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Xilun Chen
Xiangchuan Wang
Shilong Pan

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Accuracy enhanced distance measurement system using double-sideband modulated frequency scanning interferometry

Xilun Chen, Xiangchuan Wang,* and Shilong Pan*
Nanjing University of Aeronautics and Astronautics, Key Laboratory of Radar Imaging and Microwave Photonics, Ministry of Education, Nanjing, China

Abstract. An implementation of a distance measurement system using double-sideband with suppressed carrier modulation (DSB-SC) frequency scanning interferometry is proposed to reduce the variations in the optical path and improve the measurement accuracy. In this proposed system, the electro-optic DSB-SC is used to create dual-swept signals with opposite scanning directions. For each swept signal, the relative distance between the reference arm and the measuring arm is determined by the beat frequency of signals from two arms. By multiplying both beat signals, measurement errors caused by variations in the optical path can be greatly reduced. As an experimental demonstration, a vibration was introduced in the optical path length. The experimental results show that the variations can be suppressed for over 19.9 dB. [DOI: 10.1117/1.OE.56.3.036114]

Keywords: distance measurements; sweep laser; double-sideband modulation; frequency scanning interferometry.

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1 Introduction

High accuracy distance measurement is particularly useful in applications such as radar systems, geographical research, and industrial manufacturing.[1,2] Frequency scanning interferometry (FSI) is one of the effective high accuracy distance measuring methods based on laser technology.[3,4] Using a swept laser in the FSI system, the distance can be determined by the frequency of the final received signals. The precision of an FSI system can achieve up to a micrometer.[5] However, these methods with one single swept laser source are very sensitive to vibrations that may be caused by tiny movement of the target or variations in the optical path length (OPL). It has been proved that[6] the accuracy deteriorates for over 15 dB when there are continuous small variations in the OPL, which makes FSI unsuitable for harsh environments and dynamic measurement. A Kalman filtering algorithm[7] is proposed to compensate the influence of vibrations in the OPL. Compared with conventional FSI, the measuring accuracy is improved for 12.2 dB under the condition of vibrations. Using dual-laser scanning is one additional effective method to solve this problem to improve the accuracy with variations in the OPL.[8–10] A specialized scheme of dual-sweep FSI based on four-wave-mixing (FWM) effect is proposed in Ref. 6. A fixed wavelength laser used as the pump light and a swept laser source are sent to a semiconductor optical amplifier in order to achieve FWM. The generated swept idler light and the original swept signal are the necessary signals in this dual-sweep FSI system. The measurement results indicate that the influence of the vibrations in OPL is suppressed effectively for over 12 dB.

However, the use of two different sweeping laser sources would greatly increase the complexity and cost of a dual-laser scanning FSI system. In this article, an FSI structure using only one fixed laser and electro-optic double-sideband with suppressed carrier modulation (DSB-SC) technique to create two swept laser sources with opposite sweep rates is presented. As only one laser is used, an FSI system with low complexity and cost is achieved. In addition, the influence of vibrations in the OPL can also be counteracted by these two opposite sweep laser signals, which realizes a high accuracy dynamic FSI absolute distance measurement.

2 Principle

In our proposed dual-sweep FSI system, the two swept laser sources are generated using DSB-SC modulation technique with only one fixed laser. The fixed laser is modulated by a swept microwave signal via an electro-optic modulator (EOM). Bias voltage is applied to the EOM for carrier suppression. Then the two swept laser sources with different speeds and opposite directions are generated. These two swept frequency laser lights are divided into two different paths: one path as the reference arm with a known distance and the other whose distance is to be determined as the measuring arm. After passing through the optical paths, the two swept signals are then separated by an optical filter in the detection section. Because there is a time delay τ between the two paths at the receiver, two beat signals with stable frequency are achieved at the photodetector (PD). The simplified electrical responses can be expressed as follows:[6]

$$I_1(t,\tau) = A_1 \cos\{2\pi[\alpha_1(\tau+\delta_t)t + f_1(\tau+\delta_t)]\}, \tag{1}$$

$$I_2(t,\tau) = A_2 \cos\{2\pi[\alpha_2(\tau+\delta_t)t + f_2(\tau+\delta_t)]\}, \tag{2}$$

where $f_{1,2}$ is the initial optical frequency of the swept laser, $A_{1,2}$ is the magnitude of the beat signal, and $\alpha_{1,2}$ is the

*Address all correspondence to: Xiangchuan Wang, E-mail: wangxch@nuaa.edu.cn; Shilong Pan, E-mail: pans@nuaa.edu.cn

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frequency sweep rate of the laser, and δ_t is the variation in the OPL.

As shown in Eqs. (1) and (2), the variations would induce an unwanted phase modulation of the interference signal. The measurement precision would be greatly decreased. In order to suppress the interference δ_t in the OPL, the two beat signals are multiplied, which will produce

$$I(t,\tau)=\frac{A_1A_2}{2}\cos\{2\pi[(\alpha_1-\alpha_2)(\tau+\delta_t)t+(f_1-f_2)(\tau+\delta_t)]\}+\frac{A_1A_2}{2}\cos\{2\pi[(\alpha_1+\alpha_2)(\tau+\delta_t)t+(f_1+f_2)(\tau+\delta_t)]\}. \tag{3}$$

The second term shown in Eq. (3) can be suppressed using a digital filter. In the first term, the influence of the variations in the phase term are effectively suppressed because $f_1 \approx f_2$. When the amplitude of the variations in the OPL is too small to be measured by the frequency term, the frequency of the first term can be written as

$$f=(\alpha_1-\alpha_2)\tau=2\alpha_1\tau. \tag{4}$$

Therefore, the first term can be a new measuring signal for distance measurement, which is negligibly affected by the variation in the OPL. Thus measurement errors caused by variations in the optical path are strongly reduced.

3 Experiment Results and Discussion

The schematic of the experimental setup is shown in Fig. 1. The Teraxion narrowband laser fixed at 1550 nm with a linewidth of about 2 kHz is modulated by a linear continuous swept microwave signal through a Mach–Zehnder modulator (MZM, Lucent, 10 GHz). The swept signal is produced by an arbitrary waveform generator (AWG, Keysight M8195A) with a sweep rate of 625 GHz/ms and a sweep range from 6 to 7 GHz. A DC power supply is used to generate suppressed carrier modulation to achieve the −1st and +1st sidebands, which leads to a carrier rejection ration for 20 dB. After passing through an optical coupler (OC), the modulated beam of laser is divided into two paths: the reference arm and the measuring arm. The reference arm is replaced by a half-meter long fiber. A motorized variable optical delay line (General Photonics) is used in the measuring component for measurement under vibration conditions. The position accuracy of the optical delay line is ± 3 μm. The laser signals of two paths are combined by another OC and sent to a programmable optical filter (Waveshaper 4000s, Finisar) in order to separate the −1st and +1st sidebands of the modulated signals. Then each swept sideband signal is received by the PD.

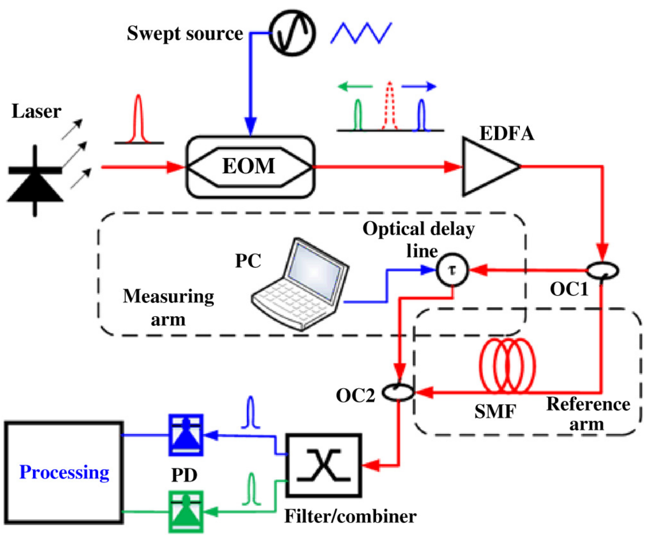


Fig. 1 Schematic of the double-sideband modulated FSI. EOM, electro-optic modulator; EDFA, erbium-doped fiber amplifier; OC, optical coupler; SMF, single mode fiber.

3.1 *Fixed Distance*

The motorized variable optical delay line was set at a reference fixed point, and the initial relative distance between the reference arm and the measuring arm was measured at about 3.480 m. Corresponding measured frequencies of each path were recorded as reference frequencies. Then the optical delay line was extended to 3, 4, 6, and 10 mm, respectively. As the accuracy of the optical delay line is ± 3 μm, these positions can be considered as accurate values. Each measurement of those experiment parameters was repeated three times. This meant that the results of single sweep FSI (the −1st and +1st sideband, separately) were average numbers for three measurements.

Table 1 shows the comparisons of the measured relative distance between the reference point and the altered distances for different FSI methods. The relative distance can be precisely fixed at 3, 4, 6, and 10 mm, due to the high position accuracy of the optical delay line. Relative errors between the measuring results and the distance of the delay line are 2.00%(2.67%), 6.25%(4.25%), 5.83%(9.67%), and 1.8%(4.2%) for −1st(+1st) sideband measurements while dual-sweep analysis has higher accuracy, corresponding to errors of 0.33%, 0.25%, 1.83%, and 1.2%, respectively, as shown in Table 1. Due to the nonlinearity of the swept signal causing a variable α in Eq. (3), measuring errors are generated in these measurements. The dual-sweep analysis has a standard deviation of 0.08 mm. However, for the −1st and +1st sideband analysis, these values are 0.23 and 0.37 mm. Therefore, the proposed dual-sweep FSI can efficiently improve the distance measurement accuracy.

Table 1 Measured distance relative to the reference point.

Distance (mm)	−1st sideband sweep analysis (mm)/relative error (%)	+1st sideband sweep analysis (mm)/relative error (%)	Dual sweep analysis (mm)/ relative error (%)
3.00	3.06/2.00	2.92/2.67	2.99/0.33
4.00	3.75/6.25	4.17/4.25	3.96/0.25
6.00	6.35/5.83	5.42/9.67	5.89/1.83
10.00	9.82/1.80	10.42/4.20	10.12/1.20

3.2 *Vibration*

To measure the distance under vibration conditions, the motorized variable optical delay line was sent "scanning" commands through serial port programming to achieve continuous vibrations. The vibration center was the reference point in Sec. 3.1 (3.480 m). The frequency was 64 Hz and the variation amplitude was 0.3 mm.

When the motorized variable optical delay line was scanning back and forth, data of vibrations within 20 ms were collected. The measured positions in every 2 ms were captured and recorded by the use of the fast Fourier transform algorithm, in order to study the influence of the vibrations in the OPL during the 20 ms. Figure 2 shows the detected spectrum of the -1st and $+1$st sidebands sweep measurements. It can be seen that there is a residual peak in the spectrum. This is because the frequencies of two swept sidebands are approximate (only 12 to 14 GHz difference), which makes the Waveshaper hardly filter out one sideband from the other completely. This means that the two swept signals are sent to each PD, which causes both beat signals existed in both the -1st and $+1$st sweep analysis as shown in Fig. 2. In addition, the -1st sideband sweep analysis has less residual peak rejection ratio and more visible noise in high frequency, which is mainly induced by the Waveshaper, two different amplifiers, and PDs.

Table 2 shows the detected distances relative to the central position of the vibration of the motorized variable optical delay line with a scanning frequency of 64 Hz and a range of 0.3 mm. In our previous experiment, the distance difference of the vibration amplitude (0.3 mm) is proved too small to be detected in this dual-sweep FSI system under fixed distance conditions. It indicates that the measured distance differences in Table 2 are induced by the phase term in Eq. (1), which makes it possible to reduce the variation using the dual-sweep method according to Eq. (3). There is an obvious symmetry between the results of -1st and $+1$st sidebands sweep measurements, while the dual-sweep results agree with the theoretical value (0 mm) well. The average absolute values of two sidebands sweep measurements and dual-sweep measurements are 6.75, 6.80, and 0.07 mm, which indicates that the vibrations are suppressed for over 19.9 dB.

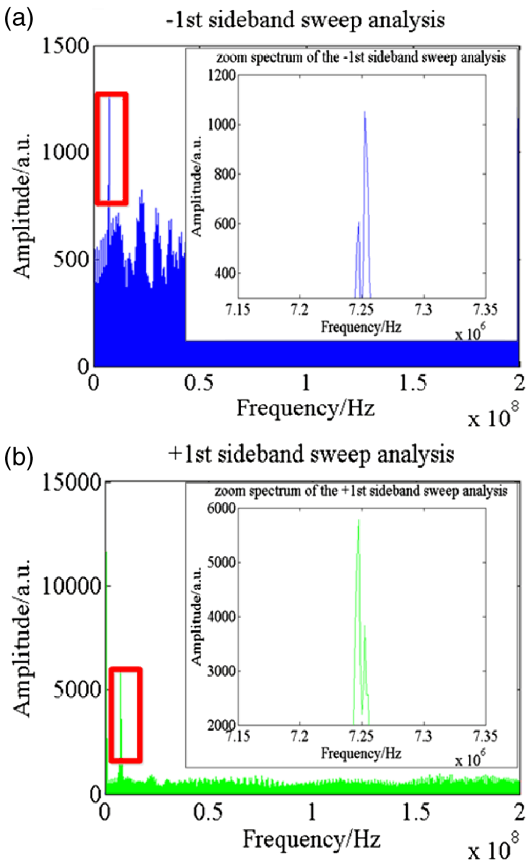


Fig. 2 Detected spectra different sweep FSI methods under vibration conditions with the frequency of 64 Hz (a) -1st sideband sweep analysis and (b) $+1$st sideband analysis.

Table 2 Measured distance relative to the central position of the vibration.

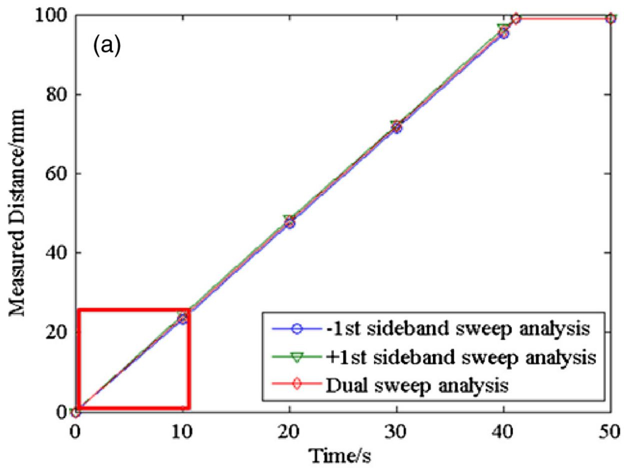
Time (ms)	Distance (mm) -1 sideband analysis	$+1$ sideband analysis	Dual-sweep analysis
2	5.40	−5.95	0.27
4	12.04	−11.95	0.046
6	14.04	−13.95	0.045
8	4.045	−3.95	0.045
10	0.046	0.045	0.046
12	0.045	0.045	0.042
14	−1.95	2.045	0.045
16	−7.95	8.045	0.045
18	−11.95	12.04	0.04
20	10.04	−9.955	0.045

Because the motorized variable optical delay line is scanning back and forth with constant velocity, the measuring error caused by the vibrations should be a constant. This means that measured positions should be identical theoretically when the delay line moves in a certain direction, which is not achieved in the experiment as shown in Table 2. Two main reasons may explain this issue. The first one is that the swept signal generated by the AWG was not perfectly linear, leading to a varied α_1 and α_2. in Eq. (3). The second one is that two swept sidebands have a linewidth of more than 2 kHz, which also reduces the FFT accuracy of the received signals.

3.3 *Movement*

It has been proved that the distance can be accurately measured by a dual-sweep FSI system when there are variations in the OPL, which indicates that this method can also be used for velocity measurement. Here we present the results of -1st, $+1$st sideband and dual-sweep distance measurements under the condition of movement at constant velocity. The motorized variable optical delay line was set to be scanning from the start point (0 mm) to a final point (maximum 99 mm) at 2.4 mm/s. The position information was recorded for each 10 s from the beginning.

The results are shown in Fig. 3; the velocity can be determined by the distance divided by the time. The measured



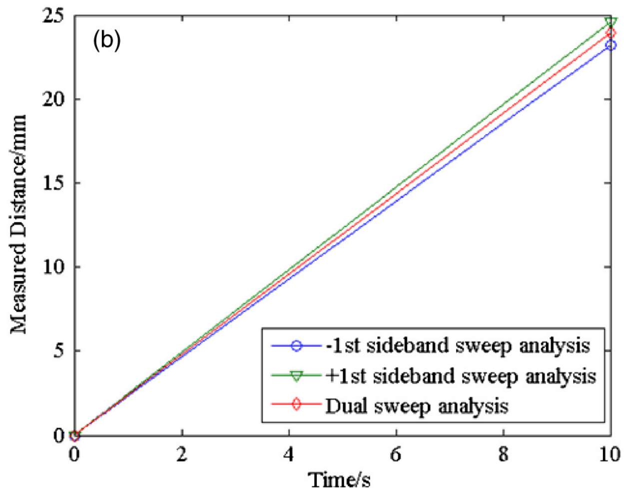


Fig. 3 Measured distance versus time plot of different FSI methods for uniform straight line motion at 2.4 mm/s: (a) distance versus time in 0 to 50 s. (b) Distance versus time plot in 0 to 10 s.

velocity is quite similar in 10 to 40 s of these three FSI methods because the variation δ_t in Eq. (1) is constant in the process of the movement. The start part is zoomed in because the measuring error at the first 10 s is obvious due to the variations in the OPL. We know that the average velocity is defined as the distance traveled divided by the time elapsed. Therefore, more measuring errors of the average velocity during 0 to 10 s are generated by −1st and +1st sideband analysis than the proposed dual-sweep FSI method. The acquired velocities of the single sweep analysis and dual-sweep analysis are 2.32, 2.46, and 2.39 mm/s, respectively. Relative errors of single sideband measurements are 3.33% and 2.50%, compared to 0.42% of the dual-sweep analysis. Compared to measurements with vibrations in the OPL, the results under movement conditions between −1st, +1st sideband sweep and dual-sweep analysis show less difference. This is because of the slower speed in movement measurements, which means a smaller variation δ_t in Eq. (1). The divergence can be more obvious if there is greater speed, which requires a larger range of the optical delay line in experiments.

4 Conclusion

In this paper, a dual-sweep FSI structure is proposed. The swept laser signals are generated using electro-optical DSB-SC. Instead of using two independent swept laser sources, the proposed system brings lower complexity and lower cost. Experimental results present improvement of the dual-sweep method over −1st and +1st swept sidebands under fixed distance conditions. The accuracy is improved for 19.9 dB using dual-sweep analysis under the condition of vibrations, compared with 12 dB at most of other currently known dual-sweep FSI methods. In addition, the proposed FSI system is also applied to measure the speed in a uniform straight line motion environment.

In this dual-sweep FSI system, the measuring precision is mainly limited by the linearity of the swept signal. For further research development, a laser with narrower bandwidth and a microwave swept signal generator with better linearity are necessary to achieve higher accuracy. In addition, the SNR of this system can be increased by the use of a wideband MZM (the two swept sidebands can be filtered out separately) and low noise PDs.

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Xilun Chen is a postgraduate of the Key Laboratory of Radar Imaging and Microwave Photonics, Ministry of Education, Nanjing University of Aeronautics and Astronautics (NUAA). His research has focused on microwave photonics and distance measurement technology.

Xiangchuan Wang received the BEng degree in automation and the PhD in microelectronics and solid-state electronics from Nanjing University, China, in 2009 and 2015, respectively. Currently, he is a lecturer at the Key Laboratory of Radar Imaging and Microwave Photonics, Ministry of Education, NUAA, China. His current research interests are microwave photonic measurement and optical fiber sensing technologies.

Shilong Pan joined NUAA in 2010, where he is currently a professor, and director of the Key Laboratory of Radar Imaging and Microwave Photonics, Ministry of Education. He is a member of IEEE, OSA, and SPIE. His research interests include ROF systems and microwave photonic measurement, as well as microwave photonic signal processing and generating. He has authored or coauthored over 230 papers in refereed journals and conference proceedings.