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A ballistocardiography monitor based on optical fiber interferometer

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ABSTRACT

Ballistocardiography (BCG) is a non-invasive method to detect the heartbeat signal, which reflects the body recoils introduced by cardiac ejection. Compared with traditional heartbeat monitors, such as Electrocardiography (ECG), the BCG detection method can acquire heartbeat signals without any wearable devices, which is user-friendly. The device can be integrated into a cushion, which is convenient for users to monitor the heartbeat in long-term. In this paper, a BCG monitor based on the Mach-Zehnder interferometer (MZI) with a new phase modulation method is demonstrated. A low-cost and compact phase shifter is introduced to solve the problem of signal fading in the fiber-optic interferometer. The baseline drift produced from breath and noise can be removed by the phase modulation and accuracy BCG signal can be detected in the sitting position. Compared with existing BCG monitors, such as accelerometer-based and bathroom scales-based, our optical fiber interferometer-based BCG monitor has many merits including sensitivity, stable, and immune to electromagnetic interference (EMI). In conclusion, the BCG monitor based on optical fiber sensor has great potential in the long-term and real-time heartbeat monitoring.

Keywords: Ballistocardiography monitor, Optical fiber sensor, Mach-Zehnder interferometer.

1. INTRODUCTION

Cardiovascular diseases (CVDs) are the number one death causes around the world. World Health Organization (WHO) reports that in 2016, about 17.9 million people died from CVDs, which accounts for 31% of deaths in the world. CVD patients or people at high cardiovascular risk, such as hypertension, diabetes and hyperlipidaemia, need to be detected and managed in the early stage and use appropriate counselling and medicines. Many CVDs are hard to be detected in the early phase since the symptoms is not obvious. Therefore, long-term heartbeat signal monitoring is significant to CVDs and potential patients, which can help them to maintain the health condition of heart. At present, most CVDs diagnosis is according to the domain technology, electrocardiography (ECG) signal, since the abnormal cardiac activities introduce by disease can be recorded as physiological electrical signal. However, ECG measurement needs to attach multiple electrodes on the skin of the user, which is inconvenient and could discomfort the user. It is not suitable and impractical to conduct a long-term heartbeat monitoring utilizing traditional ECG devices. As a comparison, ballistocardiography (BCG) signal, which reflects the body recoils in reaction to cardiac ejection during each heart cycle, can be detected in a non-invasive way. CVDs, such as arrhythmia, can also introduce abnormal signal to the BCG. Therefore, the BCG signal can assist in the diagnosis of some CVDs, which has tremendous potential in long-term heartbeat monitoring.

BCG signal was first observed by Gordon in 1877 [1] and Isaac Starr et al. developed an instrument to measure the BCG signal in a scientific manner in 1939 [2]. However, the BCG signal was gradually replaced by ECG due to the technology limitation. With the faster growth of sensing and signal processing technologies, the BCG signal was starting to attract increasing interest from researchers again. In the past decade, many researchers were involved in the study of BCG signal detection and different sensing schemes have been proposed. These schemes can be divided into electronic sensor-based, optical fiber sensor-based, video-based, radar-based in the sensing technologies level. For example, Inan et al. proposed a BCG monitor based on a bathroom scale in 2009 [3-4]. The demonstrated sensor could detect BCG signal when the subject stands on the electronic scale. The obtained BCG signal from the scale was proved to agree well with the simultaneous measured doppler echocardiogram signals through Bland-Altman methods. J. Alametsa et al. presented a sitting position BCG monitor based on the electromechanical film (EMFi) sensors [5]. Ł. Dziuda et al. developed a

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fiber Bragg grating (FBG) strain sensor, which could monitor the BCG signal during a magnetic resonance imaging (MRI) survey [6]. M. A. Hassan et al. demonstrated a remote health monitoring through video-based signal processing method. They obtained the approximative BCG signal by estimating the microscopic color change or rigid motion in the face [7]. O. Postolache et al. proposed to use 24GHz microwave FMCW (frequency modulated continuous wave) Doppler radar (MDR) to monitor radar Ballistocardiography (R-BCG) of less mobility people [8]. The BCG monitoring technology has evolved from the single technology in the early stage (mostly focusing on electronic sensor-based approaching) to multiple technologies at current (including optical fiber-based method, etc.).

However, these existing BCG detection schemes have some limitation. For example, electronic sensor-based and radar-based BCG monitor will be affected by electromagnetic interference (EMI), and video-based method is greatly limited by body movement. Optical fiber sensor-based scheme is a good choice of biomedical signal monitoring due to the inherent merits of optical fibers such as high sensitivity, low cost, light weight, immune to EMI. Bending loss-based, FBG-based, interferometer-based heartbeat monitors have been reported in recent years. However, bending loss-based mothed has low sensitivity and FBG-based method requires expensive demodulation equipment. Compared with the mentioned two optical fiber sensor methods, interferometer-based scheme owns the advantages of high sensitivity and low cost. The main problem of optical fiber interferometer is signal fading. Therefore, in this paper, we propose a Mach-Zehnder interferometer (MZI)-based sensor using inexpensive and easy-to-integrated phase shifter to monitor BCG signal. This BCG monitor can provide long-term monitoring for people, which has tremendous potential in the field of health care.

2. METHOD

2.1 Experiment setup

The experiment setup of BCG monitor based on the optical fiber sensor is demonstrated in the Figure.1. The monitor includes three parts of optical fiber MZI, phase shifter and proportional-integral-derivative (PID) controller. The BCG monitor is packaged in a cushion and it can be placed on the chair to conduct heartbeat monitoring. As shown in the figure, MZI in the yellow dashed box is the sensing area of the monitor, and the 1550 nm DFB laser diode and low-speed photodetector (PD) are used as the light source and receiver. The phase shifter is fixed with the reference arm of MZI outside the sensing area. To solve the signal fading problem in the MZI and keep the output in quadrature, the PID controller is introduced to form a closed loop control system. The received signal in the PD will be divided into two channels: channel 1 (CH1) is the raw signal acquired by MZI and channel 2 (CH2) is the low pass signal, which will be fed into the PID controller. The controller will calculate the error degree to which the system is out of quadrature and compensate the system through the phase shifter. The raw signal from CH1 can be detected by a DAQ card. Therefore, the obtained BCG signals are stable and without baseline drift.

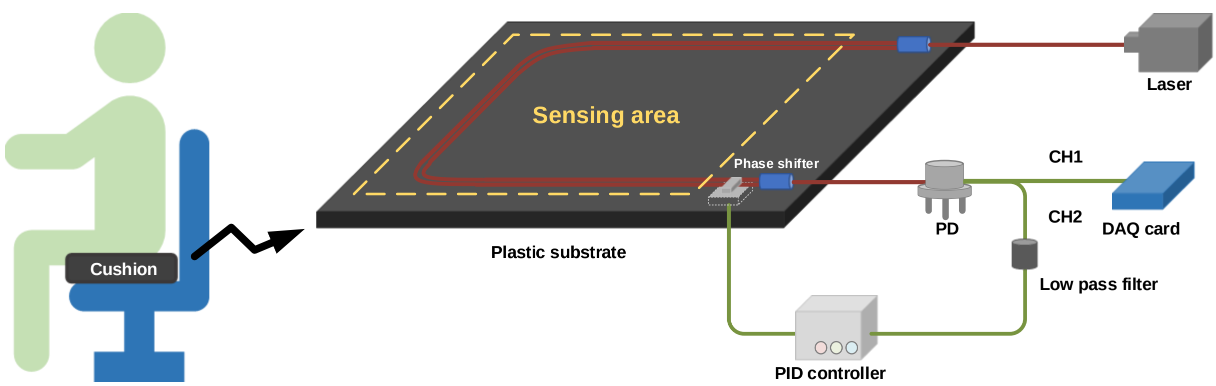

Figure 1. Setup of BCG monitor.

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2.2 Mach-Zehnder interferometer

The optical fiber MZI contains two 3dB couplers, which work as optical splitter and optical coupler to form interference. A PD is pleased in the end of the system and converts the received variational light intensity introduced by phase difference into the electrical signal. The light intensity of transmission spectra can be determined by

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\varphi), \tag{1}$$

where I_1, I_2 are intensities of two arms and φ is the phase difference between these two arms, which can be given by

$$\varphi = \frac{2\pi}{\lambda}(n_1 L_1 - n_2 L_2) = \frac{2\pi n}{\lambda}\Delta L, \tag{2}$$

where λ is the central wavelength of laser. n and L are the effective index and length of two arms, respectively. The two arms of the interferometer are about 40 cm long with a 5 mm difference between each other. These two arms are bended side by side without overlap in a semicircle and fixed on a plastic substrate, which can be integrated in a cushion. When the subject sits on the cushion, the body recoils resulted from heartbeats introduces phase difference in the interferometer, which can change the output intensity. The output signal can be detected by the PD, which is the BCG signal.

2.3 Phase shifter

The phase shifter used in the BCG monitor is a moving-coil transducer. This transducer is low cost and in a compact size, which is 18(Length)×12(Width)×3(Height) mm. The transducer is embedded in the plastic substrate and the arm of MZI is tightly fixed on the transducer. The tiny displacement variation from the transducer can introduce the strain to the optical fiber interferometer and thus the phase can be modulated by the transducer. The insertion loss of the system is nearly zero since the light never propagates through other optical elements except the optical fiber. In addition, compared with traditional PZT phase modulation method, the bending loss introduce by coiled fiber will be eliminated [9]. As shown in the Figure. 3, the output signal of MZI will vary with the increasing driven current of phase shifter. It can be calculated from the figure that the induced phase change is about 0.22 rad/mA.

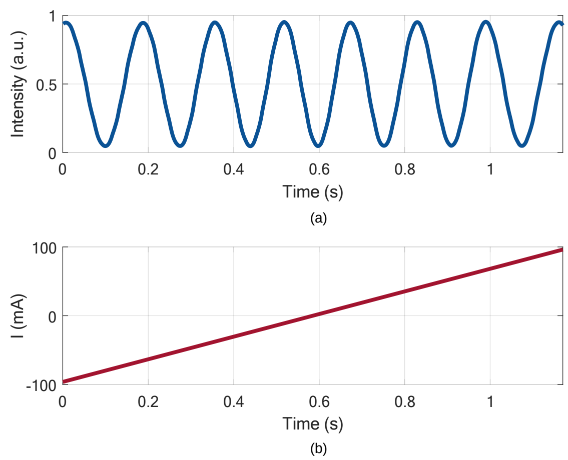

Figure 2. Relationship between output signal in the MZI and driven current.

2.4 PID controller

The PID controller is used in the system to control the phase shifter and maintain the MZI system in quadrature. The principle of the PID controller can be described in the Figure 3. Set point (SP) and process variable (PV) are the desired value of system and feedback value, respectively. Error is the difference between SP and PV, which represents the deviation degree from the desired value in the system. After obtaining error from the subtractor, PID controller will output the control variable (CV) according to the following equation [10]:

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$$U(t)=K_P\left(e(t)+\frac{1}{T_I}\int e(t)dt+T_D\frac{de(t)}{dt}\right), \tag{3}$$

Where U(t) is CV, and e is error. The K_P, T_I and T_D are coefficients of proportional, integral and derivative controller. In our experiment, SP is equal to the half peak-to-peak value of optical intensity output and PV is the output of CH2. CV is the driven current of phase shifter. Therefore, the PID controller can adjust the driven current of phase shifter to change the phase in the system and maintain the output in quadrature.

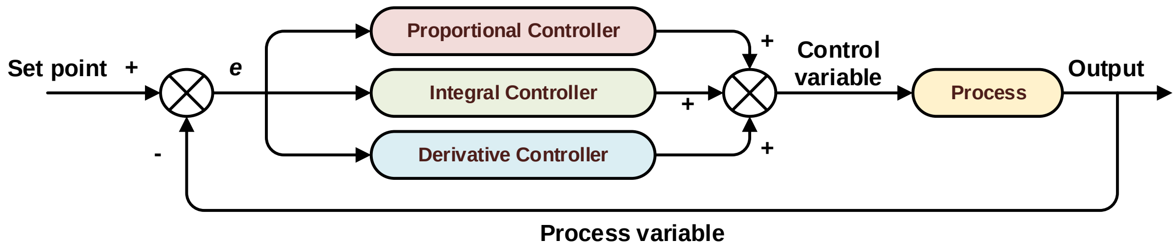

Figure 3. Principle of PID controller.

3. EXPERIMENT AND RESULT

During the experiment, the subjects are asked to sit on the cushion and remain still, vibration signals from body recoils in reaction to heartbeat can be caught by the BCG monitor and recorded by DAQ card (NI, USB6001) at the sampling rate of 500 Hz. To compare the improved result introduced by closed loop control system, the raw data of BCG signals detected by MZI-based monitor with and without phase modulation method are shown in the Figure. 4. The BCG signal in the Figure. 4(a) is the 20 second raw data obtained by the MZI without phase modulation. It is easy to find that the signal in the red dashed box is severely distorted since the working point is far from the quadrature point. In addition, by contrasting the J peaks in two yellow dashed boxes, we can find that the direction of two J peaks are opposed since the working point changes from rising edge to falling edge. The BCG signal in the Figure. 4(b) shows the 20 second raw data detected by the MZI with phase modulation method. This BCG signal is stable and has no need for any filter to remove baseline drift introduced by breath and ambient noise. In addition, the J peaks in the BCG signal are in the same direction. Consequently, the phase modulation method guarantees that the obtained BCG signals contain completed meaningful information, including I, J, K peaks.

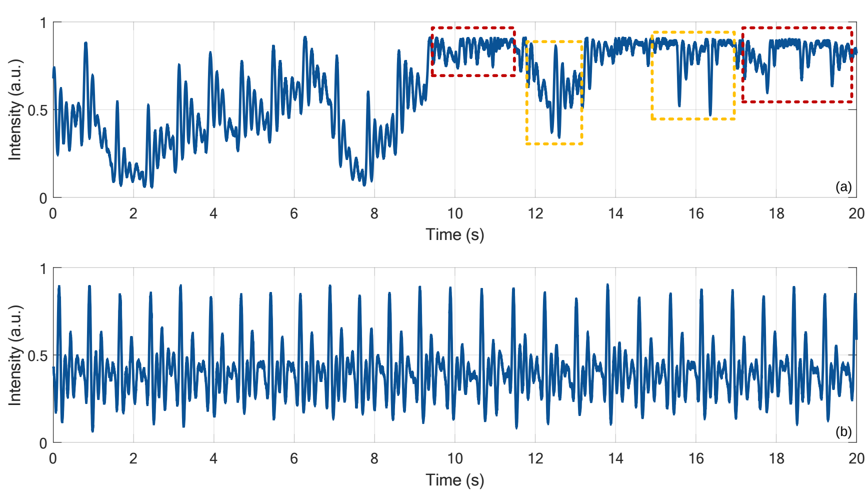

Figure 4. Raw BCG data detected with (a) and without (b) phase modulation.

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Figure. 5 shows the raw BCG signals from 7 subject based on the MZI with phase modulation and each data lasts for 10 second. It can be clear seen that the baseline introduced by breath and ambient noise can be eliminated by the phase modulation method. Most J peaks of subjects with different heartbeat rate can be detected clear by the monitor. The result shows that the proposed BCG monitor has great competitiveness in the application of long-term heartbeat monitoring.

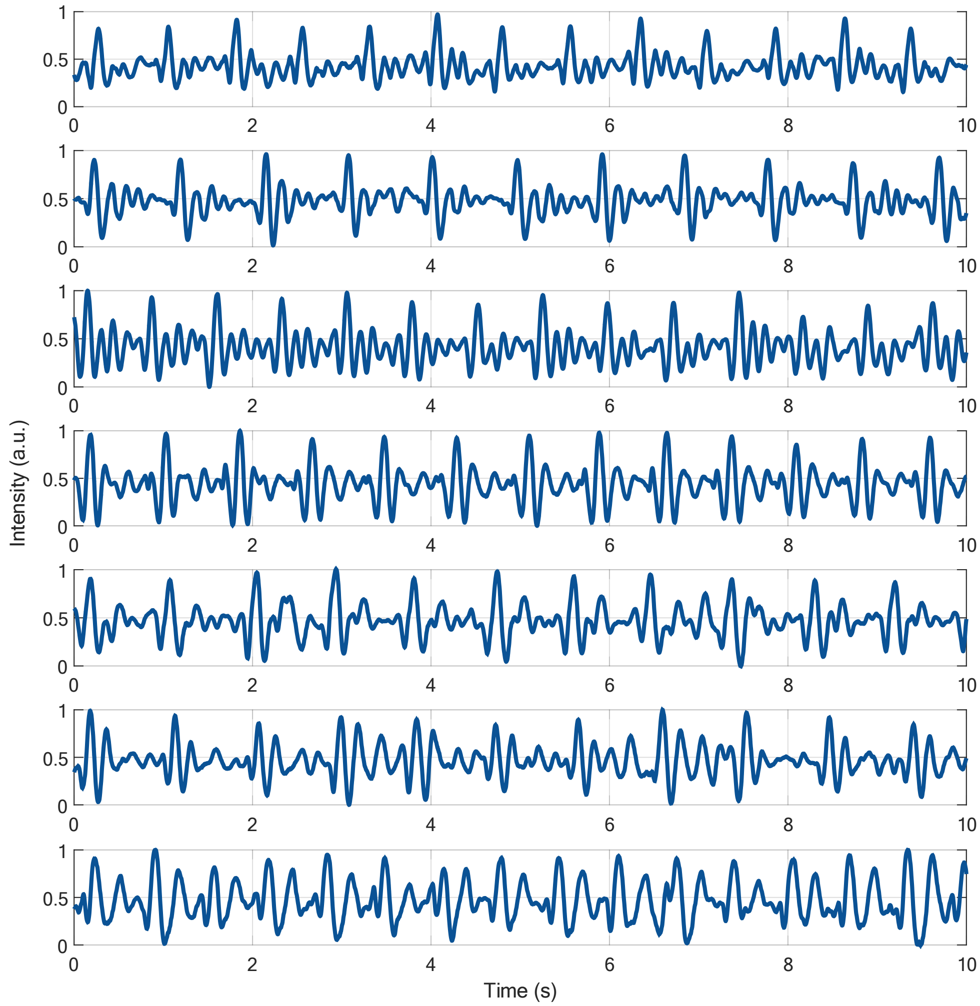

Figure 5. Raw BCG signal from 7 subjects.

4. CONCLUSION

In this paper, we demonstrate an optical fiber interferometer-based BCG monitor utilizing a low-cost and easily integrated phase modulation method. The proposed moving-coil transducer-based phase shifter can maintain the optical fiber MZI system in quadrature by the PID controller, which addresses the problem of signal fading. More than that, the phase modulation method can also compensate the baseline drift introduced by the breath and noise. In conclusion, optical fiber sensor has numerous intrinsic merits of optical fiber including low cost, high sensitivity, immune to electromagnetic interference, light weight. The proposed MZI-based BCG monitor can provide a stable and long-term heartbeat monitoring for users, which has the tremendous potential in the field of biomedical.

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5. ACKNOWLEDGMENT

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REFERENCES

[1] J. W. Gordon, "Certain molar movements of the human body produced by the circulation of the blood," J. Appl. Physiol. 11(Pt 3), 533–536 (1877).

[2] I. Starr, A. J. Rawson, H. A. Schroeder, and N. R. Joseph, "Studies on the estimation of cardiac output in man, and of abnormalities in cardiac function, from the heart's recoil and the blood's impacts; the ballistocardiogram," Am. J. Physiol. 127(1), 1–28 (1939).

[3] O. T. Inan, M. Etemadi, R. M. Wiard, L. Giovangrandi, and G. T. A. Kovacs, "Robust ballistocardiogram acquisition for home monitoring," Physiol. Meas. 30(2), 169–185 (2009).

[4] O. T. Inan, M. Etemadi, A. Paloma, L. Giovangrandi, and G. T. A. Kovacs, "Non-invasive cardiac output trending during exercise recovery on a bathroom-scale-based ballistocardiograph," Physiol. Meas. 30(3), 261–274 (2009).

[5] J. Alametsä, A. Palomäki, and J. Viik, "Short and longer term repeatability of ballistocardiography in a sitting position with EMFi sensor," Med. Biol. Eng. Comput. 49(8), 881-889 (2011).

[6] Ł. Dziuda, M. Krej, and F. W. Skibniewski, "Fiber Bragg grating strain sensor incorporated to monitor patient vital signs during MRI," IEEE Sens. J. 13(12), 4986-4991 (2013).

[7] M. A. Hassan, A. S. Malik, D. Fofi, N. M. Saad, Y. S. Ali, and F. Meriaudeau, "Video-based heartbeat rate measuring method using ballistocardiography," IEEE Sens. J. 17(14), 4544-4557 (2017).

[8] O. Postolache, R. N. Madeira, P. S. Girão, and G. Postolache, "Microwave FMCW Doppler radar implementation for in-house pervasive health care system," 2010 IEEE International Workshop on Medical Measurements and Applications (MeMeA), 47-52, (2010).

[9] D. A. Jackson, R. Priest, A. Dandridge, and A. B. Tveten, "Elimination of drift in a single-mode optical fiber interferometer using a piezoelectrically stretched coiled fiber," Appl. Opt. 19, 2926-2929 (1980).

[10] K. H. Ang, G. Chong and Y. Li, "PID control system analysis, design, and technology," IEEE Trans. Control Syst. Technol. 13(4), 559-576 (2005).

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