Vibration measurements based on demodulating the phase of a fiber 3dB-coupler Michelson interferometer

Min Li *, Fang Xie, Junyu Ren
Optical Science and Technology Laboratory, Department of Physics,
School of Science, Beijing Jiaotong University, Beijing 100044, P. R. China
*Corresponding author: Tel: 86-10-51688200; Fax: 86-10-51840433
Email address: 09122269@bjtu.edu.cn (Min Li)

ABSTRCT

A fiber interferometric vibration measurement system which is based on demodulating the phase of a fiber Michelson interferometer which is made with a fiber 3dB-coupler is presented. In the work, the system employed the characteristics of fiber Brag gratings (FBGs) to interleave two fiber Michelson interferometers which share almost the same part of the main optical path. One of the fiber interferometers is used to stabilize the system, employing an electronic feedback loop to drive a piezoelectric actuator to tune the optical path of the reference beam in order to keep the interferometer in quadrature state. By this way, the low frequency drifts in the phase of the interferometric signals which are resulted from environmental disturbances are compensated for. The other one is used to perform the measurement task. By employing the characteristics of 3dB-coupler, the interferometric signals from the two outputs of the 3dB-couper are 180º out of phase. The two interferometric signals are input into an electronic processor and convert into currents, which are linear to the power of the optical interferometric light. The signals are collected by NI USB-5132 acquisition card and processed by a program in a personal computer. The measurement system is configured with fiber and fiber components which are integrated together. As the cutoff frequency of the feedback loop is 1.5Hz, the measurement system is capable of measuring vibration with frequencies bigger than 1.5Hz and the amplitude of the measured vibration is not limited.

Keywords: fiber optics, interferometry, feedback control, LabVIEW

1. INTRODUCTION

Optical fiber interferometers have been widely used in metrology due to their inherent benefits such as non-contact measurement, compactness, light weight, immunity to electromagnetic interference, wide bandwidth, multiplexing capability, high resolution and low cost[1-4].Besides of having these benefits, compared with the normal optical interferometers which are configured with separate optical components, optical fiber interferometers can be carried with great ease because all the fiber components are integrated together. And what is more, there is no need for optical fiber interferometers to adjust and keep the relative positions of separate components necessary for normal optical interferometers. Hence, there is a great interest in the exploitation of optical fiber interferometers for the measurement of a large variety of parameters such as displacement, vibration, velocity, strain and temperature.

For a fiber interferometer measurement system, the fiber should be used just for transmitting the light while the phase change in the interferometric signal should be induced only by the measured displacement. But in fact, as the fiber is not only sensitive to vibration but also the temperature fluctuations and other types of the environmental disturbances, the length of the fiber that used in the interferometric arms will change randomly, low frequency random phase drifts would

2009 International Conference on Optical Instruments and Technology: Optoelectronic Measurement Technology and Systems, edited by Shenghua Ye, Guangjun Zhang, Jun Ni, Proc. of SPIE Vol. 7511, 75110C · © 2009 SPIE · CCC code: 0277-786X/09/$18 · doi: 10.1117/12.837952

be induced in the interferometric signal. The random phase drifts will decrease the measurement accuracy, and in the worst circumstances, even make the fiber interferometer un-working. With the need for ultra high precision measurement, especially in precision on-line measurement that the measurement needs to be performed at the place where the measured piece is manufactured, the random phase drifts induced by the environmental disturbances must be eliminated[3-5].

Fiber interferometer measurement systems with high stability which are able to resist the environmental disturbances should be developed. Although techniques such as common-path interferometric arms[1]and feedback compensating loop[3]are able to compensate the random phase drifts in interferometric signals, the measurement range of Ref[1] is very small because of being limited by the interferometric visibility and Ref[3] can not continue the measurement function if a reset voltage action takes place. Besides, both of these techniques do not provide the directional sense of the vibration.

We present an interleaved fiber Michelson interferometer measurement system which is able to self-compensate effectively the influences resulting from the environmental disturbances and offers high stability for on-line precision measurement. By employing fiber Bragg gratings(FBGs) as in-fiber reflective mirrors, the measurement system includes two fiber Michelson interferometers which are interleaved together and share the common-interferometric-optical path. In this system, one of the fiber Michelson interferometers is used to compensate the differential phase drifts in the interferometer arms resulting from the environmental disturbances, while the other one is used to perform the measurement task. A simple electronic feedback loop drives a piezoelectric cylinder wound with the fiber used in the reference arm, and the piezoelectric cylinder tunes the length of the reference arm and keeps the interferometer in quadrature position (keeping the phase difference of the two arms at $\pi/2$ radians). By this way, the influences resulting from the environmental disturbances has been compensated. Therefore, the system is stabilized and is suitable for on-line precision measurement and sensing. What is more, as the components used in the system are inexpensive, the cost of the system is very low.

Compared to software demodulation, hardware demodulation is more complicated in structure and more expensive in manufacture. After getting stable interferometric signals,we used LabVIEW programming to deal with signals.LabVIEW is referred to the Laboratory Virtual Instrument Engineering Workbench which is developed by the USA National Instruments. It is a integrated developing program environment based on the “graphical”, the only internationally graphical programming language.LabVIEW has a series of advantages, from its flowchart-style programming which is not need pre-compiled grammar testing and debugging process of the use probe date, to its abundance of functions, numerical analysis, signal processing ,device driver and so on. It can demodulate a large rang of frequency efficiently. Thence,LabVIEW is recognized as the standard date acquisition and instrument control software. So in our work, we use LabVIEW to achieve phase demodulating.

2. THE PRINCIPLE OF THE SYSTEM

2.1 The measurement optical system

The principle of the measurement system is shown in figure 1. The measurement optical system is configured with two fiber Michelson interferometers which share the common-interferometric-optical path by employing four FBGs as in-fiber reflective mirrors. Two temperature-stabilized DFB laser sources with center wavelengths at 1553nm and 1553.7nm are used in the system. Both lasers give output power 2.5mW with spectral bandwidth 0.2nm at 20dB. Three FBGs - FBG1, FBG2 and FBG3 used in the system have the same Bragg wavelength at 1553nm with bandwidth 0.3nm at 3dB. The fourth FBG - FBG4 has a Bragg wavelength at 1553.7nm with bandwidth 0.3nm at 3dB. Because the bandwidth of the DFBs is much narrower than the bandwidth of the FBGs and the sensitivity of the Bragg wavelength shifts of FBGs to temperature variation is 13pm/ºC, so under ordinary temperature fluctuation, the fiber Bragg gratings will always be able to reflect the DFB lasers wavelength.

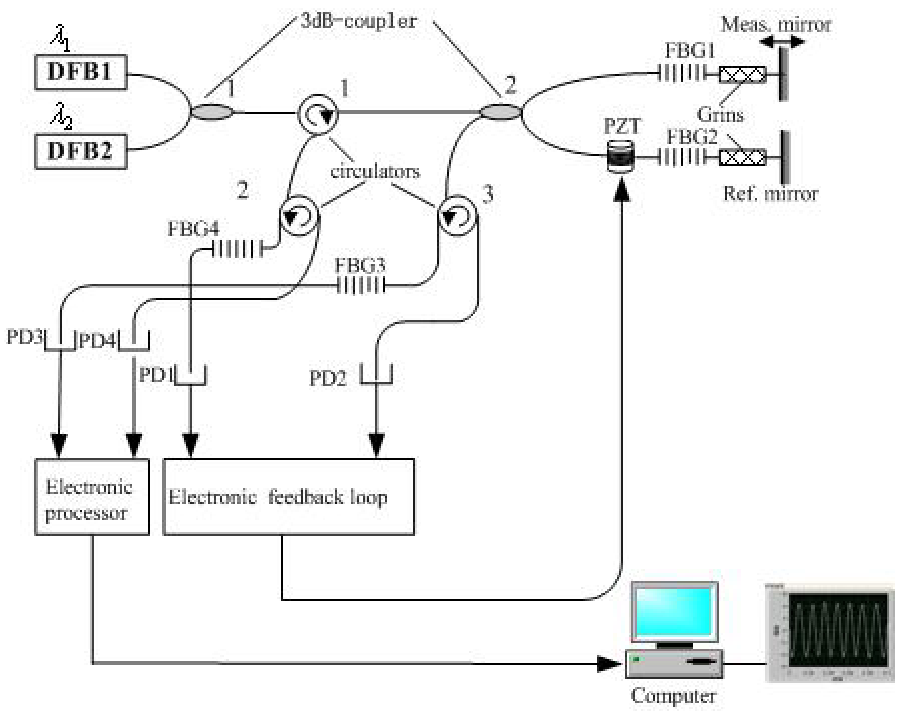

Figure 1. The principle of the measurement system

The first fiber Michelson interferometer, which employs FBG1 and FBG2 as reflective mirrors that are placed just behind the two Grin lenses, is used to monitor and compensate for the differential phase drifts in the two arms resulting from the environmental disturbances. Light emitted from the λ_1 1553nm DFB passes through 3dB-coupler 1, circulator 1, 3dB-coupler 2, and is divided into two beams which are then reflected back by FBG1 and FBG2, respectively. The two reflected beams are combined again at 3dB-coupler 2 then interfere with each other. The interferometric signal from one output of 3dB-coupler 2 passes through circulator 1, circulator 2, and FBG4 and is received by photodetector1 (PD1), while the interferometric signal from the other output of 3dB-coupler 2 goes through circulator 3, is reflected by FBG3 (so it will not reach PD3), and is received by PD2. The two interferometric signals detected by PD1 and PD2 are electrically processed by the electronic feedback loop and an information derived from this processing is used as a correction signal which is applied on the piezoelectric cylinder PZT (length 35mm, outer diameter 3.5cm, thickness 2mm). 11m of the fiber used in the reference arm is wound on the piezoelectric cylinder PZT. The feedback signal drives PZT to tune the fiber length of the reference arm to keep the interferometer at quadrature position. By means of this, the differential phase drifts in the two arms is effectively compensated and therefore the interferometer is stabilized.

The second fiber Michelson interferometer have the common-interferometric-optical path with the first one and is prevented from the environmental disturbances, when the first Michelson interferometer is stabilized. The second fiber Michelson interferometer is probed by the light from the λ_2 1553.7nm DFB and is used to obtain information from the measurement mirror. The light from the DFB is transmitted through 3dB-coupler 1, circulator 1, 3dB-coupler 2 and is divided into two beams. The two beams pass through FBG1, FBG2 and are collimated by the two Grin lenses, respectively. The two collimated beams are projected onto the measurement mirror and the reference mirror, then reflected back by the two mirrors into the system again. The two beams are combined at 3dB-coupler 2 and interfere with each other. The interferometric signal from one output of 3dB-coupler 2 passes through circulator 3 and FBG3, and is received by PD3. The interferometric signal from the other output of 3dB-coupler 2 goes through circulator 1 and 2 and is reflected back by FBG4, and then output from the third port of circulator 2, received by PD4.

The FBG1 and FBG2 are addressed just behind the two Grin lens, and the distance between the ends of the Grins to the mirrors is less than 1mm, so the optical path of the two fiber interferometers are almost the same. By probed with two DFB sources respectively and employing the characteristics of FBGs, the two fiber interferometers are actually independent. One interferometer is used to stabilize the measurement system while the other one is used for perform the measurement task.

2.2 The stability of the measurement

The feedback loop is designed based on the principle of second-order stable control. By responding to the input information instantly, output a adjusted signal to drive a piezoelectric cylinder wound with the fiber used in the reference arm, and the piezoelectric cylinder tunes the length of the reference arm and keeps the interferometer in quadrature position (keeping the phase difference of the two arms at π/2 radians).By this way, the influences resulting from the environmental disturbances has been compensated. It will not influent the phase change caused by the vibrating of measurement mirror.

Because the two wavelengths of the DFBs are very close and the two fiber Michelson interferometers have their independently reflective mirrors respectively, the voltage reset action will not interrupt the measurement action. To verify this statement we may analyze an interleaved fiber interferometer shown in figure 2. As seen in figure 2, the lengths of the two arms of the measurement interferometer are

$$L_1 = l_{11} + l_{12} \tag{1}$$

$$L_2 = l_{21} + l_{22} \tag{2}$$

Where L_1 and L_2 are the lengths of the measurement interferometric arms, l_{11} and l_{21} are the lengths of the reference interferometetric arms, and l_{12} and l_{22} are the length differences of the two interferometers arms.

The optical path difference of the measurement interferometer Δ is

$$\Delta = L_2 - L_1 = (l_{21} - l_{11}) + (l_{22} - l_{12}) \tag{3}$$

The phase difference of the measurement interferometer $\Delta\phi$ can be expressed as

$$\begin{aligned}\Delta\phi &= \frac{2\pi}{\lambda}\Delta = \frac{2\pi}{\lambda}(l_{21} - l_{11}) + \frac{2\pi}{\lambda}(l_{22} - l_{12}) \\ &= \phi_r + \phi(t) = (2n+1)\frac{\pi}{2} + \phi(t)\end{aligned} \tag{4}$$

Where ϕ_r is the phase difference of the reference interferometer caused by the environmental disturbances which is always kept at quadratrure point ,so the value of ϕ_r can be expressed as $(2n+1)\frac{\pi}{2}$, n is a interger number and $\phi(t)$ is the phase difference induced by the optical path difference between l_{12} and l_{22}. From equation (4), it is known that the effective value of $\Delta\phi$ is determined by $\phi(t)$ and does not have a relation to the optical path difference of the reference interferometer. This makes the measurement action continuous whether there is a voltage reset action occurring or not.

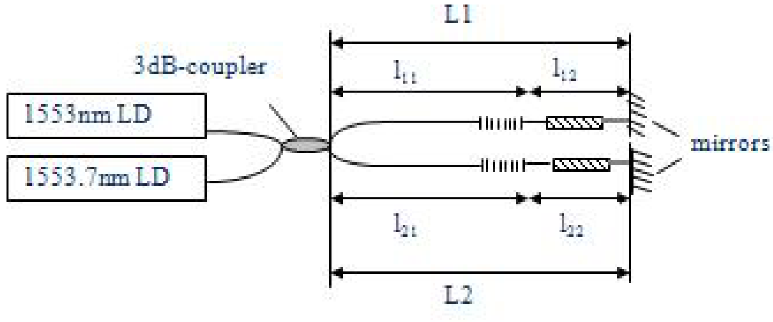

Figure 2. The relationship of the optical paths
in the two multiplexed fiber interferometers

2.3 Signals acquisition and phase demodulation

As already mentioned before, the interferometric signals detected by PD3 and PD4 are 180°out of phase because of 3dB-coupler 2. The currents from PD3 and PD4, i_1 and i_2, which are linearly proportional to the optical signals detected by PD3 and PD4, will therefore have the following forms

$$i_1 = i_0(1 - k_0 \cos\Delta\phi) \tag{5}$$

$$i_2 = i_0(1 + k_0 \cos\Delta\phi) \tag{6}$$

Where i_0 is related to the input optical power, k_0 is a function of the interferometric fringe visibility. Then PD3 and PD4 are connected to separate current-to-voltage converters which have low input impedances. By employing potentiometers in current-to-voltage electric circuit ,keep the two signals have the same DC component. So the voltages are expressed as follows

$$u_1 = u_0 - k_0 \cos\Delta\phi \tag{7}$$

$$u_2 = u_0 + k_0 \cos\Delta\phi \tag{8}$$

As mentioned before, the effective value of $\Delta\phi$ is determined by $\phi(t)$ the phase difference induced by the optical path difference between l_{12} and l_{22}, and does not have a relation to the optical path difference of the reference interferometer. So the equations can be expressed as

$$u_1 = u_0 - k_0 \cos\phi(t) \tag{9}$$

$$u_2 = u_0 + k_0 \cos\phi(t) \tag{10}$$

First of all, we need to get the voltages which are linearly proportional to the interferometric signals from the measurement system and sent them to the computer for further procedures. Here, we used NI USB-5132 acquisition card which is provided by NI corporation. The NI USB-5133 eight-bit digitizer/oscilloscope features 100 MS/s sampling rates on two simultaneously sampled channels with 10 input ranges from 40 mV_{pp} to 40 V_{pp}. It is also an interactive measurement workbench for quickly acquiring, analyzing, and presenting data with no programming required. By employing the acquisition card with corresponding program for configuring parameters. The data collecting procedure is shown in figure 3.

Data acquisition is the most important part of the virtual instrument. As shown in the figure 3,it consist of trigger control, channel control ,time control and display control. In the design of data acquisition part, we set the equipment selection, channel selection, sampling rate, sampling length as well as the coupling mode to input controls, therefore we can change input parameters just on the front panel. Besides, a “for”cycle was used for continuous sampling . Once we clicked the

“Start” button on the front panel, the data acquisition procedures began working.

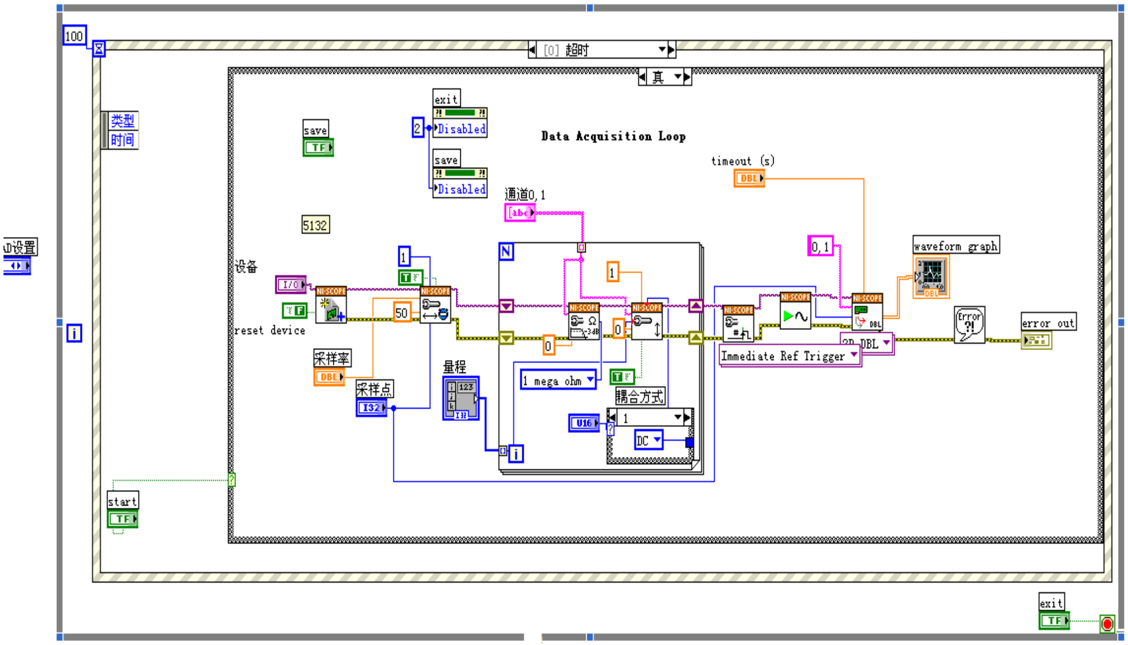

Figure 3. The program of waveform acquisition

As shown in the figure 3, the collected interferometric signals were referred to two-channel signals separately and simultaneously as shown in equation (9) and (10) in fact. Then by using a subtraction device,

$$u = u_2 - u_1 = 2k_0 \cos\phi(t) = K\cos\phi(t) \qquad (11)$$

All the symbols have been illustrated above, not need to be repeated here. To get the phase change information, the next

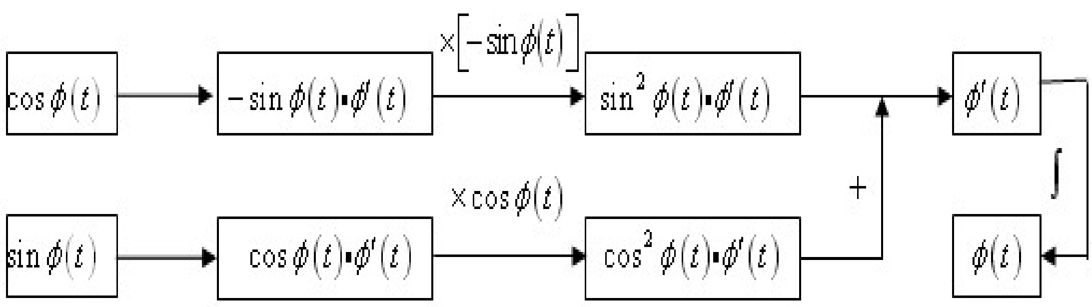

Figure 4. The principle of phase demodulation

task was to demodulate the collected interferometric signals. Above all, we used a Amplitude and Voltage vi. to get the amplitude of this interferometric signals and then divided the $u = K\cos\phi(t)$ into $u = \cos\phi(t)$.

Then the specific principle of demodulation is shown in figure 4.Here, we used Hilbert Transform vi. which has been existed in the LabVIEW. On respond to the transform, the frequency of signs had a -90°offset to get $\sin\phi(t)$.Then, we needed to calculated these two signals. Figure 4 has already revealed the specific calculation. Through a series of calculations, demodulate the phase change in the measurement system.

3. THE EXPERIMENTAL RESULT

3.1 The stabilization experimental results

With the feedback loop out of operation and the measurement and reference mirrors of the measurement interferometer in static state, the interference signals detected by PD3 and PD4 are shown in figure 5. It can be seen that the interferometric signals are fluctuating randomly at all the time and the outputs from PD3 and PD4 are 180°out of phase because of 3dB-coupler. The variation in the interferometric signals is resulted from temperature fluctuations and other types of the environmental disturbance. However, as soon as the feedback loop is turned on, the output from PD3 and PD4 is stabilized constant values, just as shown in figure 6.

Figure 5.The signal3 detected by PD3 and PD with the mirrors static and the feedback loop out of operation

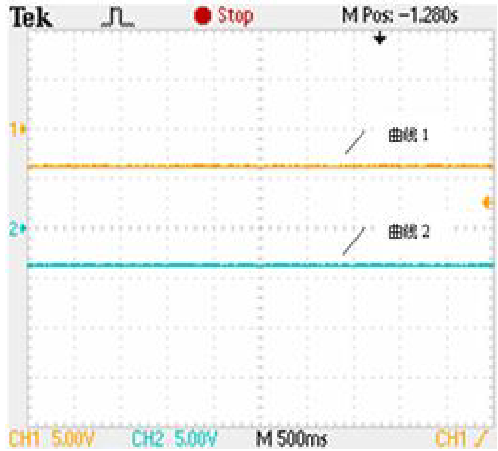

Figure 6.The signal3 detected by PD3and PD4 with the mirrors static and the feedback loop on operation

3.2 The waveform acquisition and phase demodulation results

Figure 7 is the collected interferometric signals referred to $u = K\cos\phi(t)$ which is shown on the front panel. With sample length is 10000 and sample rate is 100000,so the waveform displayed in the front panel oscilloscope in 0.1s. Figure 8 is the curves of $\cos\phi(t)$ and $\sin\phi(t)$.The red curve is referred to $\cos\phi(t)$ while the white curve is referred to $\sin\phi(t)$.As the translation in LabVIEW is a fast Hilbert Transform, the curves are a little different in the starting point with t=0,but not affect the following calculation.

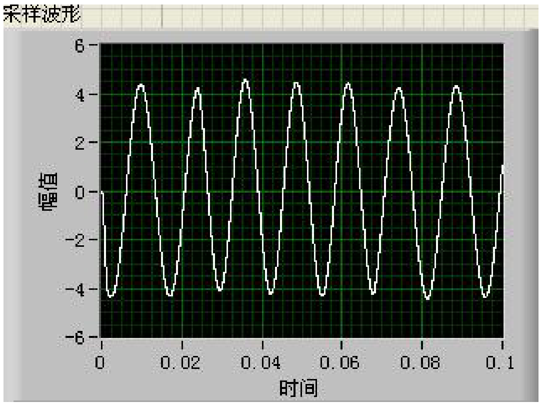

Figure 7. The collected interferometric signals

In the principle of the measurement system, we have already revealed that $\Delta\phi$ is determined by $\phi(t)$ the phase difference induced by the optical path difference between l_{12} and l_{22} , the equation of this relationship is

$$\Delta\phi(t) = \frac{2\pi}{\lambda} \cdot \Delta L \tag{12}$$

$$\Delta L = l_{22} - l_{12} \tag{13}$$

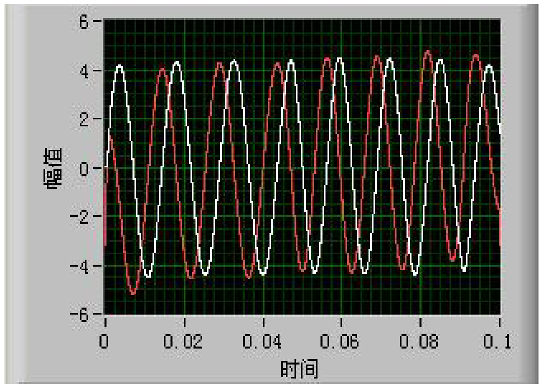

Figure 8.The curves of $\cos\phi(t)$ and $\sin\phi(t)$

When the measured mirror vibrating back and forth , $\Delta\phi(t)$ changed linearly to ΔL .As expected, the demodulation of the phase is a straight line as shown in figure 9.

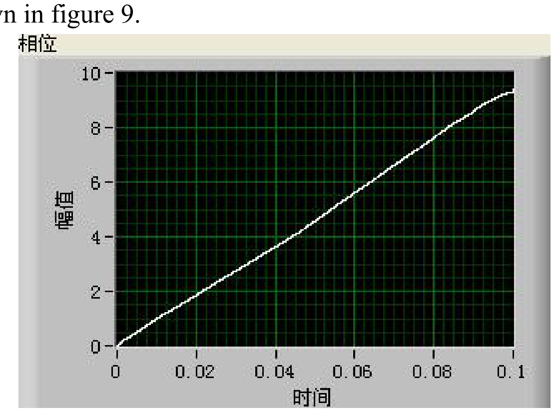

Figure 9. The curve of phase change

Take cosine calculation to the phase obtained from the demodulating program and given the original amplitude,the restored waveform ia almost the same as the collected interferometric waveform as shown in figure 10.

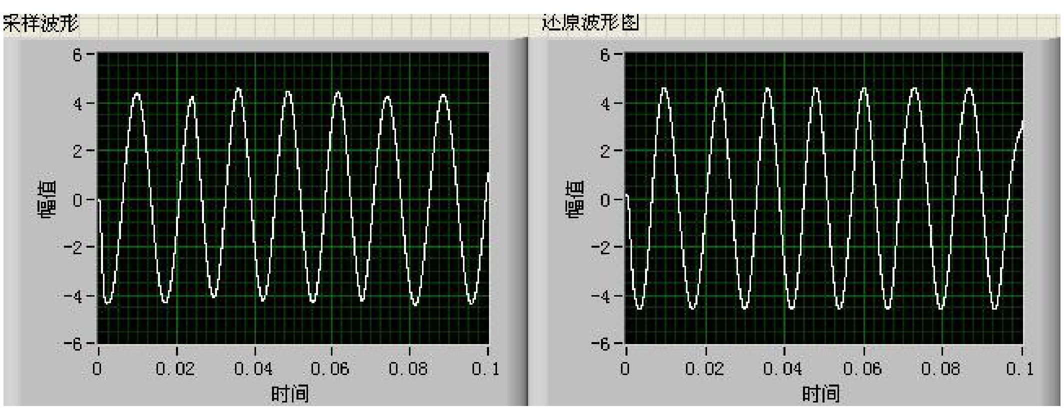

Figure 10. The restored waveform compare to the original one

4. CONCLUSION

The highly stable optical fiber Michelson interferometer system which is suitable for on-line precision measurement or sensing is presented. By employing FBGs as in fiber reflective mirrors, two optical fiber Michelson interferometers which share the common-interferometric-optical path are interleaved. One optical fiber Michelson interferometer is used to stable the system by using a simple electronic feedback loop to compensate for the differential phase drift in the interferometric arms. And the other optical fiber Michelson interferometer is used for perform the measurement or sensing task. The system is stable and robust enough for on-line precision measurement or sensing to achieve high measurement accuracy.

By using of LabVIEW which has a variety of signal processing modules, making the development of specific time-domain waveform and frequency domain processing software is more accurate, intuitive and easy. It can demodulate a large rang of frequency. It is not only used as a simulation and a powerful addition for the hardware demodulation,but also effectively process the full functions of signals independently.

5. THE PROSPECTIVE TASK

In the further experiments, When the vibrating displacement to the maximum and then returned, that the opposite direction,the waveform of the interferometric signals which distort a little is different from the figure7.At the same time ,the straight line referred to the phase had a bend point. Such special curves are shown in the figure11.

Because the PDs received the interferometric signals by responding to the power of the optical interferometric light, it cannot realize the change of direction. When the direction changed suddenly ,the light intensity became smaller instantly. Thus, the phase decreased a little,but as the procedures was unable to determine the change of direction, the phase curve slope was not negative as well. So there was only a bend on the straight line.

So the next task we need to do is determining the change of direction. Although there are many methods of determining direction in electronic technology, we want to succeed in determining direction through LabVIEW program as it is more precisely avoiding environmental disturb and less cost.

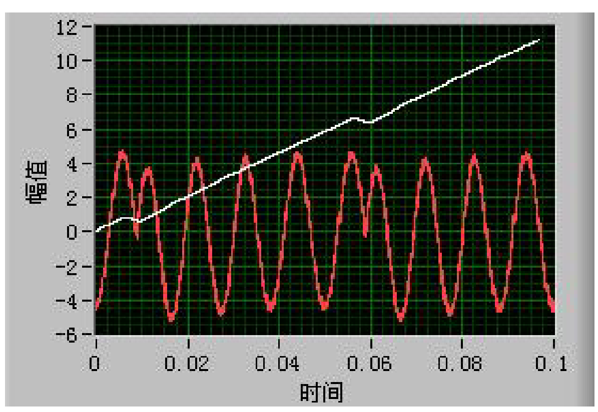

Figure 11.The special waveform of opposite direction

ACKNOWLEDGMENTS

The authors are grateful that this research is supported by National Natural Science Foundation of China(50675018) and

Beijing Natural Science Foundation(3072009) and the Key Laboratory of Luminescence and Optical Information Beijing Jiaotong University,Ministry of Education, China.

REFERENCES

[1] D.P.Hand, T.A.Carolan, J.S.Barton and J.D.C.Jones, Profile measurement of optically rough surfaces by fiber-optic interferometry, Opt. Lett. 18(1997) 1361-1363.

[2] D.A.Jackson, A.Dandridge and S.K.Sheem, Measurements of small phase shifts using a single-mode optical fiber interferometer,,Opt. Lett.5(1980)139-144.

[3] Dejiao Lin,Xiangqian Jiang,Fang Xie, High stability multiplexed fiber interferometer and its application on absolute displacement measurement and on-line surface metrology, Opt.Express 12(2004) 23.

[4] D.A.Jackson, A.Dandridge, and A.B.Tventen, Elimination of drift in a single-mode optical fiber interferometer using a piezoeletric stretched coiled fiber, Appl. Opt. 19(1980)2926-2929.

[5] K.Fritsch and G.Adamovsky, Simple circuit for feedback stabilization of a single-mode optical fiber interferometer, Rev. Sci. Instrum. 52(1981) 996-1000.

[6] Udd E, An overview of fiber-optic sensors, Rev. Sci. Instrum. 66(1995) 4015.

[7] Kersey A D, A review of recent developments in fiber optic sensor technology, Opt. Fiber Technol. 2(1996) 291.

[8] Jiang M and Gerland E, A simple strain sensor using a thin film as a low-finesse fiber-optic Fabry-Perot interferometer, Sensors and Actuators A 88(2001) 41.

[9] H C Seat, E Ouisse, E Morteau and V Metivier, Vibration-displacement measurements based on a polarimetric extrinsic fiber Fabry-Perot interferometer, Meas. Sci. Technol.14(2003) 710-716.

[10] Meggitt B T, Hall C J and Weir K, An all fibre white light interferometric strain measurement system, Sensors Actuators A 79(2000),1.