext} = 100$ mm.

signal and the SNR is extremely low; thirdly, the beat signal, which is not ideal sine wave, has apparent distortion; fourthly, the periods of each beat signal waveform corresponding to the rising edge (or falling edge) of the triangular wave are not equal surely, because the modulation coefficient $\Delta\lambda/\Delta I$ for VCSEL is not ideally linear, here $\Delta\lambda$ is the laser's modulation wavelength excursion; finally, there are abrupt phase changes in the beat signal corresponding to the inflection points of the triangular wave.

Based on the characteristics of beat signal mentioned above, not only the signal processing becomes more difficult but also the ranging accuracy and dynamic range are severely influenced. We optimize the design of range finding system as follows.

Firstly, we use the difference frequency analog PLL in place of the FFT to process signal. According to Eq. (1), the measuring accuracy of $f_{\rm avg}$ directly determines the ranging accuracy, so improving the measuring accuracy of $f_{\rm avg}$ is important to the ranging accuracy. When we use frequency counter to count the number of beat signal waveforms between the adjoining phase abrupt points for obtaining $p_{\rm avg}$ and $f_{\rm avg}$, the existence of phase abrupt point is the key point in relation to measurement error of $p_{\rm avg}$ and $f_{\rm avg}$. FFT is a kind of method to process signal[2], but evident envelope exists in the beat signal, so the result using FFT to process beat signal is not satisfiable. When the measurement range is 50—500 mm, the ranging accuracy is 8 mm using FFT method.

Analog PLL can obviously improve the measurement accuracy of $f_{\rm avg}$. The measurement range of normal analog PLL is limited in $(1\pm20\%)$ $L_{\rm ext}$ according to the 20% of lock-in range. The difference frequency analog PLL can expand the measurement range of system. The application specification integrated circuit (ASIC) KD080H is a kind of difference frequency analog PLL, which is designed by Prof. Tianpeng Zhao and produced by Microelectronic Laboratory of the University of Science and Technology of China. Its lock-in range is as large as 2 kHz — 1 MHz, AM rejection ratio is better than 40 dB, phase detection sensitivity $K_{\rm d}$ is about 1 V/rad, and voltage controlled sensitivity is about $1.1f_0$ Hz/V. Figure 2 shows the waveforms of beat signal near its phase abrupt point and the beat signal waveforms processed by KD080H. The output signal of KD080H becomes equal amplitude square wave whose SNR is enhanced, and the abrupt phase change influence is decreased. As a result, the measurement accuracy of $f_{\rm avg}$ is improved.

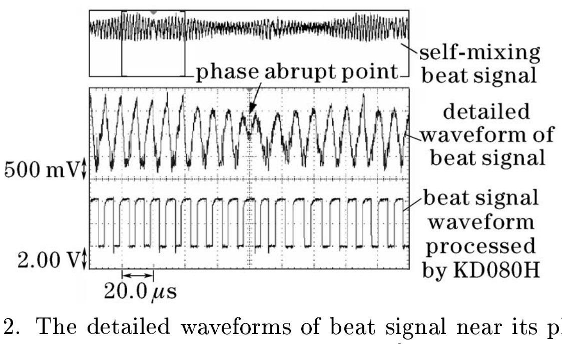

Fig. 2. The detailed waveforms of beat signal near its phase abrupt point and the beat signal waveforms processed by KD080H.

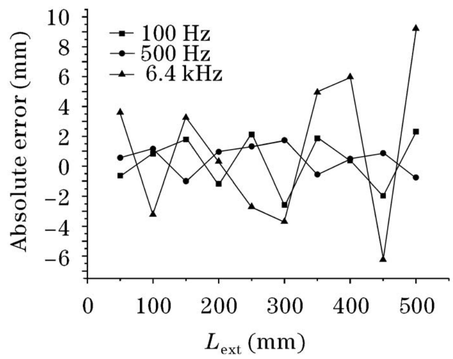

Fig. 3. The ranging absolute error versus $L_{\rm ext}$ for various triangular wave current modulation frequencies $f_{\rm m}$. Sampling time is 0.1 s, and every data point is repeatedly measured for fifteen times.

Secondly, we optimize $f_{\rm m}$ to improve the ranging accuracy. In the experiments, we find that the triangular wave current modulation frequency $f_{\rm m}$ relates to the ranging accuracy of system. Choosing the appropriate $f_{\rm m}$ is able to obviously improve the measurement accuracy of system. Figure 3 shows the ranging absolute error versus $L_{\rm ext}$ for various $f_{\rm m}$ when sampling time is 0.1 s. Every data point in the figure is repeatedly measured for fifteen times, according to the error theory, the measuring arithmetical mean is extremely approach to its true value[7]. As shown in Fig. 3, the ranging absolute error of system is better than 2 mm when $f_{\rm m}$ is 500 Hz, and it will become worse for either too high or too low $f_{\rm m}$. When $f_{\rm m}$ is 100 Hz, for instance, the ranging absolute error has already been larger than 2 mm, and the ranging absolute error is even larger than 9 mm when $f_{\rm m}$ is 6.4 kHz.

On the one hand, it is important to reject the disturbed signal using bandpass filtering for the triangular current modulation signal also being a kind of disturbed signal, which will influence the measurement accuracy of $f_{\rm avg}$. When $f_{\rm m}$ is far less than $f_{\rm avg}$, the result is good. But when $f_{\rm m}$ is near or equal to $f_{\rm avg}$, it will become difficult to separate $f_{\rm avg}$ from $f_{\rm m}$, which will greatly influence the ranging accuracy. To the range finding system, $L_{\rm ext}$ is in the range of 50—500 mm, and the corresponding range of $f_{\rm avg}$ is 5—500 kHz. As shown in Fig. 3, when $f_{\rm m}$ = 6.4 kHz, the modulation triangular wave and its higher harmonic frequency have already been included in the range of $f_{\rm avg}$. Although adopting small current modulation can reduce the amplitude of signal, the measurement accuracy of $f_{\rm avg}$ still becomes worse. When $f_{\rm m}$ = 500 Hz, however, its fundamental wave and higher harmonic are still far away from $f_{\rm avg}$, and the disturbance to $f_{\rm avg}$ is slight, so the ranging accuracy is better.

On the other hand, the beat signal frequency $f_{\rm avg}$ should not be too low, because if $f_{\rm avg}$ is too low, for example 100 Hz, corresponding to the fixed sampling time 0.1 s, the number of sampling waveforms in beat signal will be only 10. The maximum counting absolute error of $N_{T_{\rm m}}$, which is introduced by the existence of phase abrupt points in beat signal, is 2 in a period and the maximum counting relative error almost reaches to 20%, so appropriately increasing $f_{\rm avg}$ can improve ranging accuracy. Generally, $f_{\rm avg}$ should be no less than 5 kHz in the experiment.

In fact, $f_{\rm avg}$ has a selective range from 5 to 500 kHz, in which the difference frequency analog PLL has a better characteristic of noise immunity. Although the locked-in frequency range of the difference frequency analog PLL is as large as 2 kHz —1 MHz, the anti-interference ability becomes worse especially when the lock-in frequency is close to 2 kHz or 1 MHz.

According to Eq. (1), we can get

$$f_{\rm avg} = \frac{2\Omega}{c} \cdot m \cdot L_{\rm ext}. \tag{3}$$

As shown in Fig. 1, the slope of modulation triangular current m can be calculated by

$$m = \frac{\Delta I_{\rm p-p}}{T_{\rm m}/2} = 2\Delta I_{\rm p-p} \cdot f_{\rm m}, \tag{4}$$

where $\Delta I_{\rm p-p}$ is the peak-to-peak amplitude of the modulation triangular wave current. Then the beat signal frequency $f_{\rm avg}$ can be yielded by combining Eq. (3) with Eq. (4)

$$f_{\rm avg} = \frac{4\Omega}{c} \cdot \Delta I_{\rm p-p} \cdot f_{\rm m} \cdot L_{\rm ext}. \tag{5}$$

When we measure the range of target, the target should be placed at a fixed place between 50—500 mm, so $L_{\rm ext}$ can be seen as a fixed value. The other parameters c and Ω are constant, so there are only two modulated variances $f_{\rm m}$ and $\Delta I_{\rm p-p}$, which finally determine the selective range of $f_{\rm avg}$. According to Eq. (5), when $f_{\rm m}$ is too low, for example 100 Hz, the modulation amplitude $\Delta I_{\rm p-p}$ has to be increased in order to make sure that $f_{\rm avg}$ is not too low and in the range of 5—500 kHz. However, too large modulation current ΔI will cause great triangular wave current interference and decrease the ranging accuracy, which will be discussed in detail in the follows, so $f_{\rm m}$ should not be too low for improving the ranging accuracy.

As shown in Fig. 3, when $f_{\rm m}$ is 100 Hz, the ranging absolute error is obviously larger than 2 mm. But when $f_{\rm m}$ is 500 Hz, the ranging absolute error is better than 2 mm for all data points. Furthermore, if $f_{\rm m}$ is smaller than 100 Hz, the ranging accuracy will be worse. Therefore the optimized design of $f_{\rm m}$ is necessary for improving the ranging accuracy of system.

Finally, the optimization of ΔI is similar to the optimization of triangular wave current modulation frequency $f_{\rm m}$. We also find an optimized middle number of triangular wave current modulation amplitude ΔI, which is advantageous for improving the ranging accuracy of system. When I is 8 mA, the optimized value of $\Delta I_{\rm p-p}$ is 0.28 mA.

When the modulation amplitude ΔI is too large (of course the value is not out of the maximum range of modulation current amplitude), it will cause many disadvantages for the ranging accuracy. The amplitude of triangular wave also becomes too large, and the interference yielded by triangular wave and its harmonic wave will be enhanced. At the same time, the linearity of $\Delta\lambda/\Delta I$ will become worse, and the ranging accuracy will be decreased. It becomes more difficult to eliminate the triangular wave in the process of recovering the final beat signal.

On the other hand, if modulation amplitude ΔI is too small, it is also disadvantageous for improving ranging accuracy of system, because the small modulation ΔI makes the amplitude of beat signal become small, and the ability of anti-interference for signal is degraded. Meanwhile the small ΔI also means the modulation signal is weak, which goes against the basic principle that we must use triangular wave current modulation in the laser range finder using self-mixing effect.

To sum up, we consider that the optimization of triangular wave current amplitude ΔI, which has an optimized middle value, is similar to the optimization of triangular wave current modulation frequency $f_{\rm m}$. The experimental result shows that when $\Delta I_{\rm p-p}$ is 0.28 mA (I = 8 mA), the ranging accuracy of system is the best.

Figure 4 shows the light path and signal processing block diagram with the difference frequency analog PLL KD080H for the range finding system. In the experiment, the single-mode VCSEL without temperature controller (F497A, Osram Corporation) with λ = 850 nm, P_0 = 0.7 mW was used, I = 8 mA, $\Delta I_{\rm p-p}$ = 0.28 mA, the accuracy of the modulation triangular wave amplitude was better than 0.1%, $f_{\rm m}$ = 500 Hz, the sampling time was 0.1 s, the scattered target was a piece of sandblasted metal, and the room temperature was 0—55 °C. We got the experimental results of the ranging accuracy better than 2 mm and dynamic measurement range 50—500 mm as shown in Fig. 5.

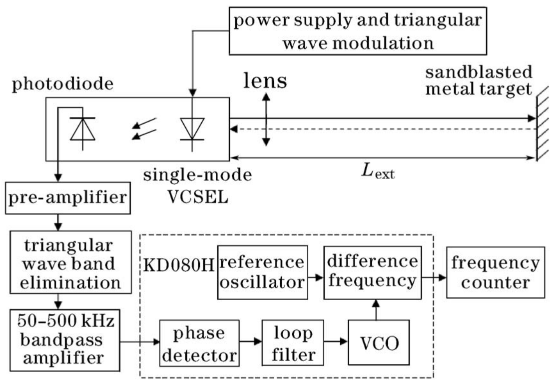

Fig. 4. Block diagram of the range finding system with KD080H.

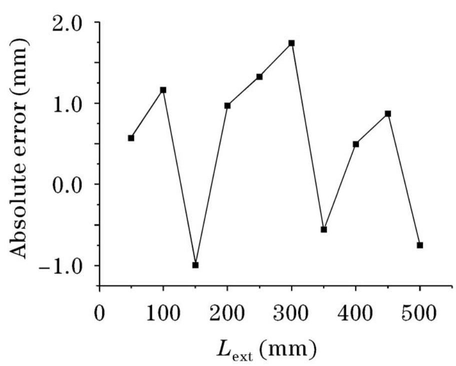

Fig. 5. The ranging absolute error versus $L_{\rm ext}$. $f_{\rm m}$ = 500 Hz, sampling time is 0.1 s, and every data point is repeatedly measured for fifteen times.

In conclusion, by applying the optimized design method of difference frequency analog PLL to process signal, choosing the optimized value of triangular wave current modulation frequency $f_{\rm m}$ and modulation amplitude ΔI and so on, the ranging accuracy is obviously improved and the dynamic measurement range is greatly expanded.

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